Detection, quantification and monitoring *Prosopis spp*. in the Northern Cape Province of South Africa using Remote Sensing and GIS

E.C. Van den Berg

Dissertation submitted in partial fulfilment of the requirements

for the degree of M. Environmental Science at the

Potchefstroom Campus of the North-West University

Supervisor: Prof. Klaus Kellner

Co-supervisor: Dr. Habil. Eng. Stalislaw Lewinski

May 2010

DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Signature: ……………………………………..

Date: ………………………………………

ABSTRACT

Invasive *Prosopis* trees pose significant threats to biodiversity and ecosystem services in the Northern Cape Province of South Africa. Several estimates have been made of the spatial extent of alien plant invasion in South Africa. The South African Plant Invaders Atlas (SAPIA) suggested that about 10 million hectares of South Africa has been invaded. However, the rate and spatial extent of *Prosopis* invasion has never been accurately quantified. The objective of the study is to use Remote Sensing and Geographic Information System (GIS) techniques to: (i) reveal areas susceptible to future invasion, (ii) describe the current extent and densities of *Prosopis*, (iii) to reveal the spatial dynamics and (iv) establish the extent of fragmentation of the natural vegetation in the Northern Cape Province.

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 *Prosopi*s 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 hectare 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 Northern Cape Province of South Africa demonstrated a high degree of accuracy (72%). While neither the image classification nor the probability map can be considered as 100% accurate representations of *Prosopis* density and distribution, the products provide use full information on *Prosopis* distribution and are a first step towards generating more accurate products. For primary invasion management, these products and the association of a small area on a map with *Prosopis* plants and patches, mean that the management effort and resources are efficiently focused.

Further studies using hyper-spectral image analysis are recommended to improve the classification accuracy of the spatial extent and density classes obtained in this study.

Keywords: Remote Sensing, GIS, *Prosopis* spp., invasion, extent, spatial dynamics and ragmentation

OPSOMMING

Indringer *Prosopis*bome veroorsaak aansienlike versteuring aan die biodiversiteit en ekosisteemdienste in die Noordkaapprovinsie van Suid-Afrika. Verskeie skattings van die ruimtelike omvang van uitheemse indringerplante in Suid-Afrika is al gemaak. Die Suid-Afrikaanse Plant Indringer Atlas (SAPIA) skat die area wat reeds ingedring is in die omgewing van 10 miljoen hektaar. Die spoed en ruimtelike verspreiding van *Prosopis* is egter nog nooit ruimtelik akuraat gekwantifiseer nie.

Die hoofdoel van hierdie studie was dus om deur die gebruik van afstandswaarneming en Geografiese Inligting Stelsels (GIS) (i) die areas van moontlike indringing te bepaal, (ii) die huidige verspreiding en digthede te beskryf, (iii) die dinamika van verspreiding te bepaal en (iv) te bepaal wat die fragmentasie van die plantegroei is as gevolg van die indringing van *Prosopis*.

Satelietbeelde is geklassifiseer deur gebruik te maak van seisoenale spektrale analise, plantegroei-indekse, verskeie resolusiebeelde, grondinligting en vloeipatrone, asook terreineenhede. Klassifikasieprosedures het verskil na gelang van die ruimtelike resolusie en die doel waarvoor die data gebruik gaan word. Lae resolusiebeelde en veldinligting van die ware voorkoms van *Prosopis* is gebruik om ‘n kaart te skep van moontike areas van indringing. Klassifikasie van beelde van 5 verskillende jare asook ‘n punt-datastel is gebruik om die ware voorkoms van *Prosopis* te kwantifiseer en om die verandering van indringing oor die laaste 30 jaar sedert 1974 te bepaal. Die fragmentasie en verandering van natuurlike plantegroeitipes is gekwantifiseer deur die digtheid van *Prosopis*kolle per hektaar in elke Bioom te bepaal.

Prosopis het reeds oor ‘n area van 1.473 miljoen hektaar of 4% van die totale oppervlak van die Noordkaapprovinsie versprei gedurende 2007. Die vermoeë van dié afstandswaarneming en GIS-tegnieke was baie suksesvol om *Prosopis* te karteer en het ‘n akkuraatheid van 72% behaal. Alhoewel die klassifikasie nie as die werklike verteenwoordiging van die bome gesien kan word nie, verskaf die kaarte waardevolle inligting oor die verspreiding van *Prosopis* en kan die data gesien word as die eerste stap in die proses om meer akurate kaarte te skep. Die gebruik van “hyper-spectral” satelietdata vir meer akurate klassifikasie van die verpreiding en digthede van *Prosopis* word voorgestel.

Sleutelwoorde: Afstandswaarneming, GIS, *Prosopis* spp., indringing, verspreiding, dinamika en fragmentasie.

DEDICATION

I would like to dedicate this study to a late friend and colleague Wendy Lloyd. I wish you were here to see me finish what we started 13 years ago.

ACKNOWLEDGEMENTS

The author would like to acknowledge the following people and institutions that made the successful completion of this study possible:

Prof. Klaus Kellner and Dr. Stanislaw Lewinski, my supervisors, for their input, support and advice;

Hennie van den Berg for all his advice, especially during the image processing and classification stages of this study;

Terry Newby and Ian Kotze at the ARC-ISCW, for giving me the opportunity to work on this project and for their inputs;

The Department of Water Affairs and Forestry – Working for Water Program who funded this project;

The Satellite Application Centre, especially Betsie Snyman, for providing me with the 2004 and 2007 Landsat data;

Ria Joubert and Maureen Fritz who travelled many kilometres with me to assist with field data collection;

Herman Stander, Arlo Biddulph en Eric Economon for assistance with the aerial surveys.

The ARC-ISCW for financial support;

Colleagues at the ARC-ISCW (Pretoria), especially Dawie van Zyl for providing all the NOAA/AVHRR and MODIS data as well as Philip Beukes and Anelda Doftling for IT support the past three years;

My two colleagues Maureen and Santie at the ARC-ISCW satellite office for providing climate data.

My husband Hennie, and two children Martinè and Maartens for their love, support and understanding when I had to share my time between them and work;

To my family and friends for their love, support and motivation.

ABBREVIATIONS AND GLOSSARY

Abbreviation or term	**Definition**
Ae	Red-yellow apedal, freely drained soil. Red, High base status, > 300mm deep, no dunes
Af	Red-yellow apedal, freely drained soil. Red, high base status, >300mm deep, with dunes
Ag	Red-yellow apedal, freely drained soil. Red, high base status, < 300mm deep.
AGIS	Agricultural Geo-Referenced Information System
Ah	Red-yellow apedal, freely drained soil. Red and Yellow, high base status, usually <15% clay
Ai	Red-yellow apedal, freely drained soil. Yellow, high base status, usually < 15% clay
ARC	Agricultural Research Council
ARC-ISCW	Agricultural Research Council-Institute for Soil Climate and Water
ArcGis	Is a suite consisting of a group of geographic information system (GIS) software products produced by ESRI
ARC-PPRI	Agricultural Research Council-Plant Protection Research Institute
Bd	Plinthic catena: Upland duplex and margalitic soils rare. Eutrophic: red soils not widespread.
Broad soil pattern	Is used to indicate the soils of an area. Land types are numbered according to broad soil patterns. Each land type was allocated a number by placing it in the broad soil pattern which accommodated it and then given the next available number in that soil pattern. Thus land type Ea39 was given to he thirty-ninth land type which qualified for inclusion in broad soil pattern (or map unit) Ea
Ca	Plinthic catena: Upland duplex and/or margalitic soils common. Undifferentiated.
CARA	Conservation of Agricultural Resources Act
CGIAR	Consultative Group on International Agricultural Research

CSIR	Council for Scientific and Industrial Research
Da	Prismacutanic and/or pedocutanic diagnostic horisons dominant. Red B horizons.
Db	Prismacutanic and/or pedocutanic diagnostic horisons dominant. B horizon not red.
Dc	Prismacutanic and/or pedocutanic diagnostic horisons dominant. In addition one or more of: vertic, melanic, red structured diagnostic horizons
DEM	Digital Elevation Model
DWAF	Department of Water Affairs and Forestry
Ea	One or more of: vertic, melanic, red structured diagnostic horizons. Undifferentiated
EM	Electromagnetic
EMS	Electromagnetic System
ERDAS	Is a raster graphics editor and remote sensing application designed by ERDAS, Inc. The latest version is 2010. It is aimed primarily at geospatial raster data processing and allows the user to prepare, display and enhance digital images for mapping use in GIS or in CADD software. http://www.erdas.com
ETM+	Enhanced Thematic Mapper
EVI	Enhanced Vegetation Index
Fa	Glenrosa and/or Mispah Forms (other soils may occur). Lime rare or absent in the entire landscape.
Fb	Glenrosa and/or Mispah Forms (other soils may occur). Lime rare or absent in upland soils but generally present in low-lying soils.
Fc	Glenrosa and/or Mispah Forms (other soils may occur). Lime generally present in the entire landscape
GIS	Geographical Information System. A geographic information system (GIS), is any system that captures, stores, analyzes, manages, and presents data that are linked to a location
GLCN	Global Land Cover Network

GPS	Global Positioning System
Ha	Grey regic sand. Regic sands dominant
Hb	Grey regic sand. Regic sands and other soils.
IR	Infra Red
Ia	Miscellaneous land classes. Undifferentiated deep deposits
Ib	Miscellaneous land classes. Rock areas with miscellaneous soils.
Ic	Miscellaneous land classes. Rock with little or no soil
ISODATA	Interactive self-organised clustering procedure
ISSG	Invasive Species Specialist Group
Land Type	Denotes an area that displays a marked degree of uniformity with respect to terrain form, soil pattern and climate
LAI	Leaf Area index
LP DAAC	Land Processes Distributed Active Archive Center
TNTmips	Is a geospatial analysis system providing a fully featured GIS, RDBMS, and automated image processing system with CAD, TIN, surface modeling, map layout and innovative data publishing tools. http://www.microimages.com/
MODIS	Moderate Resolution Imaging Spectroradiometer
MSS	Multi-Spectral Scanner
NAIPS	National Alien Invasive Plant Survey
NDVI	Normalized Difference Vegetation Index
NIR	Near Infra Red
NLC	National Land Cover
NLC2000	National Land Cover 2000
NOAA/AVHRR	National Oceanic and Atmospheric Administration/Advanced Very High Resolution

	Radiometer
R	Red
Remote Sensing	Is the small- or large-scale acquisition of information of an object or phenomenon, by the use of either recording or real-time sensing device(s) that are wireless, or not in physical or intimate contact with the object (such as by way of aircraft, spacecraft, satellite, buoy, or ship)
SAC	Satellite Application Centre
SAPIA	South African Plant Invaders Atlas
SPOT	Satellite Pour l'Observation de la Terre
SRTM	Shuttle Radar Topography Mission
TM	Thematic Mapper
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VI	Vegetation Index
WEB2007	Web based climate database of the ARC-ISCW
WfW	Working for Water
WGS84	World Geodetic System 84

TABLE OF CONTENTS

DECLARATION... i

ABSTRACT ii

OPSOMMING iv

DEDICATION v

ACKNOWLEDGEMENTS.. vi

ABBREVIATIONS AND GLOSSARY vii

TABLE OF CONTENTS xi

LIST OF FIGURES... xvi

LIST OF TABLES xx

LIST OF APPENDICES.. xxi

CHAPTER 1: INTRODUCTION 1

1.1. Invasive plants 1

1.2. Conditions that lead to plant invasions 2

1.2.1. Invasion pathways...2

1.2.2. Invasive species characteristics 2

1.2.3. Invaded community characteristics 3

1.3. Impacts of invasive alien species 3

1.3.1. Ecological impact 3

1.3.2. Socio-economic impacts 5

1.4. Legislation on invasive plants in South Africa...6

1.5. Prevention and control of invasive alien plants..7

1.6. Problem statement...9

1.7. Objectives..10

CHAPTER 2: LITERATURE REVIEW 12

2.1. Historical review..12

2.2. Present trends in the mapping of *Prosopis* spp. in South Africa 13

2.3. Gaps in knowledge 14

2.4. Remote Sensing 15

2.4.1. Spectral reflectance of vegetation 15

2.4.2. Remotely sensed data 16

2.4.3. Spectral vegetation indices 18

2.4.4. Normalized Difference Vegetation Index 18

2.4.5. Enhanced Vegetation Index 19

2.5. Characteristics of *Prosopis* species 20

2.5.1. Botanical description and natural habitat 20

2.5.2. Invasive status 22

CHAPTER 3: STUDY AREA 23

3.1. Geographical location 23

3.2. Climate 24

3.3. Vegetation 25

3.4. Geology 29

3.5. Soils 29

3.6. Land use and management 31

3.6.1. Mining 31

3.6.2. Agriculture 32

3.6.3. Conservation 32

3.6.4. Land cover 35

CHAPTER 4: MATERIALS AND METHODS 37

4.1. Software 37

4.2. Datasets 37

4.2.1. Satellite data 37

4.2.1.1. The use and application of different resolution images 38

4.2.1.2. The National Oceanic and Atmospheric Administration/ Advanced Very High Resolution Radiometer (NOAA/AVHRR) satellite system. 39

4.2.1.3. The Moderate Resolution Imaging Spectroradiometer (MODIS) satellite system 40

4.2.1.4. Landsat 40

4.2.1.5. The SPOT 5 satellite system 41

4.2.2. Ancillary data 44

4.2.2.1. Field data collection..44

4.2.2.2. Land Types of South Africa 45

4.2.2.3. Digital Elevation Model (DEM)..46

4.2.2.4. Climate information 46

4.3. Areas susceptible to *Prosopis* invasion 46

4.3.1. Generalised Soil Classes of South Africa 47

4.3.2. Terrain units and flow path data 48

4.3.3. Satellite Data..52

4.3.3.1. Pre-processing of coarse and medium resolution imagery 52

4.3.3.2. Seasonal profiles...52

4.3.3.3. Processing of coarse and medium resolution satellite data 58

4.3.4. Construction of *Prosopis* probability map 59

4.4. Mapping the actual and historic extent of *Prosopis* using Landsat images 59

4.4.1. Pre-processing of imagery 60

4.4.2. Spectral Vegetation Indices...61

4.5. Analysis of the extent of *Prosopis* using Landsat data 64

4.5.1. Invasion history of *Prosopis* as derived from satellite images 65

4.5.2. Current extent and density of *Prosopis*..66

4.5.3. Spatial dynamics of *Prosopis* 66
4.5.4. Transformation and fragmentation of natural vegetation by *Prosopis* 66
4.6. Accuracy assessment of classifications 66
CHAPTER 5: RESULTS AND DISCUSSION 69
5.1. Results....69
5.1.1. Areas susceptible to invasion 69
5.1.2. Invasion history of *Prosopis* from 1974 to 2007 71
5.1.3. Extent and densities of *Prosopis* canopy cover for 2007 76
5.1.4. Spatial dynamics of *Prosopis* in the Northern Cape Province 81
5.1.5. Fragmentation of natural vegetation in the Northern Cape Province by *Prosopis* 85
5.1.6. Assessment of classification accuracies 87
5.2. Discussion 89
5.2.1. Areas susceptible to *Prosopis* invasion 89
5.2.2. Invasion history of *Prosopis* from 1974 to 2007 90
5.2.3. Extent and densities of *Prosopis* canopy cover for 2007 90
5.2.4. Spatial dynamics of *Prosopis* 90
5.2.5. Quantifying the spread of *Prosopis* spp. in the major natural vegetation types 91
5.2.6. Assessment of classification accuracies 92
CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS 93
6.1. Summary 93
6.2. Conclusions 93
6.3. Limitations of the data 96
6.4. Recommendations 96
REFERENCES 98

APPENDICES 109

LIST OF FIGURES

Figure 2.1: *Prosopis* distribution and abundance in the Northern Cape Province according to the SAPIA database (Henderson, 1998). Coloured squares indicate the abundance of the species in each quarter-degree cell. Red squares indicate areas of high abundance and white squares areas of no abundance. 13

Figure 2.2. Typical spectral reflectance curves of common earth surface materials in the visible and near to mid-infrared range. The positions of spectral bands for some remote sensors are also indicated (AMU, 2006)..16

Figure 2.3: A dense stand of *Prosopis* in a floodplain in the Northern Cape Province....20

Figure 3.1: Regional map of the Northern Cape Province of South Africa. 23

Figure 3.2: Detailed map of the Northern Cape Province of South Africa 24

Figure 3.3: Average annual rain fall of the Northern Cape Province (WEB2007, 2007). Rainfall increases gradually from west to east. Most of the northern, eastern and central areas of the province receive their rain during summer, whereas the western and southern parts lie within the winter rainfall area. 25

Figure 3.4: Biomes and Vegetation Types of the Northern Cape Province (Low and Rebelo, 1996). Vegetation types are colour coded according to the different biomes. 26

Figure 3.5: Generalised Soil Classes of the Northern Cape Province (Land Type Survey Staff, 1972-2006). The soil classes associated with *Prosopis* occurrence are described in Table 4.2. 31

Figure 3.6: Location of protected areas per biome in the Northern Cape Province (SANParks, 2010). 33

Figure 4.1: Spatial resolution or pixel size. High resolution images provide better accuracy but low spatial resolution images provide better temporal information on a national and regional scale. Tree stand areas are over estimated (6.2ha vs. 1.6ha) with low spatial resolution data compared to higher spatial resolution data. 39

Figure 4.2: Arial photographs of the four canopy density classes used in the study. 45

Figure 4.3: Flow chart of the process followed and data used to create the probability map of areas susceptible for *Prosopis* invasion on a provincial or a regional scale. Green squares indicate the raw datasets used in die study. Blue squares represent datasets created from the raw datasets and orange squares the processes used to create the datasets used as input (yellow squares) into the model to create the *Prosopis* probability map (yellow square with thick red outline). 47

Figure 4.4: Terrain units where 1 represents a crest, 2 scarp, 3 a mid slope, 3(1) a secondary mid slope, 4 a foot slope and 5 a valley. 49
Figure 4.5. Detailed image of the different classes of flow paths created from the DEM data. Flow paths were buffered according to size to improve the uplands and lowlands dataset. Derived from SRTM DEM (CGIAR, 2008). 50
Figure 4.6: Detailed image of the terrain units created using the DEM. The small areas (clatter) of uplands (green) in between the larger lowlands (yellow) before any filters were applied are visible. Derived from SRTM DEM (CGIAR, 2008).......................51
Figure 4.7: Detailed image of the improved uplands and lowlands dataset, after the filters were applied and the buffered flow paths merged with the terrain units. Derived from SRTM DEM (CGIAR, 2008). 52
Figure 4.8: The median NOAA/AVHRR value per point (Y-axes) over four growing seasons was calculated for each vegetation cover class and plotted against each decile (X-axes). 53
Figure 4.9: Mean NOAA/AVHRR NDVI with annual rainfall for the 1997/1998 season at available weather stations indicated by points (WEB2007, 2007)..........................54
Figure 4.10: Mean NOAA/AVHRR NDVI with annual rainfall for the 1998/1999 season at available weather stations indicated as points (WEB2007, 2007)..........................55
Figure 4.11: Mean NOAA/AVHRR NDVI with annual rainfall for the 1999/2000 season at available weather stations indicated as points (WEB2007, 2007)..........................56
Figure 4.12: The median EVI values over nine growing seasons (Y-axes) plotted against the 16 day EVI bands (B) (X-axes) for each vegetation cover class. 57
Figure 4.13: The median EVI values (Y-axes) for *Prosopis* over nine seasons (X-axes) from 2000 to 2009. 57
Figure 4.14: The average rainfall (Y-axes) for the period 2000 to 2008 (X-axes) for the Northern Cape Province. 58
Figure 4.15: Flow chart of the process followed to create the data on the historic and current extent of *Prosopis* invasion. Green squares indicate the raw datasets used and purple squares the final raster datasets of the extent of *Prosopis*. Orange squares indicate the processing performed on the datasets. The final vector datasets are indicated by yellow squares with thick red outlines. 60
Figure 4.16: Scaled IR/R images with five *Prosopis* canopy density classes and a cultivation class. 62
Figure 4.17: Classified and masked IR/R image with five *Prosopis* canopy density

classes and a cultivation class. 63

Figure 4.18: Classified IR/R images of *Prosopis* canopy density classes after the filters were applied. 64

Figure 4.19: Flow chart explaining the use of the historic and current data of the extent of *Prosopis* to perform different analysis on the spatial data. The yellow squares indicate the datasets used for the analysis of the historic and current data (purple squares). Blue squares indicate the type of analysis done on the data. Green squares indicate raw datasets used for the study. 65

Figure 4.20: Distribution of the combined accuracy assessment points selected from the NLC2000 and NAIPS datasets. 68

Figure 5.1: The distribution correspondence between the actually mapped density classes (points) of the Landsat 2007 data and the MODIS probability classes. 70

Figure 5.2: *Prosopis* cover during 1974 for an area between Kenhardt, Brandvlei and Van Wyksvlei is indicated by the amount and distribution of the points. The *Prosopis* density classes at the points are indicated by the different colours in the map legend. 72

Figure 5.3: *Prosopis* cover during 1990 for an area between Kenhardt, Brandvlei and Van Wyksvlei is indicated by the amount and distribution of the points. The *Prosopis* density classes at the points are indicated by the different colours in the map legend. 73

Figure 5.4: *Prosopis* cover during 2002 for an area between Kenhardt, Brandvlei and Van Wyksvlei is indicated by the amount and distribution of the points. The *Prosopis* density classes at the points are indicated by the different colours in the map legend. 74

Figure 5.5: *Prosopis* cover during 2007 for an area between Kenhardt, Brandvlei and Van Wyksvlei is indicated by the amount and distribution of the points. The *Prosopis* density classes at the points are indicated by the different colours in the map legend. 75

Figure 5.6: Expansion of *Prosopis* cover from 1990 to 2007 for an area between Kenhardt, Brandvlei and Van Wyksvlei, visually displayed by the 500m grid points indicating the presence of *Prosopis* using a different colour point for each year. 76

Figure 5.7: A patch of closed *Prosopis* trees consisting of a mixture of small and big multi-stemmed trees. 78

Figure 5.8: A patch of sparse *Prosopis* trees consisting mostly of small multi-stemmed

trees. 79
Figure 5.9: *Prosopis* cover during 2007 for an area between Van Wyksvlei and Carnarvon is indicated by the coloured areas on the map. The *Prosopis* density classes are indicated by the different colours in the map legend. 80
Figure 5.10: Comparison between percentage *Prosopis* invasion per catchment and area of moderately and dense infestation indicated by the size of the purple circles. 81
Figure 5.11: The increase in number of *Prosopis* patches per canopy density class from 1974 to 2007. 83
Figure 5.12: Increase and decrease in canopy density between 1990 and 2007. Green points indicate the points where the canopy density class has increased and purple where the canopy density has decreased...84
Figure 5.13: Coalescences of small patches with low canopy cover to large patches with higher density canopy cover. 84
Figure 5.14: *Prosopis* invasion of biomes in the Northern Cape indicated by canopy cover points using different colours for each density class. 87

LIST OF TABLES

Table 3.1: Protected status of biomes in the Northern Cape Province (SANParks, 2010) 34
Table 3.2: Area calculation of the main land cover classes during 2000 (Van den Berg *et al.*, 2008) 36
Table 4.1: Main comparative characteristics of the NOAA/AVHRR, MODIS, Landsat and SPOT satellite sensors used in the study 43
Table 4.2: Properties of the Generalised Soil Classes associated with *Prosopis* as obtained from the National Land Type Survey (Land Type Survey Staff, 1972 – 2006)..48
Table 4.3: Buffer sizes used to for the different classes flow paths to improve the upland and lowland dataset 50
Table 5.1: Area estimations of MODIS probability map. 70
Table 5.2: Percentage correspondence between the Landsat classification using the 500m grid points and the MODIS probability map. 71
Table 5.3: Summary statistics for *Prosopis* cover from 1974 to 2007 71
Table 5.4: Percentage increase of *Prosopis* cover, in riparian zones and lowlands from one dataset to another 73
Table 5.5: Summary statistics of *Prosopis* cover during 2007.......................................77
Table 5.6: Summary of *Prosopis* patch dynamics per density class from 1974 to 2007 .82
Table 5.7: Summary of *Prosopis* invasion as percentage (%) and area (ha) in the five biomes of the Northern Cape Province for the vegetation types according to the different canopy density classes in 2007(Low and Rebelo, 1996) 85
Table 5.8: Transformation of biomes in the Northern Cape Province.............................87
Table 5.9: Error matrix of the relationship between reference data and the result of the 2007 Landsat image classification..88
Table 5.10: Errors of omission and commission describe the errors of the Landsat 2007 classification, based upon the results of the error matrix 88
Table 5.11: Quantifying the omission and commission error of the Landsat 2007 classification...89

LIST OF APPENDICES

Appendix 1: Field data collection sheet used to capture descriptive information of actual *Prosopis* occurrence. The information was used to create a spatial layer in a GIS to assist with the analysis of satellite images and other spatial data........................109

Appendix 2: NLC2000 field verification points for the Northern Cape Province (Van den Berg *et al*., 2008)..110

Appendix 3: National Alien Invasive Plant Survey (NAIPS) points for the Northern Cape Province (Kotze *et al*., 2009). 111

Appendix 4: Generalised Soil Patterns of South Africa for the Northern Cape Province (Land Type Survey Staff, 1972 – 2006)..112

Appendix 5: Flow paths for the Northern Cape Province. Derived from SRTM DEM (CGIAR, 2008). 113

Appendix 6: Terrain units for the Northern Cape Province. Derived from SRTM DEM (CGIAR, 2008). 114

Appendix 7: Digital Elevation Model (DEM) for the Northern Cape Province (CGIAR, 2008)..115

Appendix 8: Uplands and Lowlands for the Northern Cape Province. Derived from SRTM DEM (CGIAR, 2008)...116

Appendix 9: NOAA/AVHRR NDVI generated *Prosopis* probability classes with 1km resolution and five probability classes for the Northern Cape Province. 117

Appendix 10: MODIS EVI generated *Prosopis* probability classes with 250m resolution and five probability classes for the Northern Cape Province................................118

Appendix 11: MODIS probability map for *Prosopis* distribution for the Northern Cape Province. (Details can be seen on attached CD-Rom)...119

Appendix 12: *Prosopis* distribution and density classes in 1974 for the Northern Cape Province...120

Appendix 13: *Prosopis* distribution and density classes in 1990 for the Northern Cape Province...121

Appendix 14: *Prosopis* distribution and density classes in 2002 for the Northern Cape Province...122

Appendix 15: *Prosopis* distribution and density classes in 2004 for the Northern Cape Province...123

Appendix 16: *Prosopis* distribution and density classes in 2007 for the Northern Cape Province...124

Appendix 17: Map of the extent and densities of *Prosopis* in 2007 for the Northern Cape Province. (Details can be seen on attached CD-Rom)..125
Appendix 18: *Prosopis* infestation per quaternary catchment in 2007 for the Northern Cape Province...126
Appendix 19: Prosopis patch recruitment between 1990 and 2007 for the Northern Cape Province. 127
Appendix 20: Percentage *Prosopis* invasion of vegetation types in 2007 for the Northern Cape Province...128

CHAPTER 1: INTRODUCTION

1.1. Invasive plants

An introduced, alien, exotic, non-indigenous, or non-native species, is a species living outside its native distributional range, which has arrived there by human activity, either deliberate or accidental (Groom *et al*., 2006; Mampholo, 2006). Accidental introductions occur when species are dispersed by human transport such as airplanes and ships into new geographical regions (Itholeng, 2008). There are numerous examples of marine organisms being transported in ballast water, one being the zebra mussel, altering the physical conditions (e.g., water clarity), concentrations of key nutrients (e.g., nitrogen, phosphorus), and an array of biological conditions(e.g., species abundances of other benthic invertebrates, macrophytes, phytoplankton, zooplankton, fishes, and waterfowl) (Groom *et al*., 2006). Increasing rates of human travel are providing more opportunities for species to be accidentally transported into areas in which they are not considered native (Verling *et al*., 2005). Species are introduced deliberately or intentionally for economic, agricultural, aquaculture, recreation and ornamental purposes (Groom *et al*., 2006; Mampholo, 2006). Many non-native plants have been introduced into new environments, initially as either ornamental plants or for erosion control, animal fodder, or forestry (Van Wilgen *et al*., 2001). Examples in South Africa include the introduction of fish species such as Carb as a potential food source and the introduction of *Pinus spp.* as a commercial timber crop (Ciruna *et al*., 2004; Roura-Pascual *et al*., 2009).

The number of introduced species in South Africa is estimated at about 8000 shrub and herb species and 750 tree species (Groom *et al*., 2006). Fortunately only a small percentage of these introduced species are able to establish themselves in their new environment, and even a smaller percentage become invasive. An "invasive species" is defined as a species that is non-native (or alien) to a specific ecosystem that spreads rapidly by natural means, out competes native species and whose introduction is likely to cause economic or environmental harm (Groom *et al*., 2006; USDA, 2009).

One such introduction of a woody plant is *Prosopis.* The tree originated in the dry south westerly parts of the USA, Mexico and Chile, from where it was imported to South Africa at the turn of the century to provide shade, wood for fuel and pods for fodder (Wild and Du Plessis, 2007). Of the various *Prosopis* species and their hybrids, there are mainly two that flourish in South African conditions, namely *Prosopis glandulosa* (Honey mesquite) and *Prosopis velutina* (Velvet mesquite) (Visser, 2004). The nature of the tree and its extraordinary ability to adapt in extreme weather conditions, together with the high protein content of its pods which can be fed to animals in times of drought, made this a very valuable tree till the end of the 1950's (Wild and Du Plessis, 2007).

1.2. Conditions that lead to plant invasions

Most alien plants can survive in their adopted environment only if they are cared for, especially if the conditions in the adopted country differ a great deal from those they are adapted to (PPRI, 2007). However, a certain proportion of alien plants manages to thrive, reproduce and maintain populations without human help, and is then called naturalised plants. If such naturalised plants are able to spread over large distances into new, undisturbed, natural areas and replace the indigenous vegetation, they are regarded as invasive alien plants (PPRI, 2007). Whether an exotic plant will become invasive is seldom known, and many non-native plants languish in nature for years before suddenly naturalizing and becoming invasive. The success of any plant invasion is determined by the interaction between species and ecosystem characteristics (Kolar and Lodge, 2001). The incipient invasion depends on a series of criteria which are briefly discussed below.

1.2.1. Invasion pathways

First an invasion pathway must be in place and must deliver a sufficient number of quality organisms (Groom *et al*., 2006). Repeated patterns of human movement from one location to another, such as ships sailing to and from ports or cars driving up and down highways, allow for species to have multiple opportunities for establishment (also known as a high propagule pressure (Groom *et al*., 2006).

1.2.2. Invasive species characteristics

Invasive species appear to have specific traits or combinations of specific traits that allow them to out perform native species. Sometimes they just have the ability to grow and reproduce more rapidly than native species; other times it is more complex, involving a multiple number of traits and interactions (Groom *et al*., 2006).

Common invasive species traits include:

- The ability to reproduce both asexually as well as sexually.

- Fast growth.
- Rapid reproduction.
- High dispersal ability.
- Tolerance of a wide range of environmental conditions (generalist).
- Association with humans or animals.
- Lack of natural enemies.

An introduced species might become invasive if it can out-compete native species for resources such as nutrients, light, physical space, water or food. Some invasive species are also able to use resources previously unavailable to native species, such as deep water sources accessed by a long taproot, or an ability to live on previously uninhabited soil types. *Prosopis* species and their hybrids became invasive in the arid northern parts of South Africa because of their adaptability to the harsh climatic conditions, vigorous growth, high seed production leading to large seed banks, the absence of natural seed-feeding insects and efficiency of seed dispersal mechanism (Lloyd *et al*., 2002).

1.2.3. Invaded community characteristics

All biological communities can potentially be invaded when faced with the right introduced species, but some communities are more easily invaded than others. Conservation efforts can therefore be directed and prioritized to protect vulnerable communities (Groom *et al*., 2006). The main drivers promoting the establishment and spread of invasive alien species in a community can be both natural and socio-economical. Natural drivers include the climatic conditions such as temperature and rainfall, while disturbance regimes include fires, droughts and floods. Socio-economic drivers emerge directly from human activities (agriculture, mining, forestry and tourism), population dynamics, policies and invasive alien plant management (Roura-Pascual *et al.,* 2009).

1.3. Impacts of invasive alien species

1.3.1. Ecological impact

Invasive alien trees and shrubs pose significant threats to biodiversity and ecosystem services in South African Biomes (Roura-Pascual *et al.,* 2009; Van Wilgen *et al*., 2008).

The ecological impacts of invasive alien species on ecosystems vary significantly depending upon the type of invading species, the extent of the invasion, and the vulnerability of the ecosystem being invaded (Ciruna *et al*., 2004). Loss and degradation of biodiversity due to invasive alien species can occur throughout all biological levels from genetic and population levels to the species, community, and ecosystem levels, and may involve major alterations to physical habitat, water quality, essential natural resources and ecological processes (Ciruna *et al*., 2004). These impacts can vary in terms of the lapse of time between the initial introduction and subsequent spread of the specific invasive alien species (Levine, 2008)

Invaded impacts on ecosystems can be direct such as predation or parasitism, for example the brown tree snake which was introduced from Australia and New Guinea to Guam which caused a decline in the numbers of native bird's species (Groom *et al*., 2006). Indirect impacts include resource competition and habitat modification. Reviews of the effect of invasions suggest that the most damaging invasive species transform ecosystems by using excessive amounts of resources (water, light and oxygen), adding certain other resources (nitrogen), promoting or suppressing fire, stabilizing sand movement and/or promoting erosion, and accumulating litter or redistributing salt in the soil (Richardson, 2004). Such changes potentially alter the flow, availability and quality of water and nutrient resources in the biogeochemical cycles (Ciruna *et al*., 2004).

Biodiversity plays a key role in the delivery of ecosystem services (Van Wilgen *et al*., 2008). Despite the importance of the impact of invasive alien species on biodiversity, few studies have sought to estimate the impact on the delivery of ecosystem services on a broader scale (Le Maitre *et al*., 2000; Richardson, 2004; Van Wilgen *et al*., 2008). The few studies that have been done have either focused on a single ecological aspect such as water use (Enright, 2000; Le Maitre *et al*., 2000; Van Wilgen *et al*., 1997), quality and availability of nutrients (Geesing *et al*., 1998) or on a single species but for a small study area (Richardson, 2004). Research by Holmes and Cowling (as quoted by Richardson, 2004) has however shown that dense stands of alien trees and shrubs can reduce abundance and diversity of native plant species due to the decline of soil seed banks. In the arid environments the widespread replacement of *Acacia* dominated habitats by alien *Prosopis* species have radically changed the habitat for birds, leading to reduced species richness and diversity (Dean *et al*., 2002).

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. The destruction of riparian ecosystems and water use by invasive alien species in South Africa have been studied and documented by Blignaut *et al*., 2007, Holmes *et al*., 2005, Le Maitre *et al*., 2000, Le Maitre *et al*., 2002 and Van Wilgen *et al*., 1997. *Prosopis* invasion is estimated to use up to 192 million m^3 of water per year. A single *Prosopis* tree can use between 135 and 930mm water per year, with an average of between 350 and 500mm (Jordaan, 2009). It has been estimated that the additional volume of water used by the 10 million ha of alien vegetation across the country is about 3.3 billion cubic meters, roughly 7% of mean annual runoff (Versveld *et al*. 1998).

Other effects of invasive alien species include suppression and replacement of indigenous vegetation, increased transpiration and reduction in stream flow as a result of larger biomass of the invaders compared to indigenous vegetation (Cullis *et al*., 2007; Enright, 2000). No specific literature could be found regarding the competition of *Prosopis* with specific species within each biome. Through personal observation the following woody species could be considered as vulnerable species which may be at risk of being displaced by *Prosopis*: *Acacia karoo, Acacia erioloba, Acacia mellifera, Grewia flava* and *Boscia albitrunca.* Local soil erosion increases in areas densely invaded by alien trees, as the ground cover that provides surface stability is excluded by the alien canopy (Holmes *et al*., 2005). A further consequence may be the change to the natural fire regime, for example, a decrease in frequency following invasion by less flammable species or an increase in the intensity caused by flammable aliens altering the fuel structure or tree to grass ratio (Holmes *et al*., 2005).

1.3.2. Socio-economic impacts

Invasion by alien plants in South Africa results in many negative ecological impacts, as mentioned above. The positive benefits are often overlooked and need to be taken into account when assessing the economic impacts from invasions (Van Wilgen *et al*., 2001). Almost all the important crops in South Africa are harvested from alien plants, and only a small percentage of these alien plants become invasive. In addition, some invasive alien species have substantial value, despite their negative impacts. Conflicts of interest arise from time to time in cases where invaded species are used for economical benefits. These include forestry plantations (*Pinus* species) (Richardson, 1998); woody species used for fuel and firewood (*Acacia* species) (Higgins *et al*., 1997), species utilized for food (*Opuntia* species) (Brutsch and Zimmermann, 1993), fodder or nectar for bees (*Prosopis* species) (Pasiecznik, 1999), and where species have aesthetic or utilitarian value (ornamentals, shade trees or windbreaks).

Studies have however shown that invasive alien plant species can directly or indirectly affect the food security of local communities (Admasu, 2008). In areas where they spread, invasive species can destroy natural pasture, displace native trees, and reduce grazing potential of natural rangeland (Admasu, 2008) or compete for water and nutrients reducing the productivity of croplands (Mwangi and Swallow, 2005). Some invaders may even pose a health risk to people and animals, especially if they are poisonous or have defensive structures, such as spines or latex (Berhanu and Tesfaye, 2006).

Van Wilgen *et al*. (2001) states that it is difficult to express the economical impact (positive or negative) of invasions in monetary terms, as very few studies have attempted this. Turpie and Heydendrych (as quoted by Van Wilgen *et al*., 2001) estimated the value of harvesting wildflowers and plants used for recreational value in protected areas. Results have shown that harvesting income reduced from $9.7 to $2.3/ha and the recreational values of protected areas reduced from $8.3 to $1/ha, when pristine areas became invaded by alien plants. On the positive side, however, plantation forestry contribute $300 million to the South African economy and employ 100 000 people (Van Wilgen *et al*., 2001). The South African Working for Water (WfW) program has spent over $100 million on the removal of alien invasive plants between 1995 and 2000 (Van Wilgen *et al*., 2001), contributing to job creation and reduction in poverty. At a conservative expansion rate of 5% per annum, the impacts of aliens could double in 15 years (Versveld *et al*. 1998). The removal of invasive alien species is therefore a priority, although it is estimated to cost about R5.4 billion per year (DWAF, 1999).

1.4. Legislation on invasive plants in South Africa

The present South African legislation on invasive alien plants forms part of the Conservation of Agricultural Resources Act (CARA), 1983 (Act No 43 of 1983) (ARC-PPRI, 2006). Regulations 15 and 16 under this Act, which concern problem plants, were amended to include a comprehensive list of species that are declared weeds and invader plants and has also divided the species into four categories: declared weeds (Category 1 plants), plant invaders for commercial use (Category 2) and Category 3 plants characterized as invader plants for ornamental use, such as *Jacaranda* and *Lilium* species. The first three groups consist of undesirable alien plants and are covered by Regulation 15. Bush encroachers, which are indigenous plants that require sound management practices to prevent them from becoming problematic, are covered separately by Regulation 16. The actions required with regard to any plant species depend on the category in which the plant appears, and might differ from province to province.

Category 2 species such as *Prosopis* are problematic but are more commonly grown for commercial purposes or any viable and beneficial function, such as woodlots, fire belts, building material, animal fodder and soil stabilization. These invader plants can only be grown in areas demarcated as sites where such plants may be established and retained.

In terms of demarcation, any area where a water use license for stream flow reduction activities has been issued (in terms of section 36 of the National Water Act, 36 of 1998) (South Africa, 1998) is deemed to be demarcated in the terms of the CARA act. An example is a registered timber plantation. No area can be demarcated for the growing of Category 2 plants unless the land user is able to prove that the invader plants shall be confined to the area, and that the cultivation of the invader plants shall be strictly controlled. The land user also has to ensure that steps are taken to curb the spread of propagating material of the invader plants to land and inland water surfaces outside the demarcated areas. The species are regarded as weeds outside of these demarcated areas, and landowners are required to take steps to control the species where they occur on their properties.

1.5. Prevention and control of invasive alien plants

The control of invasive species is a key objective of the South African Government through initiatives such as the National Working for Water (WfW) program but requires considerable effort, time and money. Depending on how these programs are carried out, they may not always be effective (Richardson and Van Wilgen, 2004). The WfW program was started in 1995 to conduct and coordinate alien-plant management throughout SA. It has grown into one of the worlds' biggest programs dealing with invasive alien species (Richardson and Van Wilgen, 2004). Invaders are often not controlled by a single method or single chemical application. Government therefore needs a management tool such as a Geographic Information System (GIS) with up to date spatial information to better understand *Prosopis* invasion and to identify potential high risk ecosystems in order to manage the Working for Water program.

The strategy to prevent the further spread of *Prosopis* should start with strictly enforced quarantine procedures. Further introductions of weedy *Prosopis* species which could potentially cross-breed and produce more hybrids should be avoided. Other measures aim to prevent the spread of *Prosopis* seed. For example, stock should be quarantined before transport into uninfested areas, and animals should be fenced off from *Prosopis* infestations. Feral animal numbers could be reduced as part of *Prosopis* management. Infestations in upper catchments should be targeted for strategic control to prevent continual re-infestation of downstream sites (Csurhes, 1996; Weeds in Australia, 2003).

Chemical and mechanical methods have traditionally been used to control mesquite but current research is investigating the integration of traditional management practices (chemical and mechanical control) with fire, grazing management and biological control, which are more time- and cost-effective mechanisms.

The Agricultural Research Council's – Plant Protection Research Institute (ARC-PPRI) describes the following four basic methods of controlling invasive alien plants (ARC-PPRI, 2007):

Mechanical control: This involves removing the invasive plants or damaging them severely by physical actions such as uprooting, clear-felling, slashing, mowing, ring-barking or bark-stripping or by hauling aquatic weeds out of the water. Felled trees often coppice and the soil disturbance caused during the control action often stimulate the seeds to germinate after clearing. Therefore, follow-up actions are very important.

Chemical control: This involves the application of registered herbicides to the invasive plants or to the soil surrounding them, with the aim of killing or suppressing the plants. The choice of herbicides, the correct application method, dosage, time of application and follow-up actions are very important.

Biological control: This consists in the use of host-specific natural enemies such as *Algarobuis prosopis* and *Neltumius arizonensis* to reduce the populations of the invasive plant to an acceptable level. These are small beetles, feeding only on the seeds of *Prosopis.* Only seeds within the seed pods are damaged by the beetles. The seed pods and vegetative parts of the plants are not affected.

Indirect control: This refers to methods that are not primarily aimed at killing invasive plants, but that can contribute towards their control, such as:

Ploughing and over-sowing of an area with beneficial plant species such as grass to compete with seedlings (Weeds in Australia, 2003);

Fire can control some *Prosopis* spp. effectively (Mampholo, 2006). If necessary, mechanical control, such as chaining can be used before burning to provide enough fuel to generate the heat required to kill *Prosopis*. Fire is relatively inexpensive and, even when it does not kill the entire plant, can reduce seed production by removing vegetation and killing seed lying on the soil surface. Some *Prosopis* species are more resistant to fire, and re-sprout from the rootstock if the crown is removed by fire.

Grazing management is an important part of the integrated approach to *Prosopis* control for three reasons (Weeds in Australia, 2003):

- Cattle are mainly responsible for the spread of seeds and therefore infestations.
- Grazing may need to be reduced before burning in order to allow the build-up of sufficient fuel loads.
- Grazing should be discouraged after any control efforts, to encourage growth of perennial grasses and help reduce *Prosopis* seedling germination and establishment.

Preventing animal's access to infestations during seed drop will help reduce the spread and density of mesquite (Mampholo, 2006).

The best results are often obtained if two or more of the above methods are combined. This strategy is called integrated control.

1.6. Problem statement

As mentioned previously, a serious threat exists as a result of the consequences of the *Prosopis* species invasion in the Northern Cape Province of South Africa. These include:

- The loss of agricultural potential as these natural resources is already limited in the arid and semi-arid region of the country (Admasu, 2008).
- The negative impact of mono-stands and competition by *Prosopis* on the biodiversity within already over utilized drainage lines result in a reduction

of the carrying capacity of the rangeland (Van Wilgen *et al*., 2008).

- The negative impact on the water resources in areas where the ground water reserves are limited (Enright, 2000; Le Maitre *et al*., 2000; Van Wilgen *et al*., 1997).
- The increase in soil erosion (Holmes *et al*., 2005)
- Very limited spatial data of the historic and current extent of *Prosopis* spp. invasion are available to direct management interventions.

Several estimates have been made of the spatial extent of alien plant invasion in South Africa to try and address the above mentioned problems of *Prosopis* invasion in the Northern Cape Province. (Harding and Bate, 1991; Le Maitre *et al*., 2000; Richardson and Van Wilgen, 2004; Versveld *et al*., 1998). The most comprehensive set of records for the whole country is the South African Plant Invaders Atlas (SAPIA) by Henderson (1998) while a rapid reconnaissance in 1996/97 suggested that about 10 million ha of South Africa has been invaded (Richardson and Van Wilgen, 2004). There is evidence that *Prosopis* spp. has spread by an alarming rate over the past decades (Visser, 2004). 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. Most studies were done on a broad scale using expert local knowledge, or were carried out in small study areas focusing on different objectives, such as nutrient cycling or water use (Le Maitre *et al*., 2000).

Fortunately the availability of remotely sensed data and image processing techniques provide a cost and time effective means of mapping and monitoring the invasions, such as *Prosopis* spp. (Joshi *et al*., 2003; Lloyd *et al*., 2002). Because of their spatial, temporal and spectral characteristics, satellite data have been very effective in mapping and monitoring the status and distribution of plant communities (Coops *et al*., 2009; Robertson *et al*., 2008).

1.7. Objectives

This project specifically looked at using remotely sensed data to:

- Determine the invasion history of *Prosopis* spp. in the Northern Cape Province in South Africa over the past 30 years using remotely sensed data;

- Describe the current extent and densities of *Prosopis* spp. in the Northern Cape Province;
- Reveal the spatial dynamics of *Prosopis* spp. spread and the areas susceptible to future invasion, and
- Quantify the spread of *Prosopis* spp. in the major natural vegetation types in the Northern Cape Province;

The study used Remote Sensing and GIS techniques to map and monitor the current invaded areas and to predict and monitor areas susceptible to invasion over the long-term.

CHAPTER 2: LITERATURE REVIEW

2.1. Historical review

Several estimates have been made of the spatial extent of alien plant invasion in South Africa (Henderson, 1998; Le Maitre *et al*., 2000; Richardson and Van Wilgen, 2004). As already mentioned about 10 million ha of SA have been invaded by invasive alien plants (Richardson and Van Wilgen, 2004). However, the only systematic source of data on species abundance is the SAPIA database (Figure 2.1). SAPIA is an important resource for planning the effective control of invasive alien plants in South Africa and currently contains almost 60 000 locality records of 600 naturalized alien plant species in 1 500 quarter degree squares mainly in South Africa, Swaziland and Lesotho. The records include data from almost three decades. The SAPIA dataset only incorporates a roadside survey of the spread of *Prosopis* spp. in the Northern Cape Province and the whole of South Africa, as carried out by Lesley Henderson and other contributors, from 1979 – 1993 with no detailed indication of where the invasive alien species actually occur in a specific quarter degree square other than next to roads.

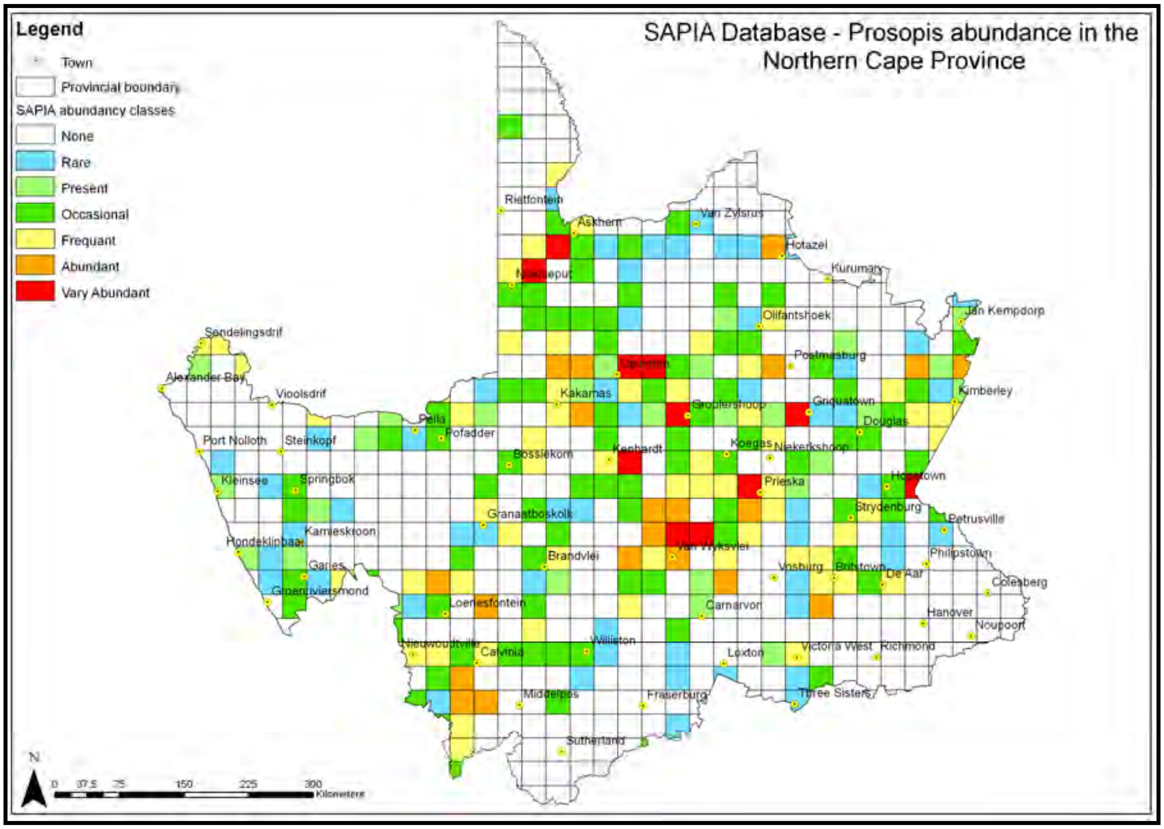


Figure 2.1: *Prosopis* distribution and abundance in the Northern Cape Province according to the SAPIA database (Henderson, 1998). Coloured squares indicate the abundance of the species in each quarter-degree cell. Red squares indicate areas of high abundance and white squares areas of no abundance.

Records of 1991 suggest that 180,000 ha were invaded (Harding and Bate, 1991) while a study by Versveld *et al*. (1998) in 1996/97 suggests that about 1,047 million ha of the Northern Cape have been invaded by *Prosopis*. Le Maitre *et al*. (2000) estimated the total area invaded by all alien invasive plants in the Northern Cape Province at 1 178 373 ha and total invasion by *Prosopis* in South Africa at 1 809 229 ha. According to Van Wilgen *et al*. (2001) the Nama Karoo Biome is the fourth most invaded biome. It is estimated that woody invaders, notably *Prosopis* trees, have invaded at least 18 000km² of the low lying alluvial plains and seasonal ephemeral water courses.

2.2. Present trends in the mapping of *Prosopis* spp. in South Africa

From the above section, it is evident that the information of the true extent of *Prosopis* invasions at different densities is poor and outdated, which limits our ability to accurately predict impacts for the Northern Cape Province in South Africa (Holmes *et al*., 2005). The data as presented by the SAPIA database on the geographical distribution of invasive alien plant species only provides information at a broad level. However, it is important to know what the spread of this woody invader is at a much finer and more accurate scale, how abundant or dense these invasive species are or can potentially become, in order to plan and execute control operations and allocate resources for especially the agricultural and conservation sector (Richardson and Van Wilgen, 2004; Roura-Pascual *et al*., 2009).

Maps of the spatial distribution of *Prosopis* spp. are often generated on printed topographic maps by manually drawing polygons around areas where local experts know or think the species could occur (Le Maitre *et al*., 2000). This data are often not quantified, which may suggest, that regions where no expert knowledge exists some form of generalisation or automated interpolation has been used to fill the gaps in the data (Joshi *et al*., 2003). These databases are often compiled from a variety of studies and sources which varies in scale and accuracy such as SAPIA, the Agricultural Research Council (ARC) and Council for Scientific and Industrial Research (CSIR). Most South African research on alien-plant impact has focused on high detailed small spatial scales (small study areas/plots or communities), and much of this work has been carried out in the Fynbos Biome of South Africa. Studies from other biomes have therefore produced scattered information of the impact of invasive alien plant species (Richardson and Van Wilgen, 2004). As the data of previous surveys were carried out at different times, using different sources, such as maps and reports and mostly relying on expert knowledge, it is not easy to merge them to produce a national or provincial overview of especially the invasion of *Prosopis* spp. for future planning (Van Wilgen *et al*., 2001).

2.3. Gaps in knowledge

Predicting the probability of biological invasion and probable invaders has long been the goal of ecologists in both the agricultural and conservation sector (Richardson and Van Wilgen, 2004). A major challenge of invasion biology lies in the development of pre and post predictive models and understanding of the invasion processes (Joshi *et al*., 2003). Van Wilgen *et al*. (1997) mentioned than the rate at which alien plants spread, is mostly influenced by the initial degree of infestation. The other reasons for the high rate of alien invasions are mentioned above (Chapter 1). Very few estimates of the historical extent of invasions of *Prosopis* exist, and when available, the data are usually not very accurate (Van Wilgen *et al*., 2004). An improvement of the understanding of the rates of naturalisation and spread of alien plants, such as *Prosopis*, is therefore needed for realistic scenario development. Future research could therefore include the development of a predictive understanding of the rates of spread of invasive alien plants using remote sensing and GIS (Richardson and Van Wilgen, 2004). The need for robust, comprehensive estimates of the distribution of invasive alien species, accompanied by approximations of the density of invasive species, as well as the techniques to estimate the rate at which invasive alien plants will spread are mentioned as challenges for future research (Van Wilgen *et el*.,2008; Lodge *et al*., 2006).

2.4. Remote Sensing

Remote sensing is the small or large-scale acquisition of information of an object or phenomenon, by the use of either recording or real-time sensing device(s) that are wireless, or not in physical or intimate contact with the object (such as by way of aircraft, spacecraft or satellite) (AMU, 2006).

Electromagnetic energy reaching the earth's surface from the sun is reflected, transmitted or absorbed. A basic assumption made in remote sensing is that specific targets (soils of differed types, water with varying degrees of impurities, or vegetation of various species) have an specific combination of reflected and absorbed electromagnetic (EM) radiation at varying wavelengths which can uniquely identify an object. This spectral signature can vary from time to time during the year, such as might be expected in the case of vegetation as it develops from the leafing stage, through growth to maturity and, finally to senescence. In principle, a material can be identified from its spectral signature if the sensing system has sufficient spectral resolution to distinguish its spectrum from those of other materials (AMU, 2006).

2.4.1. Spectral reflectance of vegetation

Vegetation has a unique spectral signature which enables it to be distinguished readily from other types of land cover in an optical/near-infrared image. The reflectance is low in both the blue and red regions of the spectrum, due to absorption by chlorophyll for photosynthesis. It has a peak at the green region. In the near infrared (NIR) region, the reflectance is much higher than that in the visible band due to the cellular structure in the leaves. Hence, vegetation can be identified by the high NIR but generally low visible reflectance.

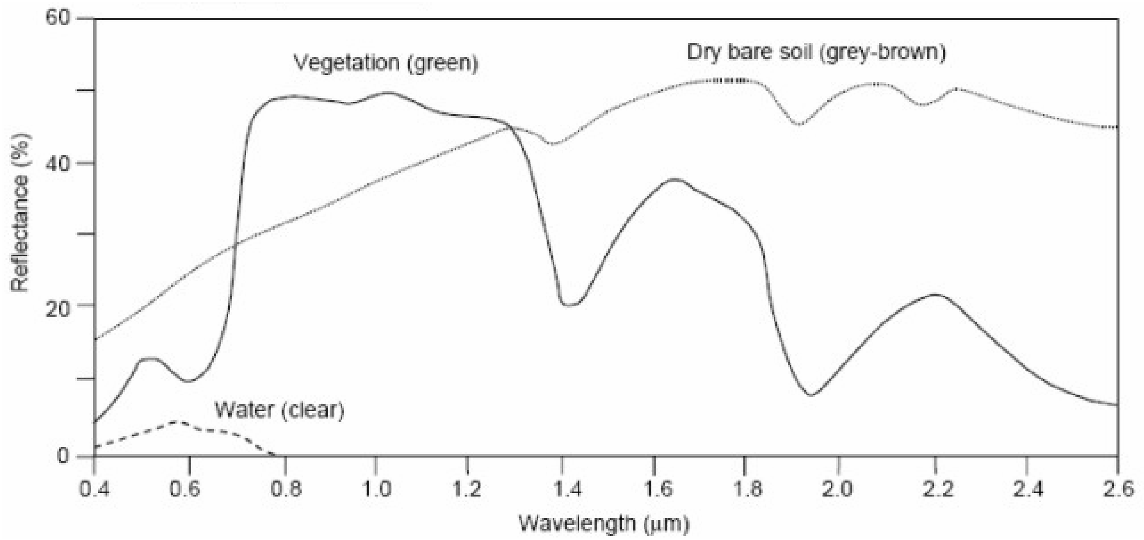


Figure 2.2. Typical spectral reflectance curves of common earth surface materials in the visible and near to mid-infrared range. The positions of spectral bands for some remote sensors are also indicated (AMU, 2006)

The spectral reflectance of vegetation can be detected in three major electromagnetic spectrum (EMS) regions (AMU,2006):

- Visible region (400-700 nm) – Low reflectance, high absorption, and minimum transmittance. The fundamental control of energy-matter interactions with vegetation in this part of the spectrum is plant pigmentation
- NIR (700-1350 nm) **–** High reflectance, very low absorption, and high transmittance. The physical control is internal leaf structures.
- MIR (1350-2500 nm) **–** As wavelength increases, both reflectance and transmittance generally decrease from medium to low, while absorption increases from low to high. The primary physical control in these middle-infrared wavelengths for vegetation is in vivo water content.

2.4.2. Remotely sensed data

The sustainable management of natural resources has become a fundamental objective, in land use planning, policy development and redistribution of land. A constant need for more exact and up-to-date resource data are therefore required (Van der Merwe, 2005). The use of spatial information presents a better understanding of the problems of natural resources and forms the foundation for the identification of appropriate strategies for sustainable management (Kidane, 2004). Vegetation is dynamic and changes constantly over spatial and temporal scales due to climatic, soil and management impacts. The composition, succession and distribution patterns also vary subtly over long time frames. Disturbances such as invasion can occur over a range of spatial scales, from individual tree level or stand/plot level to landscape and global scale (Coops *et al*., 2009). The role of remote sensing can therefore also change, using different spatial and temporal resolution images, depending on the extent, rate and magnitude of the change.

For example, to detect phenological changes of the woody species over time would require a number of satellite images within one growing season where the greening-up and down phases are sufficiently captured (Coops *et al*., 2009). Vegetation phenology refers to the timing of different life-cycle events of plants (such as leaf unfolding, flowering, leaf fall, etc.) which are related to leaf density and photosynthetic activity throughout the season. By comparison, subtle changes of the spectral response caused by infestation are detected better using sets of imagery acquired annually over two or more years (Coops *et al*., 2009). The different spatial and temporal resolutions with which the satellite data are produced are essential and provide important opportunities to study the dynamics of vegetation on all levels as shown by the study of Lloyd *et al* (2002). In the latter study, National Oceanic and Atmospheric Administration/Advanced Very High Resolution Radiometer (NOAA/AVHRR) (NOAA, 2007) and Landsat Thematic Mapper (TM) (Landsat Program, 1999) data were used to detect the invasion by *Prosopis* in the Van Wyksvlei area of the Northern Cape Province. High spectral resolution imagery provides the potential to identify unique spectral signatures of invasive plants relative to a background of non-invasive vegetation (Hamada *et al*., 2007), while high spatial resolution imaging provides the spatial detail necessary to detect individuals or patches of invasive plants. Airborne platforms provide an effective and efficient means of image acquisition for the relatively linear nature of many riparian corridors in which many of the invasive plants, such as *Prosopis*, are distributed.

Historical archives of remotely sensed images provide a rare data source that combines spatial resolution, large spatial extent and long-term coverage for quantifying rates and characterising patterns of plants invasions (Goslee *et al*., 2003; Kadmon and Harari-Kremer, 1999; Robinson *et al*., 2008). Although remotely sensed data for this project only date back to the 1970's (excluding aerial photography), a more extensive area is covered than with single plot studies, and spatial patterns are easier to discern from images than from data sampled at ground level (Laliberte *et al*., 2004).

The flexibility and rate with which results can be produced using remotely sensed data are fundamental, and provide important information for a wide range of physical and social studies conducted by government agencies for planning purposes (Stefanov, *et al*., 2001). Satellite remote sensing is therefore essential for early detection, continuous monitoring, change detection and mapping of vegetation over large areas (Burrough, 1993; Kidane, 2004). Semi-automated, computer-assisted approaches, using digital remotely sensed data are cost effective and reduce the amount of field work, enabling more frequent monitoring of control programs for natural resource management and habitat preservation (Anderson *et al*., 2007; Essa *et al*., 2006; Hamada *et al*., 2007). Remote Sensing and GIS could also be potentially used in predicting the potential distribution of invasive species over the long-term (Joshi *et al*., 2003).

2.4.3. Spectral vegetation indices

Spectral vegetation indices are used to enhance the vegetation signal in remotely sensed data and provide approximate measure of live, green vegetation. Spectral vegetation indices exploit the unique spectral signature of green vegetation as compared to spectral signatures from other earth materials such as soil.

Different types of vegetation often show distinctive variability from one another due to parameters such as shape and size, overall plant shape, water content, and associated background. Different vegetation indices have been developed based on the combinations of two or more spectral bands, assuming that multi band analysis would provide more information than a single one. Most vegetation indices use radiance, surface reflectance or apparent reflectance values in the red (R) and near infrared (NIR) spectral bands (Zoran and Stefan, 2006). These indices are correlated with various vegetation parameters such as green biomass, chlorophyll concentration, leaf area index, foliar loss, photosynthetic activity and more. Vegetation indices are also useful for image analysis such as change detection (SEES, 2003).

2.4.4. Normalized Difference Vegetation Index

The Normalized Difference Vegetation Index (NDVI) is a basic vegetation index for measuring the 'greenness' of the earth's surface. A reasonable estimation of the density and coverage of green vegetation can be determined by measuring how green the earth's surface is. The formula to calculate NDVI is: NDVI = (NIR band - R band) / (NIR band + R band). NDVI values can range from -1.0 to 1. Vegetation values typically range between 0.1 and 0.7. High NDVI values generally indicate increasing degrees in the greenness and intensity of vegetation while low values are commonly characteristic of rocks and bare soil, and values less than 0 sometimes indicate clouds, rain, and snow (Avery and Berlin, 1992). Low values of NDVI do not necessarily denote lack of vegetation. It has been used in various countries for drought monitoring, crop estimations, environmental monitoring and change detection on a national scale.

Bands from the following satellite sensors can be used to calculate NDVI:

- Landsat Multi-Spectral Scanner (MSS): bands 5 (0.6-0.7 pm) and 6 (0.7-0.8 pm) or 7 (0.8-1 .I pm); bands 3 and 4, for Landsat 4 and Landsat *5*
- Landsat Thematic Mapper (TM): bands 3 (0.63-0.69 pm) and 4 (0.76-0.90 pm)
- Landsat Enhanced Thematic Mapper+ (ETM): bands 3 (0.63-0.69 pm) and 4 (0.75-0.90 pm)
- NOAA/AVHRR: bands 1 (0.58-0.68 pm) and 2 (0.72- 1.0 y m)
- Terra Moderate Resolution Imaging Spectroradiometer (MODIS): bands 1 (0.62-0.67), 2 (0.841 -0.876)

NDVI can be used as an indicator of relative biomass and greenness if sufficient ground is available (Boone and Calvin, 2000; Chen and Brutsaert, 1998). It is also highly correlated with climatic variables, and precipitation (Schmidt and Karnieli, 2000). The NDVI is successful as a vegetation measure, since it is sufficiently stable for seasonal and inter-annual comparison of vegetation growth and activity (Huete *et al.,* 2002).

2.4.5. Enhanced Vegetation Index

The MODIS Enhanced Vegetation Index (EVI) minimizes canopy background variations and maintains sensitivity over dense vegetation conditions. The EVI also uses the blue band to remove residual atmosphere contamination caused by smoke and thin clouds. The EVI is more responsive to canopy structural variations, including Leaf Area Index (LAI), canopy type and canopy architecture (LP DAAC, 2008). MODIS core standard vegetation index products include the NDVI and the EVI to effectively characterize and process vegetated surfaces (LP DAAC, 2008). There exists a complete, time series record of these products at the Agricultural Research Council-Institute for Soil Climate and Water (ARC-ISCW), at 250m spatial resolution and 16 day temporal resolutions from 2000 to 2009.

2.5. Characteristics of *Prosopis* species

2.5.1. Botanical description and natural habitat

The *Prosopis* spp. (Figure 2.2) is a woody, multi-stemmed, *Acacia*–like shrub or tree growing up to 4 or 10m high with strait spines (Visser, 2004; Mampholo, 2006). *Prosopis* are also commonly referred to as mesquite or "suidwesdoring" in some countries (Henderson, 2001; Wild and Du Plessis, 2007). Leaflets are greyish-green to dark green while flowers are yellow spikes. Fruits are slender woody pods, yellow and more or less strait, constricted between seeds. Mature trees produce 20 to 100kg of nutritious pods every year. *Prosopis* is semi-deciduous and flowers from June to November (WIP, 2006).

Figure 2.3: A dense stand of *Prosopis* in a floodplain in the Northern Cape Province.

Prosopis grows in arid to semi-arid environments including deserts, open woodlands, grasslands, shrublands and floodplains (ISSG, 2006). Being frost tolerant, it thrives under very low and high temperatures (-12 to 40 deg. C) and survives in areas with very low precipitation (AFDbases, 2004). *Prosopis* is mostly found in sandy and even poor saline or alkaline soils. *Prosopis* species are deep rooted (up to 18m), allowing trees to reach water tables of between 3 to 10m below the surface, such as drainage lines and low lying areas. This allows them to grow and fruit even in the driest of years (AFDbases, 2004).

Prosopis occurs mainly in vegetation arcs or patches of dense and sparse vegetated areas. These patterns of vegetation mainly occur in alluvial fans of arid and semi-arid zones with slopes of 0.2 to 2% at altitudes of 300m to 1200m (Lopez-Portillo *et al*., 1996). Soil moisture is more important in determining mesquite distribution than soil type (ISSG, 2006). *Prosopis* often colonises disturbed, eroded, over-grazed or drought-affected land, associated with unsustainable agronomic practices (ISSG, 2006).

Seeds survive passage through the guts of most animals and the hard seed coat is softened in the process, aiding germination (ISSG, 2006). On fertile sites, *Prosopis* seedlings may be out-competed by grasses and other plants or removed during cultivation. However, on degraded, bare, overgrazed land of low fertility, *Prosopis* has a competitive advantage, and will quickly spread. Dense impenetrable thickets severely reduce the growth and availability of palatable forage plants (AFDbases, 2004). Goats, sheep, horses and donkeys are considered to be the most effective dispersers when occurring in high density infested areas with a high level of animal movement. Birds, bats, reptiles and ants also feed on *Prosopis* fruits and are potential, if only minor, agents of dispersal (Pasiecznik, 1999). Mesquites were widely planted, primarily as a shade tree around homesteads, but occasionally as shade and fodder trees around boreholes (Zimmerman, 2005).

Prosopis trees are the source of multi-purpose valuable products. Fruit pods are high in sugar (16%) and protein (12%) and are a rich food source for man and beast. Honey produced from *Prosopis* flowers is of high quality (Pasiecznik, 1999). Larger branches and trunks yield a high quality of wood for use in manufacturing furniture. While shrub species cannot be used for timber production, their leaf litter improves soil quality. Pods are stored year-round for fodder and can be used as flour or nutritious syrup (Mwangi and Swallow, 2005).

Eradication of *Prosopis* has proven to be extremely difficult or impossible (Visser, 2004). Better management of *Prosopis*, different land use strategies and the exploitation of *Prosopis* as a resource, may reduce its invasiveness in some regions, as well as improving local economies (Pasiecznik, 2002). Control measures are based on the principle that prevention is better than cure (Visser, 2004; Wild and Du Plessis, 2007). Where light infestation occurs, small trees can be pulled up by hand during favourable moisture conditions. Young trees can be hacked out, while big trees have to be chopped or sawn down. Seed-eating beetles are applied biologically to control *Prosopis*. The beetles penetrate the pods and then eat the seeds. These beetles, however, are merely supportive of other combating measures. The registered chemical products, Garlon 480 EC, Triclon and Viroaxe (active ingredient triclophyr), has been developed to spray or paint the herbicide onto the trunks of the clear felled trees at a cost of R1 714/1000 trees (Jordaan, 2009). Molopo 500 SC (active ingredient tebuthuiron) can be applied to the soil with less than 25% clay where the trees are smaller than 2m at a cost of R288/ha.

2.5.2. Invasive status

Three *Prosopis* species were introduced to South Africa from North and Central America, i.e. *P. chilensis*, *P. grandulosa* and *P. velutina* (Visser, 2004; Mampholo, 2006). All three are declared category 2 invaders meaning they are allowed in demarcated areas by permit holders for economical use such as production of charcoal or fire wood, building material, erosion control and for medicinal use (CARA, Act no. 43 of 1983) (South Africa, 1983). Early hybridisation between *P. velutina* and *P. grandulosa* var. *torreyana* displayed what is today known as the “hybrid vigour”, which proved to be very invasive. The invasive trees lost most of their valuable properties which had a negative impact on their exploitation. Large and rampant invasions developed, mainly in low lying areas and along water courses, which out-competed and replaced indigenous plants and lowered the water tables to the detriment of other vegetation and native trees. Once populations had reached a certain density, they reverted to multi-stemmed, dense impenetrable thickets. These trees ceased to produce pods because of intra-specific competition, which resulted in the loss of the valuable positive attributes (Zimmerman, 2005). The greatest negative impact on surface water resources in the Northern Cape, are primarily caused by *Prosopis* (Le Maitre *et al*., 2000). A single tree uses on average about 350 to 500mm water per year highlighting the negative effect it has on the water table of densely invested areas.

CHAPTER 3: STUDY AREA

3.1. Geographical location

The vast and arid Northern Cape Province in South Africa (Figure 3.1), is the largest province, taking up 363 203 square kilometres, nearly a third or 30.5 % of South Africa's land area. The province lies to the south of the Orange River forming the border with the country of Namibia in the north, while the Molopo River is at the border with Botswana to the northeast (Figure 3.2). The Atlantic Ocean forms the western boundary and Kimberley the capital of the province lies on the eastern border. The altitude ranges from 1m at the coastal western parts, to 900m in the north and central interior and as high as 2000m in the south (CGIAR-CSI, 2008).

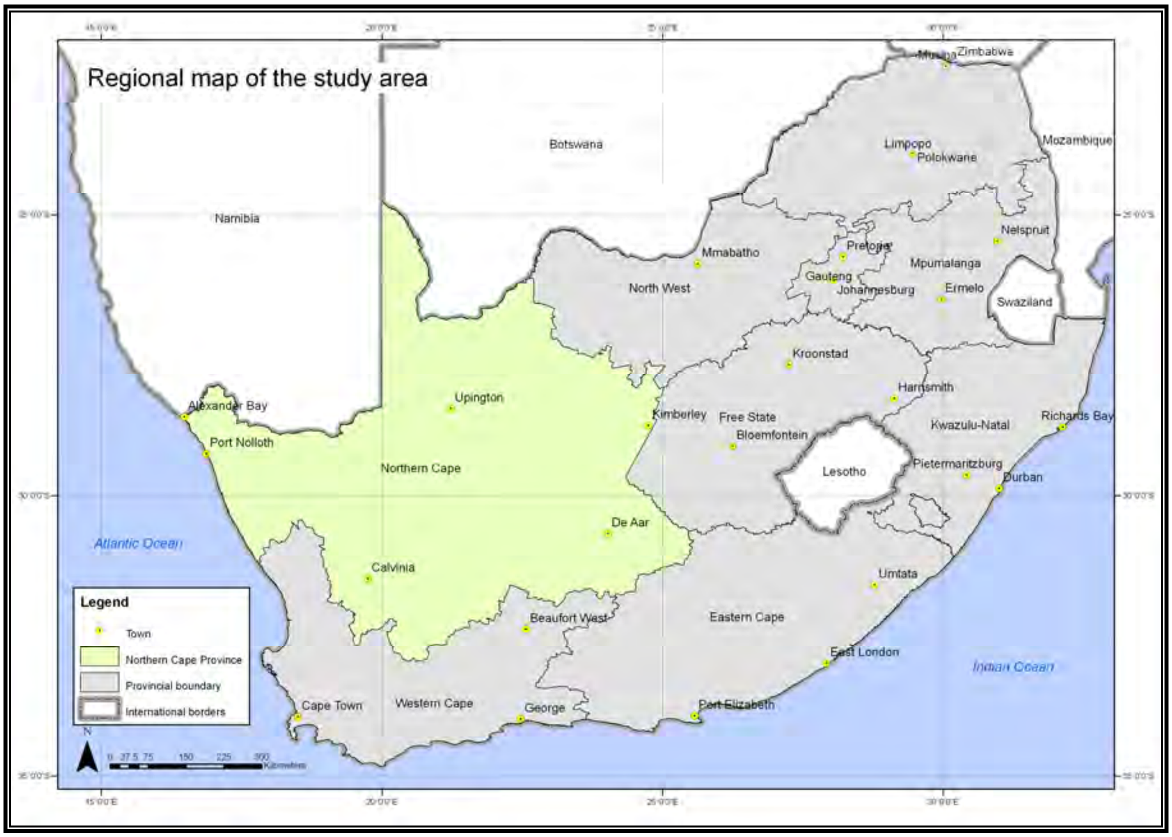


Figure 3.1: Regional map of the Northern Cape Province of South Africa.

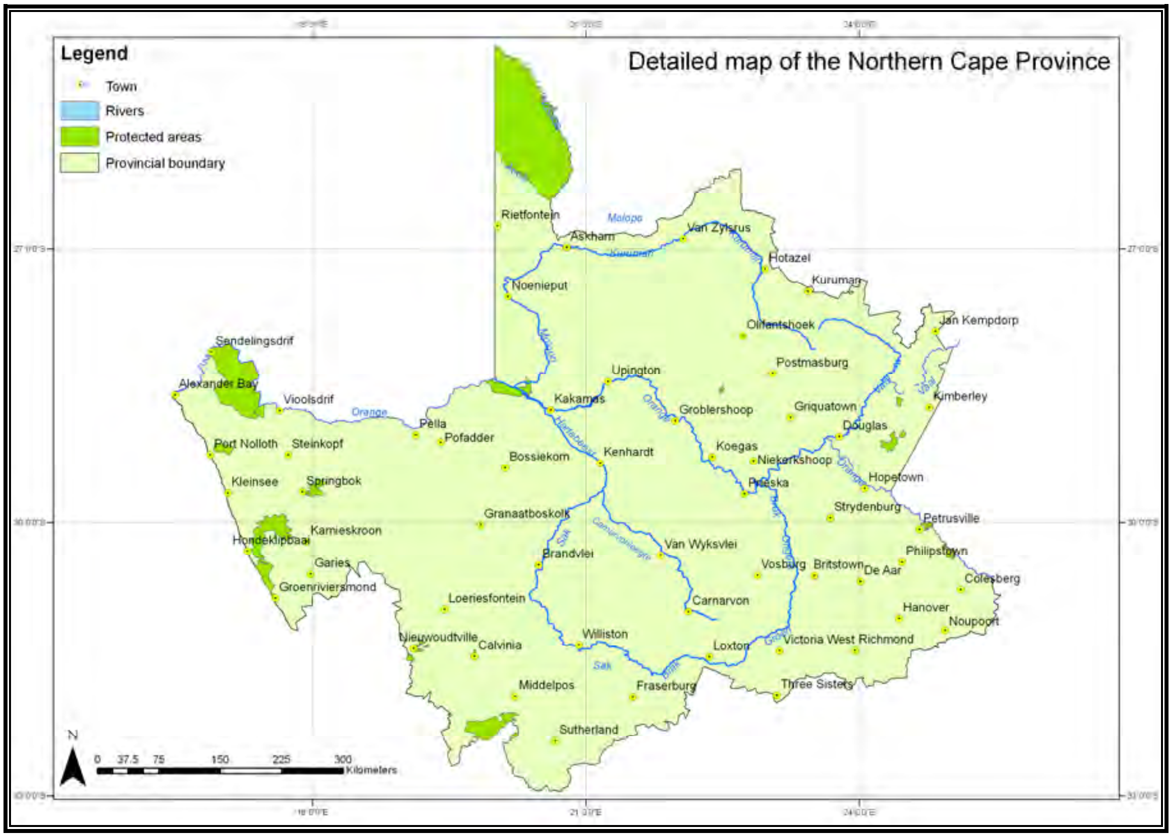


Figure 3.2: Detailed map of the Northern Cape Province of South Africa

3.2. Climate

It is a dry region of fluctuating temperatures and varying topographies. Afternoon temperatures in the Kalahari (area north of the Orange River) in January are usually between 33 - 36℃. Winter days are warm with dew and frost during night to supplement the low rainfall. Sutherland, in the Hantam Karoo, is one of the coldest towns in South Africa, averaging a minimum of 3℃. The cold Benguela current along the Atlantic Ocean has a noticeable effect on the climate and temperature of Namaqualand, resulting in relatively mild temperatures with moderate variation. The average daily minimum and maximum temperatures at Port Nolloth for example are 10℃ and 18℃ respectively (WEB2007, 2007).

According to UNESCO (1977) the Northern Cape Province can be described as being semi-arid in the east from Kuruman southwards to Hanover, to arid in the central region (Van Wyksvlei and Springbok) to hyper-arid in the far western parts of Namaqualand (Sendelingsdrift and Kleinsee). The central, northern and north-eastern parts of the province are situated in an area dominated by a high-pressure system. Precipitation

(Figure 3.3) is therefore low, ranging from 150 mm to 600 mm per annum. The region from Calvinia in the south to Alexander Bay in the north-west is arid, with an average rainfall of between 50 mm and 200 mm per annum. The mean average rainfall at Sendelingsdrift in the Richtersveld ranges from 15 mm to 100 mm per annum (WEB2007, 2007). Most of the northern, eastern and central areas of the province are in the summer rainfall area, whereas the western and southern parts of Namaqualand lie within the winter rainfall area.

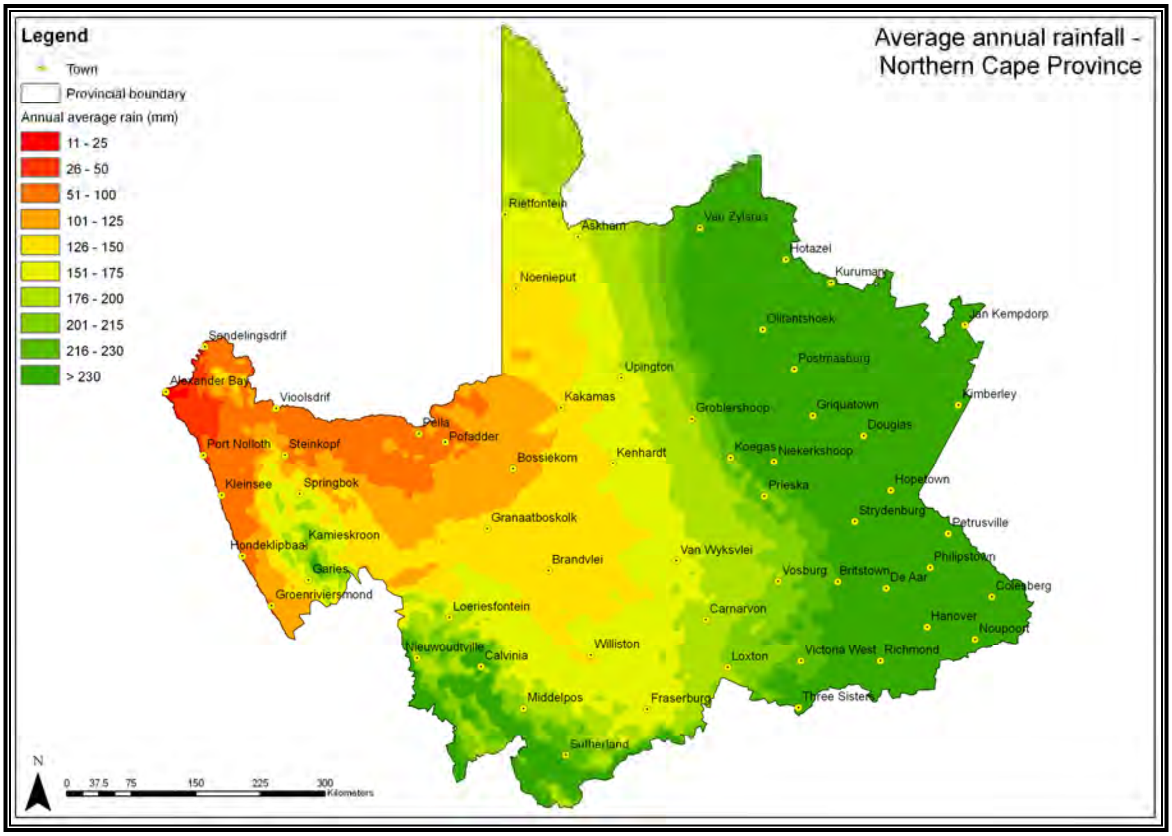


Figure 3.3: Average annual rain fall of the Northern Cape Province (WEB2007, 2007). Rainfall increases gradually from west to east. Most of the northern, eastern and central areas of the province receive their rain during summer, whereas the western and southern parts lie within the winter rainfall area.

3.3. Vegetation

The Northern Cape Province consists of 5 biomes and 20 vegetation types (Figure 3.4) (Bredenkamp *et al*., 1996). The northern part is dominated by the Savanna Biome, the west by the Succulent Karoo Biome while small patches of the Fynbos Biome also occurs (Bredenkamp *et al*., 1996). The central part of the province is dominated by the Nama Karoo Biome with small patches of the Grassland Biome occurring in the eastern corner of the province. The major vegetation types in the Northern Cape are defined by Low and Rebelo (1996) as: Bushmanland, Orange River and Upper Nama Karoo, Shrubby Kalahari Dune Bushveld, and Upland Succulent Karoo.

According to the latest vegetation classification by Mucina and Rutherford (2006), the Northern Cape is also characterised by the three main biomes mentioned above. Mucina and Rutherford (2006), however divided these biomes into 63 vegetation units, whereas Low and Rebelo (1996) classified it into 20 vegetation types. The description of broad geological and soil types as described by Mucina and Rutherford (2006) may also differ at some places when compared to Low and Rebelo (1996). For the purpose of this study, the classification by Low and Rebelo (1996) has been followed, as this classification is more suited for the scale of the study and because the study done for the National Department of Water Affairs mainly focuses on the invasion of biome and catchment level. It is however realised that for studies at a more detailed level the classification of Mucina and Rutherford (2006) may be more appropriate.

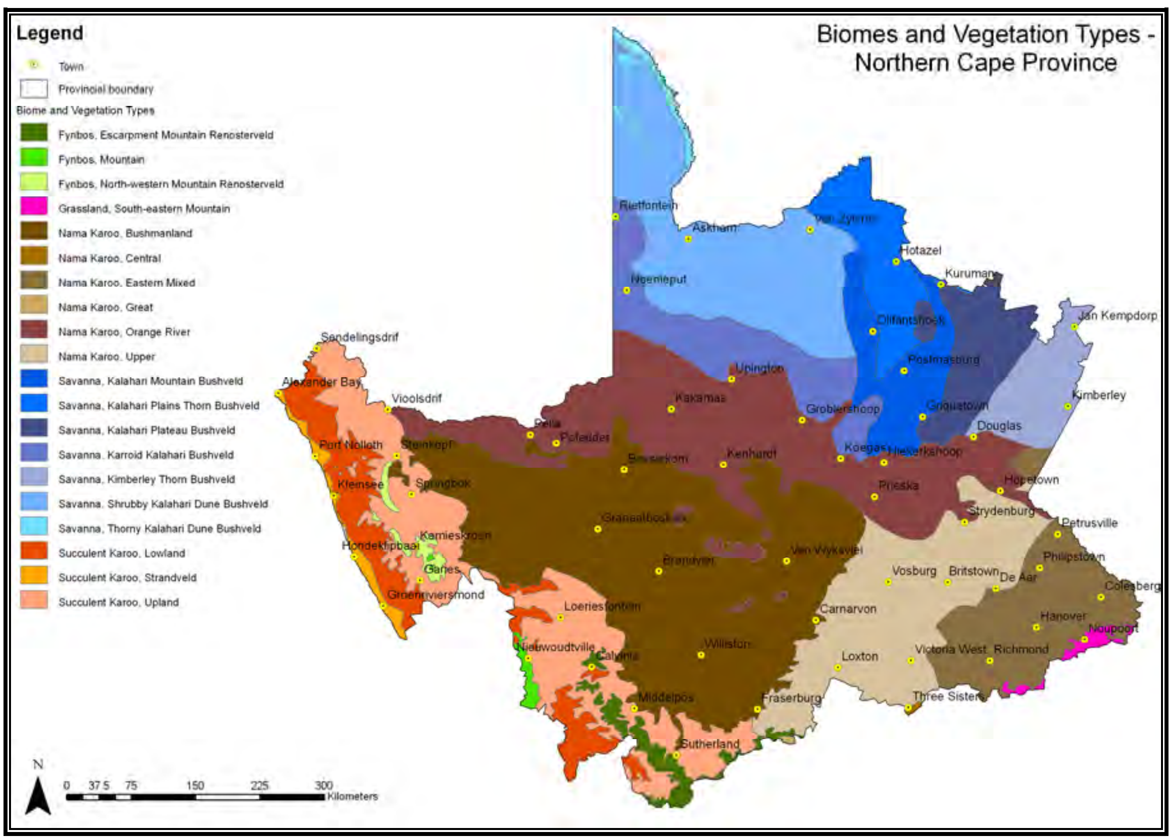


Figure 3.4: Biomes and Vegetation Types of the Northern Cape Province (Low and Rebelo, 1996). Vegetation types are colour coded according to the different biomes.

The largest part of the province falls within the Nama-Karoo Biome (195 805km^2), consisting of 3 main vegetation types; Bushmanland Nama Karoo, Orange River Nama Karoo and Upper Nama Karoo. Structurally the Bushmanland Nama Karoo is dominated by open shrubland, dominated by knee-high, dwarf, woody shrubs, white Bushman Grass (*Stipagrostis spp.*) as well as scattered annuals and succulents in some areas. Vegetation on the flats is dominated by Cauliflower Ganna (*Salsola tuberculata*), Thorny Kapokbush (*Eriocephalus spinecens*) and Three-thorn (*Rhigozum trichotomum*). On deeper pockets of soil trees such as Camel Thorn (*Acacia erioloba*) and Black-thorn Acacias (*Acacia mellifera*) can form dense stands. The common species in rocky areas are the Quiver-tree Aloe (*Aloe dichotoma*), Shepherd's Tree (*Boscia albitrunca*), Buffalo-thorn Jujube (*Ziziphus mucronata*), Namaqua Rock Fig (*Ficus cordata*) and Karee-rhus (*Rhus lancea*). The African Greenhair-tree (*Parkinsonia africana*) often occurs along roadsides and drainage lines.

The Orange River Nama Karoo is a very rocky area with Quiver Tree (*Aloe dichotoma*), Bushman Poison Tree (*Euphorbia avamontana*) and Aggenys Milkbush (*Euphorbia gregaria*). Other common trees and shrubs include Spiked-flowered Blackthorn (Acacia mellifera), Three-thorn (*Rhigozum trichotomum*) and Shepherd's Tree (*Boscia albitrunca*), while Silky Bushman Grass (*Stipagrostis uniplumis*) often dominates the plains. There are large areas of thicket along the banks of the Orange River, with Wild Tamarisk (*Tamarisx usneoides*) and Buffalo-thorn Jujube (*Ziziphus mucronata*), Camel Thorn (*Acacia erioloba*) is common along the dry river beds.

The stony plains of the Upper Nama Karoo are characterized by Kapokbush (*Eriocephalus ericoides*) and Silverkaroo (*Plinthus karooicus*) while Kunibush (*Rhus undulate*) dominates the higher mountain region. Some of the more common and widespread larger plants are Karee-rhus (*Rhus lancea*), Pioneer Spikethorn (*Gymnosporia buxifolia*), Bluebush (*Diospyros lyciodes*), Large Honey-thorn (*Lycium oxycarpum*), Karoo Cross-berry Raisin (*Grewia robusta*) and Karoo Num-num (*Carissa haematocarpa*). Along the drainage lines and river banks, the Sweet-thorn Acacia (Acacia karoo) is characteristic and widespread. Other species that also occur are Wild Tamarisk (*Tamarisx usneoides*) and Buffalo-thorn Jujube (*Ziziphus mucronata*). After good rains grasses, such as Tassel Bristlegrass (*Aristida congest*) and Lehmann's Lovegrass (*Eragrostis lehmanniana*) may dominate the plains.

The vegetation of the Savanna Biome is generally different from that of the rest of the

Northern Cape Province. This region consists of open plains with a variety of *Acacia* trees such as Camel Thorn (*Acacia erioloba*), Grey Camel Thorn (*Acacia haematoxylon*) and Umbrella Acacia (*Acacia tortillis*). Among the widespread Acacias are the occasional Shepherd's Tree (*Boscia albitrunca*), Silver Cluster-leaf (*Terminalia sericea*), Buffalo-thorn Jujube (*Ziziphus mucronata*), African Olive (*Olea europea*), Blue Guarri (*Euclea crispa*) and Velvet Raisin (*Grewia flava*). In areas where the underlying calcrete is close to the surface, the sandy plains are covered by Camphor-bush (*Tarchonanthus camphorates*). Common trees on the mountains and rocky areas are Karee-rhus (*Rhus lancea*) and Lavender Croton (*Croton gratissimus*). Along the perennial rivers a variety of other trees such as River Bushwillow (*Combretum erythrophyllum*), White Karee-rhus (*Rhus pendulina*) and Bluebush (*Diospyros lyciodes*) occur. Dry river courses and pans are characterised by Camel Thorn (*Acacia erioloba*), Grey Camel Thorn (*Acacia haematoxylon*), Candle-pod Acacia (*Acacia hebeclada*) and Black-thorn Acacias (*Acacia mellifera*). Grasses such as Kalahari Coach (*Stipagrostis amabilis*), Lehmann's Lovegrass (*Eragrostis lehmanniana*) and Giant Stick Grass (*Aristida meridionali*s) occur on the grassy plains.

The Succulent Karoo has more species of succulents than anywhere else in the world (Thomas et al., 2008). The Richtersveld region around Sendelingsdrift is characterised by small scattered vegetation. However, along the Orange River thickets of dense Sweet-thorn Acacia (*Acacia karoo*) and Karee-rhus (*Rhus pendulina*) occur. The Quiver Tree (*Aloe dichotoma)* and Giant Quiver-tree (*Aloe pillansii*) characterises much of the northern parts of the Succulent Karoo Biome. The lowlands along the Atlantic Ocean are devoid of large trees, but some larger shrubs occur such as Honey-thorn (Lycium spp.) and Ganna-bush (*Salsola spp*.). In the mountainous region between Springbok and Garies, species such as Namaqua Kuni-rhus (*Rhus undulate*), Botterboom (*Tylecodon paniculatus*), Slender Honey-thorn (*Lycium bosciifolium)* and Honey Guarri (*Euclea tomentosa*) are wide spread. The Hantam region south of Calvinia is dominated by dwarf succulent-leaved bushes. Some species of this region includes Karoo Kuni-bush (Rhus burchellii), Wild Cloe-bush (Montinia caryophyllacea), Botterboom (*Tylecodon paniculatus*) and Fire-sticks Star-apple (Diospyros austro-africana). Succulent species, particularly within the vygie family, are the dominant dwarf shrubs, grasses are generally not common in this biome. Many annuals, mainly in the Daisy (*Asteraceae*) and Vygie (*Mesembryanthemaceae*) families occur.

3.4. Geology

The geology of the Northern Cape is dominated by the following geological formations, namely the Griqualand West Super Group, Namaqualand Metamorphic Province, Dwyka and Ecca Groups, Beaufort Group and the Kalahari Group (Council for Geoscience, 2006). The oldest formation of the Griqualand West Super Group is the Vryburg Formation. It comprises mainly siltstone with subordinate shale, quartzite and andesitic lava. The Schmidtsdrif Subgroup consists of inter-layered dolomite, shale, limestone and sandstone layers. The Campbell Rand Subgroup consists mainly of grey dolomite. The Koegas Subgroup occurs in the Prieska area and consists mainly of mudstone, quartzite, jaspilite, iron and dolomite. The Namaqualand Metamorphic Province includes a group of schistose and gneissic metasedimentary, metavolcanic and intrusive rock types in an area along the Orange River to the Atlantic coast in the west. To the north and to the south the province is overlain by younger sequences like the Nama Group and the Karoo Super Group. The Dwyka Group represents the lower unit of the Karoo Super Group. It consists mainly of gravelly sediments, shale and mudstone. The Ecca Group was deposited in a marine environment and consists predominantly of dark-grey shale which is carbon-rich in places, with inter-layered sandstone. The Beaufort Group occupies the largest portion of the Karoo basin and comprises sand and clay deposits which represent deposition on land, in contrast to the predominantly marine deposits of the underlying Ecca Group. The clay deposits are represented by mudstone, while the sand deposits comprise dirty sandstone. The Kalahari is a flat, sand-covered, semi-desert region which contains some large pans north of Upington, dry river beds such as the Nossob and Molopo, and parallel dunes running in a north westerly direction with inter-dune street in-between. Rocky outcrops are scarce in this sand-covered region.

3.5. Soils

Soils of the Savanna Biome of the Northern Cape Province are dominated by deep red sandy soils of the Hutton soil form (Soil classification working group, 1991). The soils have a considerable water storage capacity and are generally deeper than one meter. Land Types are mainly Ag (See glossary and table 4.2 for al Land type abbreviations). LandRed, yellow and greyish, excessively drained sandy soils of the Namib soil form dominate the dune areas, with Af land type almost exclusively. Deep red weakly structured, some with a calcareous layer below, and with a slightly higher clay content occupy a large area on the eastern side of the Savanna Biome. Shallow soils on rock of the Mispah and Hutton soil form dominate on the ridges and the Ghaap Platau. Land types mainly Ae, Fc and Dc.

The Nama- Karoo Biome can be divided into several soil regions (Soil classification working group, 1991). The soils around the Orange River, from Keimoes to Prieska are shallow and skeletal, dominant soil forms are Mispah and Glenrosa. Mainly of Ib and Ic land types and to a lesser extent also Fb. The area spanning from Pofadder in the west past Upington and Kenhardt to Prieska in the east are covered by recent alluvium and calcrete. The soils of most of the area are red-yellow apedal soils, freely drained, with high base stratus and < 300mm deep, typical of the Ag and Ae land type. The area between Granaatboskolk, Van Wyksvlei and Williston, also known as the Bushmanland, are dominated by mudstones, shales and arenites of the Ecca and Beaufort Group as well as Dwyka tillites, both of early Karoo age. Soils are shallow Glenrosa and Mispah forms, with lime generally present in the entire landscape (Fc land type) and, to a lesser extent, red-yellow apedal, freely drained soils with a high base stratus and usually < 15% clay (Ah and Ai land types). The salt content in these soils is very high.

The coastal region (30km wide) between Alexander Bay and Groenriviersmond of the Succulent Karoo Biome consists of sandy material of Aeolian origin. The soils consist of deep, grey, calcareous sands adjacent to the coast followed by a zone of yellow sands. Mostly of Ah land type (Soil classification working group, 1991). The inland part between Springbok and Garies is a mountainous area. The dominant rock types are granite and gneiss and the soils are generally shallow, base-rich to calcareous and reddish coloured. Land type Ic and Ib dominates. From Calvinia to Sutherland, the escarpment is underlain by shale with shallow, stony lithosols.

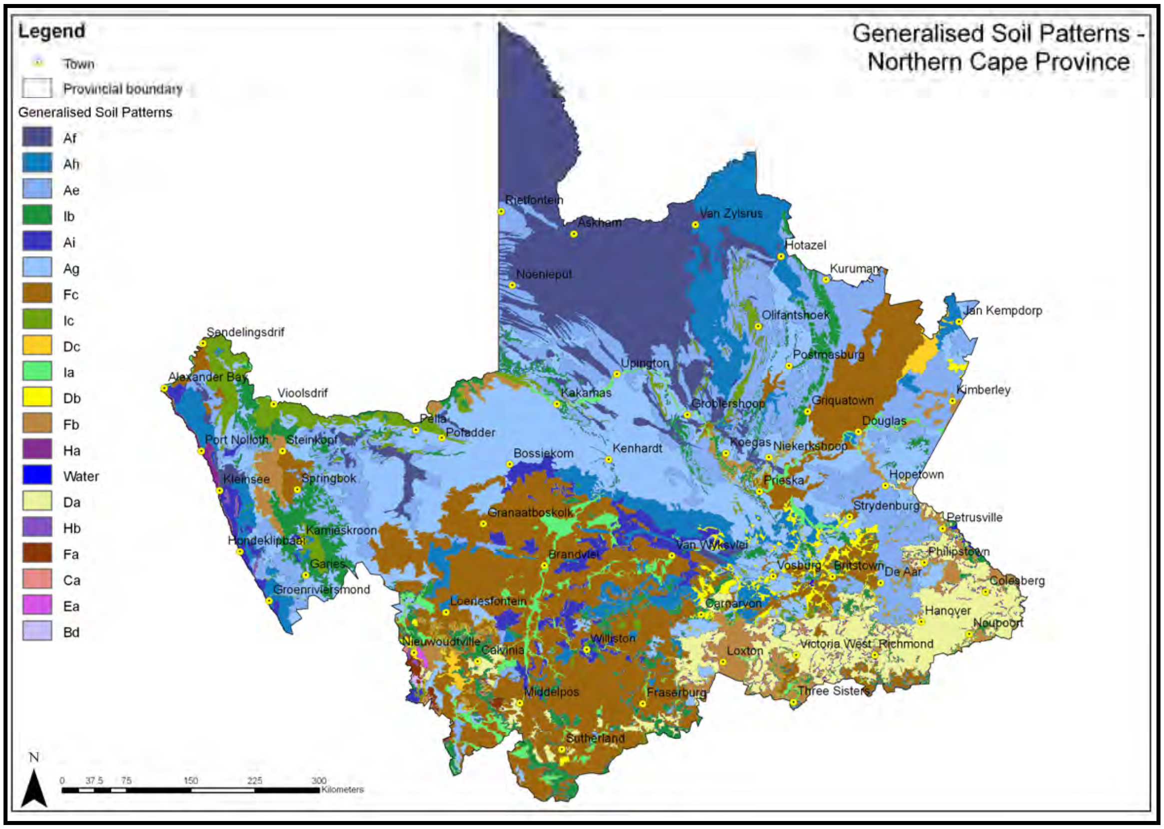


Figure 3.5: Generalised Soil Classes of the Northern Cape Province (Land Type Survey Staff, 1972-2006). The soil classes associated with *Prosopis* occurrence are described in Table 4.2.

3.6. Land use and management

The unique combination of topography, geology, climate, soils and vegetation has endowed the province with incredible biodiversity, mineral and agricultural wealth.

3.6.1. Mining

The Northern Cape Province is rich in minerals, with the country's major diamond pipes found in the Kimberley district. Strip-mining for alluvial diamonds in the coastal region as well as along the Orange River from Sendelingsdrift to Alexander Bay is causing huge environmental problems, with little assistance from legislation regarding rehabilitation. The Sishen Mine near Kathu is the biggest source of iron ore in South Africa, and the copper mine at Okiep is one of the oldest in the country. Copper is also mined at Springbok and Aggenys. The province is also rich in asbestos, manganese, fluorspar, semi-precious stones and marbles

3.6.2. Agriculture

The Northern Cape is enjoying a tremendous growth in value-added activities, including game-farming, food production and processing for the local and export market (Bredenkamp *et al*., 1996). In the Orange River Valley, especially at Upington, Kakamas and Keimoes, grapes and fruit are cultivated intensively. Generally, the vegetation of the province has not been altered much by cultivation, except for the irrigated areas along the Orange River, as the climate is too dry (Thomas *et al*., 2008). The dominant land use is the ranching of small stock (wool and mutton sheep, mohair goats), cattle (to the north and east) and game farming with indigenous antelope (Hoffman *et al*., 1999). Provision of water has allowed domestic stock to overgraze and overbrowse perennially. The combination of soils, climate and management practices have had an impact on the palatable species, and have resulted in bush encroachment of some indigenous trees such as Black-thorn Acacia (*Acacia mellifera*), growing in dense stands over large areas (Thomas et al., 2008). In addition, alien *Prosopis* spp. has invaded large areas of the province.

3.6.3. Conservation

Vast areas of the Northern Cape Province are unspoiled, but only a few formal conservancies exist (Figure 3.6). The total area protected by these national and provincial parks as well as nature reserves is a mere 4.5% of the total land area of the province.

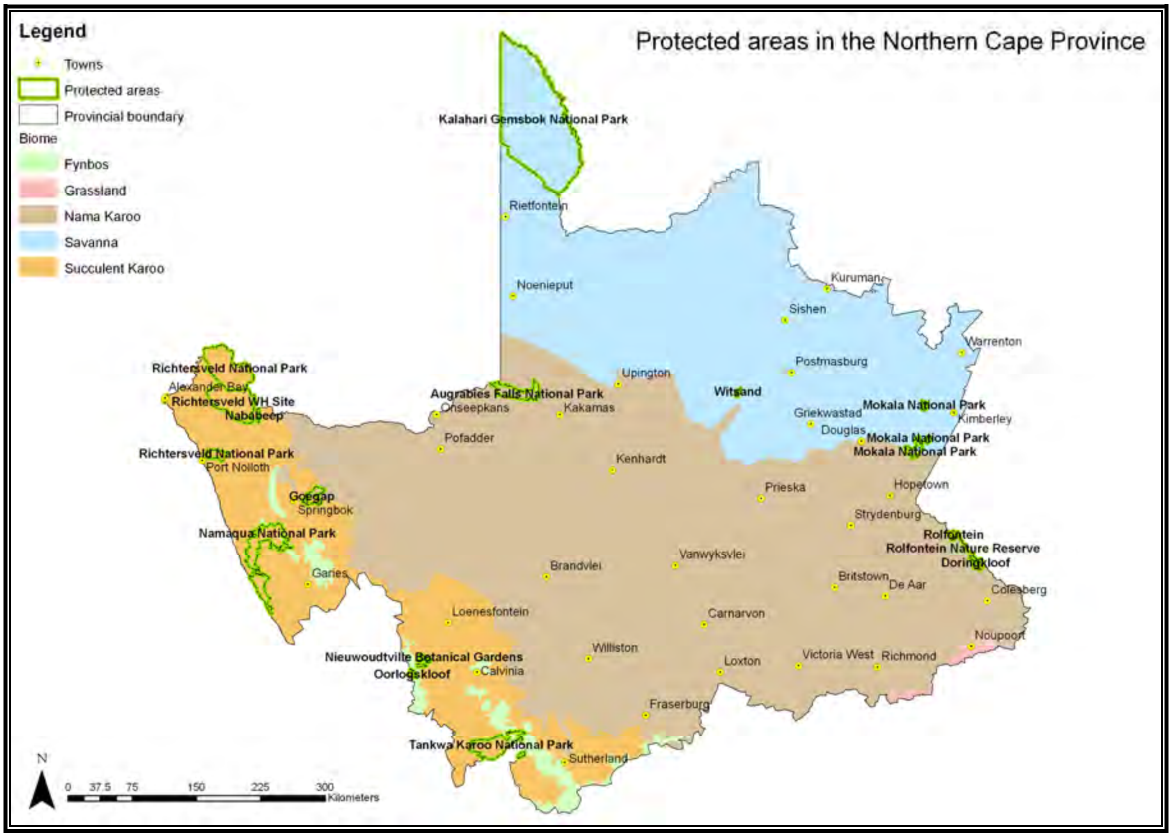


Figure 3.6: Location of protected areas per biome in the Northern Cape Province (SANParks, 2010).

Conservation of the Savanna Biome in terms of area protected is 986,897ha or 9% of the total area (Table 3.1). Formally protected areas are limited to the Kalahari Gemsbok National Park, Mokala National Park and Witsand Reserve.

There are no major reserves in the Nama Karoo except for the Augrabies Falls National Park. Less than 0.5% of the biome has been formally conserved.

Conservation of the Succulent Biome in terms of area protected is 11%. Less than 1% of the Succulent Karoo has been formally conserved. The biome has a high number of rare plant species and therefore requires urgent conservation attention.

South African National Parks has set up an Invasive Alien Species unit, to co-ordinate all efforts to prevent, control or eradicate invasives with in national parks (Preston, 2003). Altough only for a very small area, this will contribute towards the work of the WfW program in the Northern Cape Province.

Table 3.1: Protected status of biomes in the Northern Cape Province (SANParks, 2010)

Biome	Reserve Name	Reserve Type	Area (ha)	Percentage of total area
Fynbos	Oorlogskloof	Provincial Nature Reserve	4,599.16	0.01
Nama Karoo	Augrabies Falls National Park	National Park	55,151.30	0.15
	Doringkloof	Provincial Nature Reserve	9,778.05	0.03
	Rolfontein	Provincial Nature Reserve	6,092.79	0.02
	Rolfontein Nature Reserve	Nature Reserve	1,276.72	0.004
Savanna	Kalahari Gemsbok National Park	National Park	956,358.74	2.6
	Mokala National Park	National Park	28,203.78	0.08
	Witsand	Provincial Nature Reserve	2,334.71	0.006
Succulent Karoo	Goegap	Provincial Nature Reserve	23,878.34	0.07
	Nababeep	Provincial Nature Reserve	10,951.52	0.03
	Namaqua National Park	National Park	139,627.84	0.38
	Orange River Mouth RAMSAR Site	Provincial Nature Reserve	1,478.48	0.004
	Richtersveld National Park	National Park	179,650.47	0.50
	Richtersveld WH Site	Provincial Nature Reserve	136,206.24	0.38
	Tankwa Karoo National Park	National Park	89,582.31	0.25
	Nieuwoudtville Botanical Gardens	SANBI Nature Reserve	6,404.01	0.02
Total			1,651,574.48	4.5

3.6.4. Land cover

Accurate, up-to-date information on land cover and state of the environment are critical components for environmental planning and management (Fairbanks *et al*., 2000). The South African National Land Cover 2000 (NLC 2000) and 1994-95 National Land Cover (NLC '94) mapping projects' primary objective was the generation of up-to-date, GIS compatible, land cover maps of South Africa (Van den Berg *et al*., 2008). The key goal was to establish an operational procedure for long-term monitoring of landscape changes and the changing status of natural and man-impacted environments, based on the use of satellite remote sensing (Thompson *et al.*, 2001). Table 3.2 provides an overview of the areas of 13 land cover classes for the Northern Cape Province mapped as part of the National Land Cover 2000 (NLC2000) project (Van den Berg *et al*., 2008). Alien plant invasions and bush encroachment by indigenous species were not classified as degraded vegetation but as bushland or woodland, according to the definition of the NLC2000 legend. The degradation of natural vegetation by *Prosopis* should therefore impact on the figures given in Table 3.2.

Table 3.2: Area calculation of the main land cover classes during 2000 (Van den Berg *et al*., 2008)

LAND COVER CLASS	AREA NLC2000 (HA)
Bushland/woodland	7,400,902.23
Shrubland	25,679.365
Herbland	214,052
Natural grassland	1,624,929
Planted grassland	2,469
Forest plantations	3,236
Waterbodies	70,329
Wetlands	607,745
Bare rock and soil	232.775
Degraded natural vegetation	178,406
Cultivated	223,076
Urban/build-up	32,365
Mines and quarries	50,671

CHAPTER 4: MATERIALS AND METHODS

4.1. Software

All remote sensing analysis was performed using ERDAS 9.3.1 and TNTmips 7.2 image processing software. GIS analysis was done using ARCGIS 9.3.2 while Microsoft Office Excel and Access were used for statistical analysis.

4.2. Datasets

4.2.1. Satellite data

The different spatial, temporal and spectral resolutions, as well as the cost, are the limiting factors for the utilization of any satellite data for a particular study. Unfortunately, because of technical constraints, high spatial resolution is associated with low spectral resolution and vice versa. It is therefore necessary to find a compromise between the different resolutions according to the application.

Each scanner or sensor has a number of predefined spectral bands. This is referred to as the spectral resolution of the satellite. The “on board” sensors of the satellite record these spectral responses in the electromagnetic spectrum and transmit the values to receiving stations on earth. The position of these spectral bands in the electromagnetic range is equally as important as the number of spectral bands.

Each vegetation type reflects solar radiation with a specific intensity. Vegetation response or active chlorophyll response are well detected in the visible and near-infrared part of the electromagnetic spectrum. For this reason all satellites that record values in this spectrum are ideal for mapping vegetation response.

Satellites also have a spatial resolution which is unique to each sensor and in some instances unique to each band on board the satellite. The spatial resolution specifies the pixel size as illustrated in Figure 4.1 and can be classified into very high (0.6m - 5m), high (10m - 30m), medium (250m - 500m) and low spatial resolutions (> 250m) respectively. The temporal resolution refers to the frequency the satellite revisits the same location on the earth surface and is classified as high (less than 24 hours to 3 days), medium (4 to 16 days) and low temporal resolutions (more than 16 days) respectively.

4.2.1.1. The use and application of different resolution images

Selecting the correct scale or resolution of data are important when mapping or predicting the distribution and abundance of invasive alien plant species for understanding ecological processes, and management applications and monitoring strategies. Moderate resolution MODIS (250m x 250m) data are most useful at a regional or national scale to direct management interventions or to monitor potential areas of infestation (LP DAAC, 2008). High resolution Landsat (30m x 30m) (Landsat Program, 1999) and SPOT (5m x 5m) (SPOT Image, 2009) data are useful for management on provincial or district level where more detail information on actual extent and densities are required over a period of time.

The cell size of data significantly changes the level of invasion across an area, where for example, a 250m resolution pixel is compared to a 25 m resolution pixel (Figure 4.1). Figure 4.1 illustrates the potential difference in area calculation for the same study area using different resolution satellite images. Although not that accurate for area calculations, coarse resolution data make it possible to monitor potential areas of invasive alien plant invasions. Down scaling this information will help to acquire more costly high spatial and spectral images to focus species based research on, or to do more accurate quantitative analysis on the dynamics of species in quaternary catchments or district level. However, having data available at a fine resolution allows up-scaling to coarser resolution datasets on provincial level, although some detail is lost, it may be more useful when comparing with other datasets, such as SAPIA, at a national level.

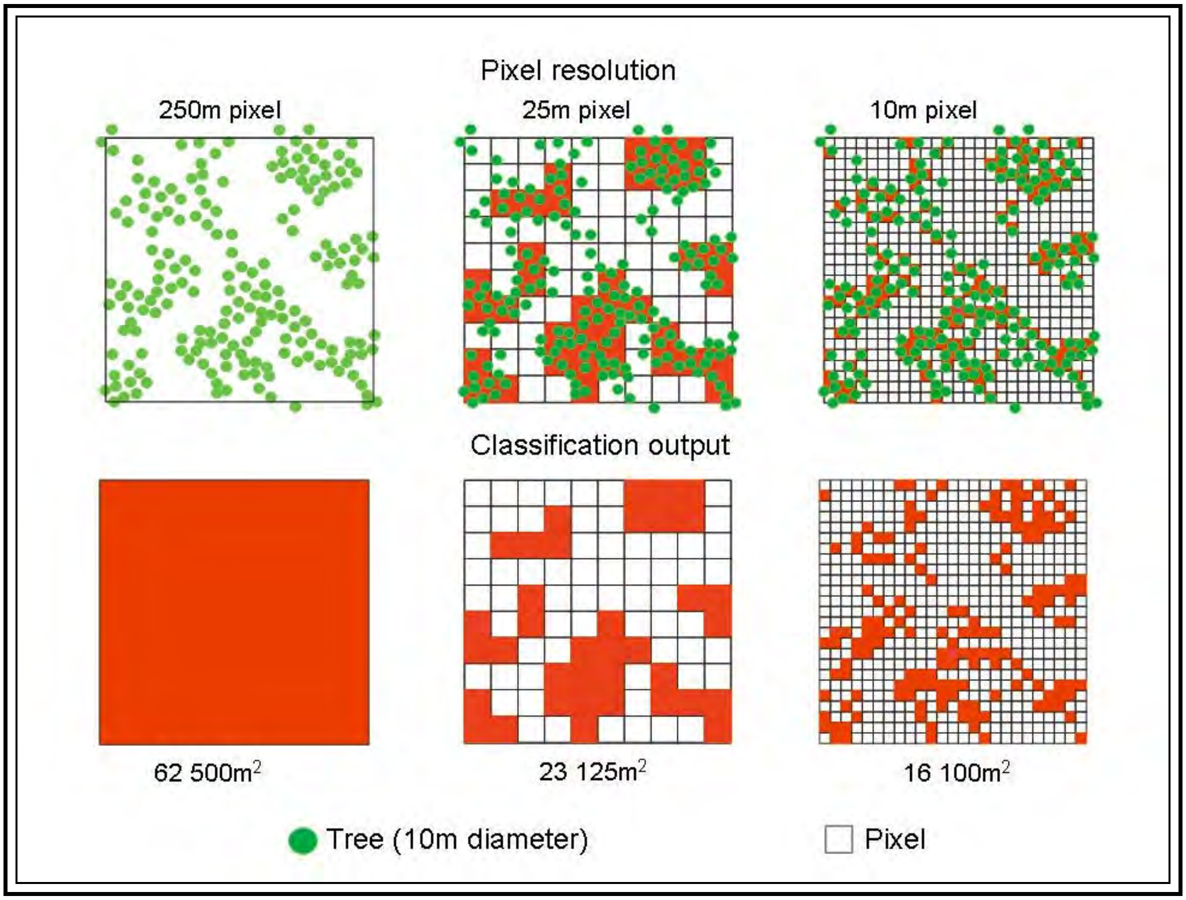


Figure 4.1: Spatial resolution or pixel size. High resolution images provide better accuracy but low spatial resolution images provide better temporal information on a national and regional scale. Tree stand areas are over estimated (6.2ha vs. 1.6ha) with low spatial resolution data compared to higher spatial resolution data.

For this study, the low resolution NOAA/AVHRR (NOAA, 2007) and moderate resolution MODIS data (250m x 250m pixel in Figure 4.1) were used to identify areas of potential invasion on a provincial level as describe by the flowchart in the Figure 4.3. The high resolution Landsat data (25m x 25m pixel in Figure 4.1) were used to more accurately map the historical and current extent and densities of the *Prosopis* species and to determine the invasion rate of the species as describe by the flowcharts in Figure 4.15 and 4.19.

4.2.1.2. The National Oceanic and Atmospheric Administration/ Advanced Very High Resolution Radiometer (NOAA/AVHRR) satellite system.

The National Oceanic and Atmospheric Administration/Advanced Very High Resolution Radiometer (NOAA/AVHRR) (NOAA, 2007) provides highly accurate spectral information. However, it has a low spatial resolution and each scene covers a large area of approximately 1000 km x 4000 km. The sensor has five relatively wide spectral bands ranging from Red to Thermal Infrared (Table 4.1). The first two bands are centered around the red (0.6 micrometer) and near-infrared (0.9 micrometer) regions and is well suited to environmental applications such as detecting vegetation response over large areas while the high temporal resolution of the 10 daily NDVI product makes it ideal to study the *Prosopis* over a number of season. The current available archive of NOAA/AVHRR NDVI data available from the ARC-ISCW are from 1996 to 2000. This archive was used to complement the MODIS data. Although it has been documented by Lloyd *et al.* (2002) that the NOAA/AVHRR data were only successful in mapping dense homogeneous stands of *Prosopis* trees, the analysis of data from more seasons might improve the results. The NOAA/AVHRR results were compared with the MODIS data that were available since 2000 to date. The NOAA/AVHRR NDVI (NOAA, 2007) was calculated using the differences between NOAA/AVHRR channels 1 and 2.

4.2.1.3. The Moderate Resolution Imaging Spectroradiometer (MODIS) satellite system

The MODIS (LP DAAC, 2008) instrument is operating on both the Terra and Aqua spacecraft and images the entire surface of the earth every one to two days. It measures 36 spectral bands and it acquires data at three spatial resolutions (Table 4.1). There are many standard MODIS data products that scientists use to study global change. These products are used by scientists from a variety of disciplines, including oceanography, biology, and atmospheric science. MODIS core standard Vegetation Index (VI) products include the Normalize Difference Vegetation Index (NDVI) and the EVI to effectively characterize and process vegetated surfaces (LP DAAC, 2008). There exists a complete, time series record of these products at the ARC-ISCW, at 250m spatial resolution and 16 day temporal resolution since 2000 to date. The MODIS data were used to create a probability map (Figure 4.3) of potential occurrence of *Prosopis* and to compare the large dense homogeneous stands of *Prosopis* with that of the NOAA/AVHRR data.

4.2.1.4. Landsat

Since 1970, Landsat satellites (Landsat Program, 1999) have provided repetitive, synoptic, global coverage of high-resolution multispectral imagery to maximize detection and monitoring of different types of earth resources. Landsat MSS data provide a historical record of the Earth's land surface from the early 1970's to the early 1990's (USGS, 2009a). The MSS sensors primarily detect reflected radiation from the Earth's surface in the visible and NIR wavelengths (Table 4.1). This is the only complete high resolution dataset at ARC-ISCW for the Northern Cape dating back as far 1970. This data gave an historical view on the extent of *Prosopis* in those early years. The dataset consists of a selection of images between 1972 and 1979.

The Landsat TM sensor or Landsat 4 and 5 with its seven spectral bands provide more radiometric information from the visible, through the mid-infrared (IR), into the thermal-IR portion of the electromagnetic spectrum (USGS, 2009b). The TM sensor has a high spatial resolution but low temporal resolution (Table 4.1). The Landsat TM datasets used for the project were for the years 1990, 2004 and 2007.

Landsat ETM+ image data consist of eight spectral bands, with a spatial resolution of 30m to 60m, and 15m for the panchromatic band (Table 4.1) (USGS, 2009c). The Landsat ETM+ data used for the project were recorded in 2002.

Landsat data provided a good balance between spectral, spatial and temporal resolution for the study area. The moderate spectral resolution (6 multi spectral bands) supplied suitable radio magnetic information, while the spatial resolution was more than adequate for such a big study area. The 16 to 18-day revisit period provided multi-temporal images for each year, making a selection of images for optimum processing and results possible. Landsat data are also relatively inexpensive or in some instances available free of charge. The availability of the 5 datasets presented a rare opportunity to map the historical, as well as the current extent of *Prosopis* in the Northern Cape Province and to do the quantitative analysis.

4.2.1.5. The SPOT 5 satellite system

The SPOT-5 earth observation satellite was placed into orbit in May 2002 (SPOT Image, 2009). The satellite provides an ideal balance between high resolution and wide-area coverage suitable for application at medium scale of between 1:25 000 and 1:10 000. The SPOT 5 satellite completes a circular orbit of the earth every 26 days has a swath width of 60km and spatial resolution of 10m for the panchromatic band and 20m for the four multi-spectral bands (Table 4.1). A complete SPOT-5 image archive for South Africa is now available from the Agricultural Geo-Referenced Information System (AGIS). The Multispectral and Panchromatic resolution merged product of 2007 with

2.5m resolution was used to calibrate the classified Landsat 2007 dataset. This SPOT product was only available for the whole province since 2007.

Table 4.1: Main comparative characteristics of the NOAA/AVHRR, MODIS, Landsat and SPOT satellite sensors used in the study

Sensor	Swath width (km)	Temporal resolution	Number of bands	Spectral resolution (µm)	Spatial resolution (m)
NOAA	2 700	0.5 days	5	0.52–12.5	1100m
MODIS	2 330	1 day by combining Terra (AM) Aqua (PM)	36	Bands 1-2: 0.62–0.87 Bands 3-7: 0.45–2.15	Bands 1-2: 250 Bands 3-7: 500
Landsat MSS	185	18 days	4	0.5–1.1	82
Landsat TM	185	16 days	7	Bands 1 -5: 0.45–1.75 Bands 6: 10.4–12.5	Bands 1-5 and 7: 30 Bands 6: 120
Landsat ETM	185	16 days	9	Bands 1-5: Bands 6-7: Band 8 (Panchromatic): 0.5-0.9	Bands 1-5 and 7: 30 Bands 6.1-6.2 Band 8: 15
SPOT	60	26 days	5	Bands 1-4 (Multi-spectral): 0.5-1.75 Band 5 (Panchromatic): 0.49-0.69	Bands 1-3: 10 Band 4: 20 Band 5: 5 (2.5m by interpolation)

4.2.2. Ancillary data

Several existing datasets, including the National Land Type Survey (Land Type Survey Staff, 1972 – 2006) and a Digital Elevation Model (DEM) 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 Province.

4.2.2.1. Field data collection

A number of field trips to the Northern Cape Province were undertaken since 1998 as part of this and other *Prosopis* studies. The purpose of the excursions were to find and select training sites representative of different densities of *Prosopis* infestation, for use in analysing the satellite images and ancillary data, as well as to produce a probability map of possible *Prosopis* infestation. At each of the more than 700 training sites, descriptive information was recorded, geographical position determined by means of a Global Positioning System (GPS) and a colour photograph taken for future reference. Since most of the land in the Northern Cape Province is privately owned, access to *Prosopis* infested properties were limited and data were therefore mainly collected along main, secondary and arterial roads and depended on what was visible from the road side edge. During May 2007 an aerial survey was done to establish the presence and absence of *Prosopis* in selected areas that were inaccessible by road. A GPS waypoint with photo and appropriate density class was recorded. Data were collected on a field data collection sheet (Appendix 1) and later put into a GIS. Four canopy density classes (Figure 4.2) were used. This were classified as closed (76% - 100%), dense (51% – 75%), medium (26 % - 50%) and sparse (0% - 25%).

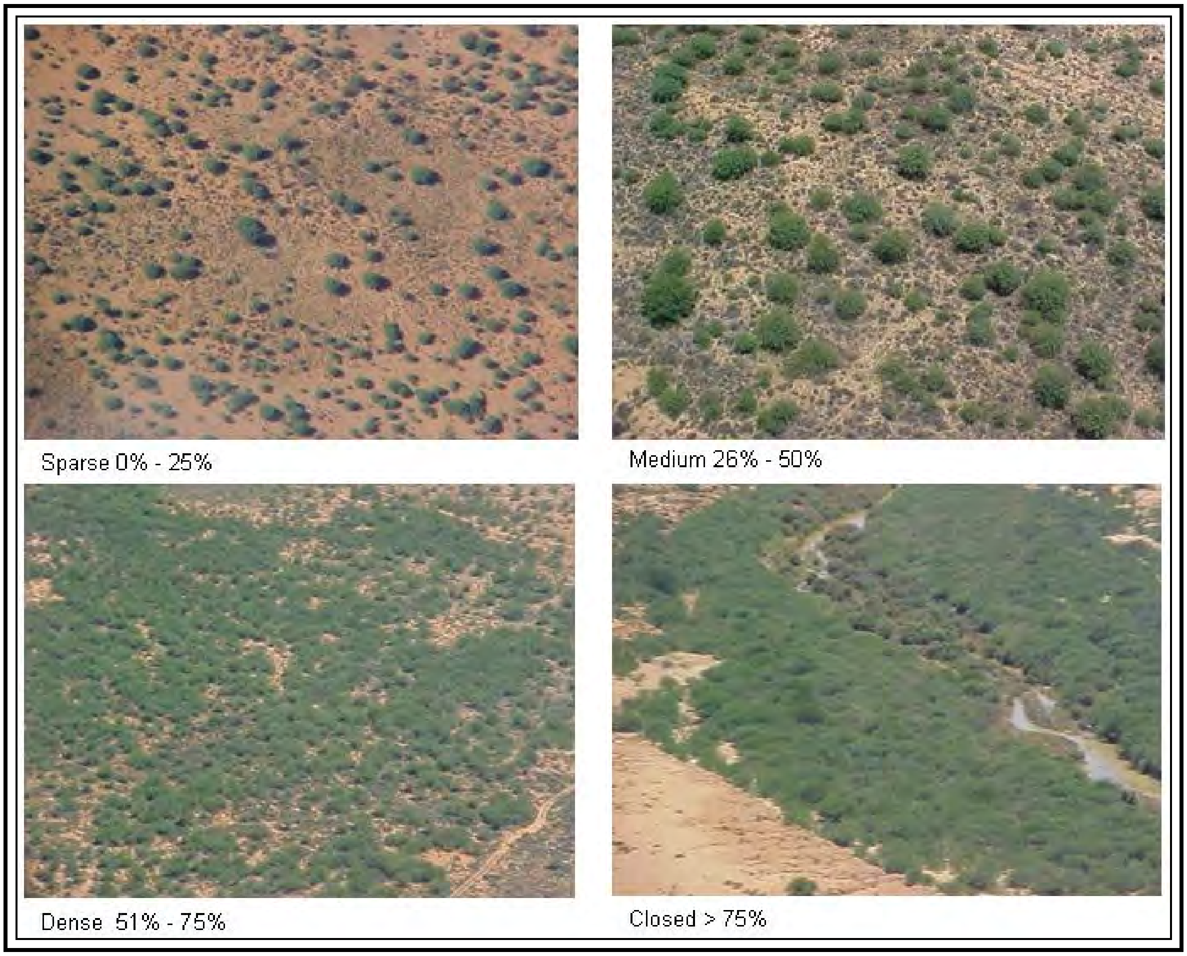


Figure 4.2: Arial photographs of the four canopy density classes used in the study.

4.2.2.2. Land Types of South Africa

The National Land Type Survey (Land Type Survey Staff, 1972 – 2006) was a reconnaissance survey (1:250 000 scale) that followed an inventory rather than a fixed legend approach and is the source of information of generalised soil maps of the country. The soils were classified based on pedogenesis and land use capability and grouped into 28 generalized soil patterns to produce a map with a scale of 1:1,000,000. The percentages of various soil components found in any particular mapping unit were estimated without the restriction of a rigid system of classes. The generalised soil information of the National Land Type Survey together with the field data were used to establish the properties of the soils on which *Prosopis* occur (Table 4.2).

4.2.2.3. Digital Elevation Model (DEM)

NASA's Shuttle Radar Topography Mission (SRTM) (CGIAR, 2008) data provide 90m DEM coverage for approximately 80% of the earth's surface. The DEM was created from duel stereoscopic radar signals and post processing. This data are provided in an effort to promote the use of geospatial science and applications for sustainable development and resource conservation in the developing world. Providing remarkable topographical detail at 1:50 000 and coarser scales. The DEM files have been mosaiced into a seamless global coverage, and are available for download as 5 degree x 5 degree tiles. The DEM data were used to create terrain units and flow paths for the Northern Cape Province.

4.2.2.4. Climate information

Monthly rainfall data were requested from the ARC-ISCW in Potchefstroom (WEB2007, 2007). Data were available since the early 1900's. It was imported not to select or use images recorded just after the first seasonal rain as these would result in the flushing of annual grasses and wetland vegetation that can influence the mapping of the dense woody vegetation in the riparian zones. Extreme wet years might also result in the over-classification of *Prosopis* stands.

4.3. Areas susceptible to *Prosopis* invasion

The distribution of plant species in their native range are influenced by a range of environmental factors (Foxcroft *et al*., 2002), which include for example soil texture, degree of slope, geology, water availability (including ground water) and climate. GIS overlays and field knowledge have shown an association between *Prosopis* position in the landscape and soil types. For this objective of the study the relationship between terrain unit or landscape position, flow paths, and spectral vegetation response were used to create a map of areas potentially susceptible to *Prosopis* invasion also called a probability map for the Northern Cape Province. The flow chart in Figure 4.3 gives an overview of the process followed and the data used to create the *Prosopis* probability map for *Prosopis* invasion in the Northern Cape Province. The circled numbers in the flow chart (Figure 4.3) are used for cross referencing between the flow chart and the explanation of the processing procedure in the text.

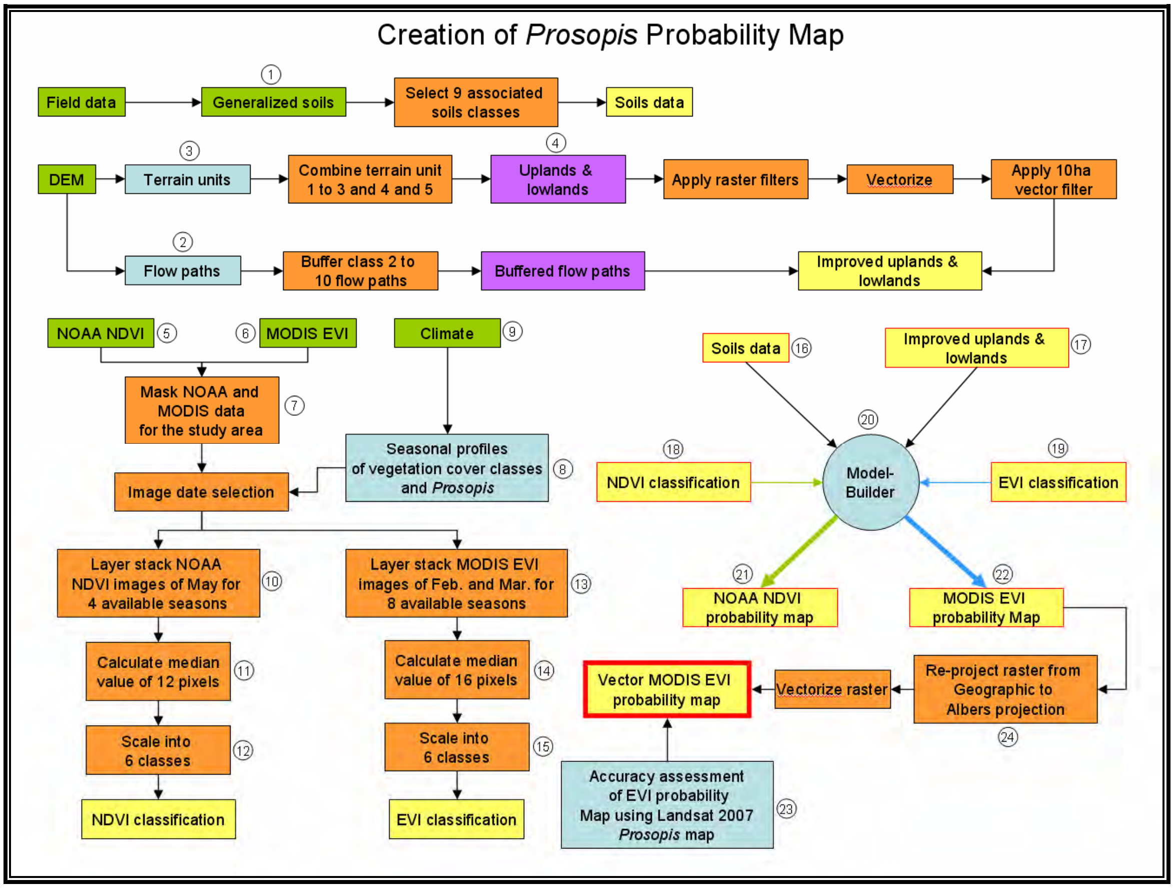


Figure 4.3: Flow chart of the process followed and data used to create the probability map of areas susceptible for *Prosopis* invasion on a provincial or a regional scale. Green squares indicate the raw datasets used in die study. Blue squares represent datasets created from the raw datasets and orange squares the processes used to create the datasets used as input (yellow squares) into the model to create the *Prosopis* probability map (yellow square with thick red outline).

4.3.1. Generalised Soil Classes of South Africa

The Northern Cape has 19 generalised soil classes (Appendix 4) and a water body class. Field data suggested that *Prosopis* occur mainly on 9 of these classes of which the properties are described in Table 4.2. These nine soil classes (1) associated with *Prosopis* were extracted from the main dataset and used in the model builder to reduce the possible area of *Prosopi*s occurrence and create the probability map.

Table 4.2: Properties of the Generalised Soil Classes associated with *Prosopis* as obtained from the National Land Type Survey (Land Type Survey Staff, 1972 – 2006)

Red-yellow apedal, freely drained soils (map units Ae – Ai)	
Ae	Red, High base status, > 300mm deep, no dunes
Af	Red, high base status, >300mm deep, with dunes
Ag	Red, high base status, < 300mm deep
Ah	Red and Yellow, high base status, usually <15% clay
Ai	Yellow, high base status, usually < 15% clay
Prismacutanic and/or pedocutanic diagnostic horisons dominant (map units Da – Dc)	
Da	Red B horison
Db	B horison not red
Glenrosa and/or Mispah Forms (other soils may occur) (map units Fa – Fc)	
Fc	Lime generally present in the entire landscape
Miscellaneous land classes (map units Ia-Ic)	
Ia	Undifferentiated deep deposits

4.3.2. Terrain units and flow path data

GIS overlays of riparian zones and field experience showed a strong association between *Prosopis* and drainage lines as well as 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 4.4). It is also possible to get a second and third phase mid slope, indicated by the relevant number in brackets after the terrain unit number e.g. 3(1) (Land Type Survey Staff, 1972 – 2006).

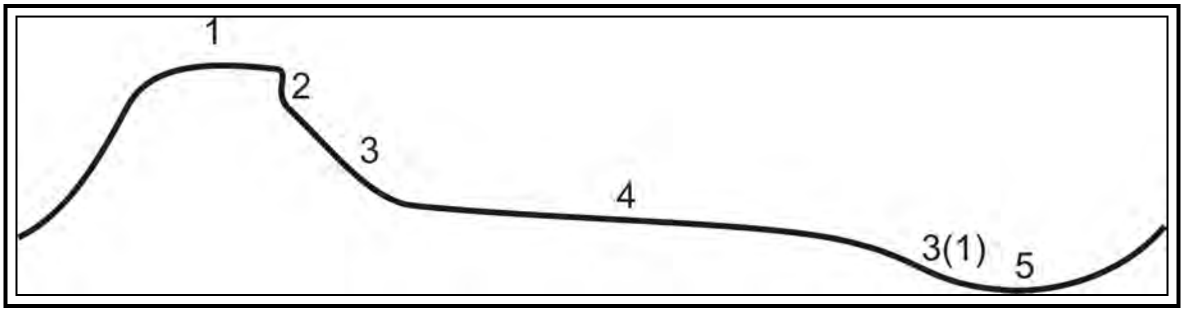


Figure 4.4: Terrain units where 1 represents a crest, 2 scarp, 3 a mid slope, 3(1) a secondary mid slope, 4 a foot slope and 5 a valley.

MIPS software was used to create accurate flow paths (2) (Appendix 5) and terrain units (3) (Appendix 6) on 90m resolution for the whole province using the DEM data (Appendix 7). The terrain units created from the 90m DEM was filtered to remove clutter created as a result of the spatial resolution and errors in the raw data by applying a 3 x 3 majority raster filter after which the data were vectorised. A vector filter with minimum mapping unit of 10ha was further applied to create a dataset more compatible with the spatial resolution of the MODIS 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 lowlands (4). Some small annual rivers were not mapped accurately by the terrain units, these dry riverbeds were included into the dataset by using the flow paths also created from the DEM data. To do this, class 2 to 10 flow paths were used and individually buffered according to the size of the river or stream (Table 4.3), class 10 being the main rivers, after which the different buffered flow paths (Figure 4.5) were merged into one vector layer again. By combining the buffered flow paths (Figure 4.5) with the uplands and lowlands data (Figure 4.6) a new improved upland and lowland dataset (Figure 4.7; Appendix 8) was created. This improved dataset was used in the model builder to reduce the area of possible *Prosopi*s occurrence and create the probability map

Table 4.3: Buffer sizes used to for the different classes flow paths to improve the upland and lowland dataset

Flow path class	Buffer Size (m)
Class 8 - 10	450 m
Class 6 - 7	230 m
Class 5	200 m
Class 4	150 m
Class 3	130 m
Class 2	100 m

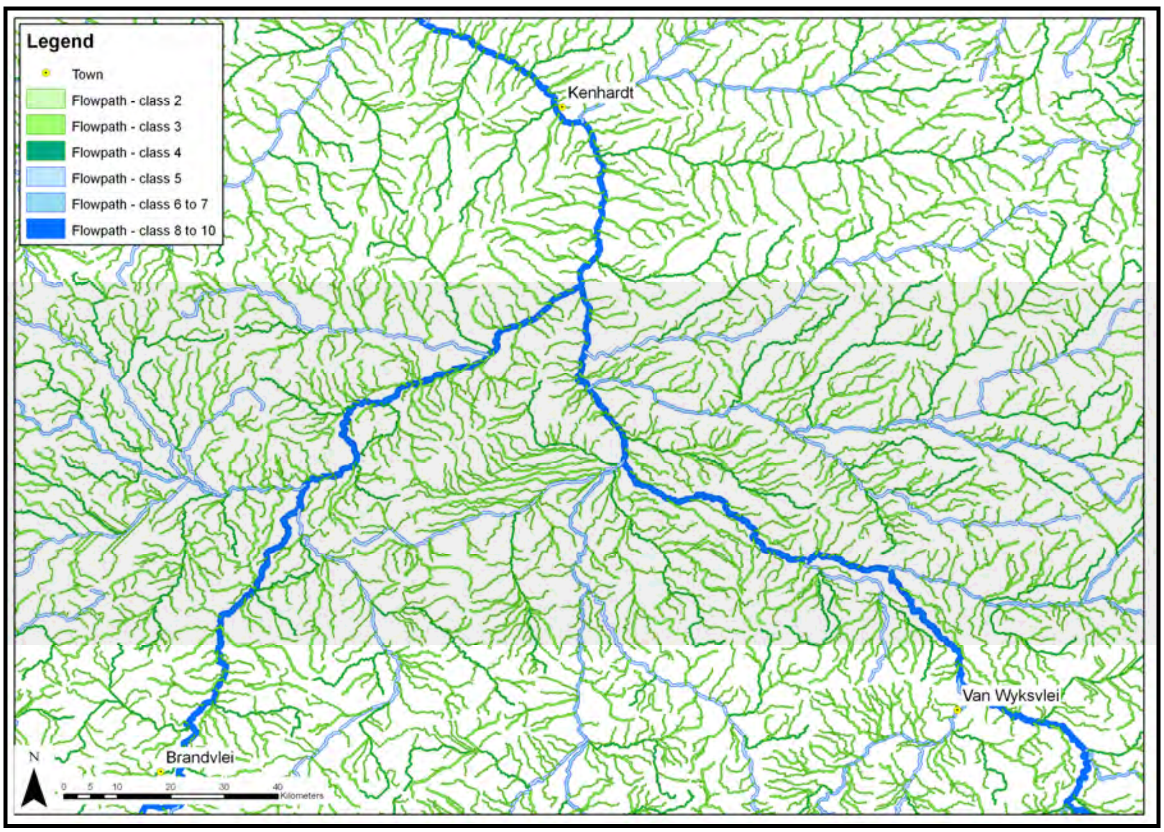


Figure 4.5. Detailed image of the different classes of flow paths created from the DEM data. Flow paths were buffered according to size to improve the uplands and lowlands dataset. Derived from SRTM DEM (CGIAR, 2008).

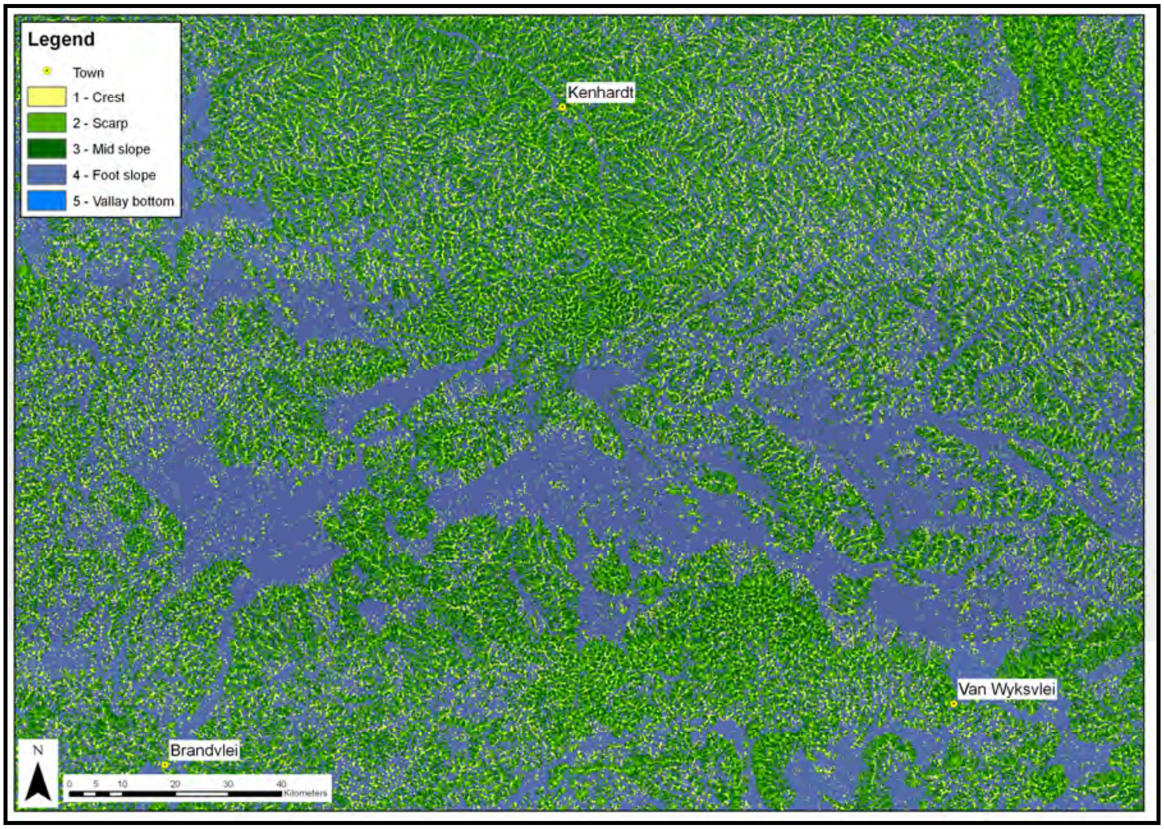


Figure 4.6: Detailed image of the terrain units created using the DEM. The small areas (clatter) of uplands (green) in between the larger lowlands (yellow) before any filters were applied are visible. Derived from SRTM DEM (CGIAR, 2008).

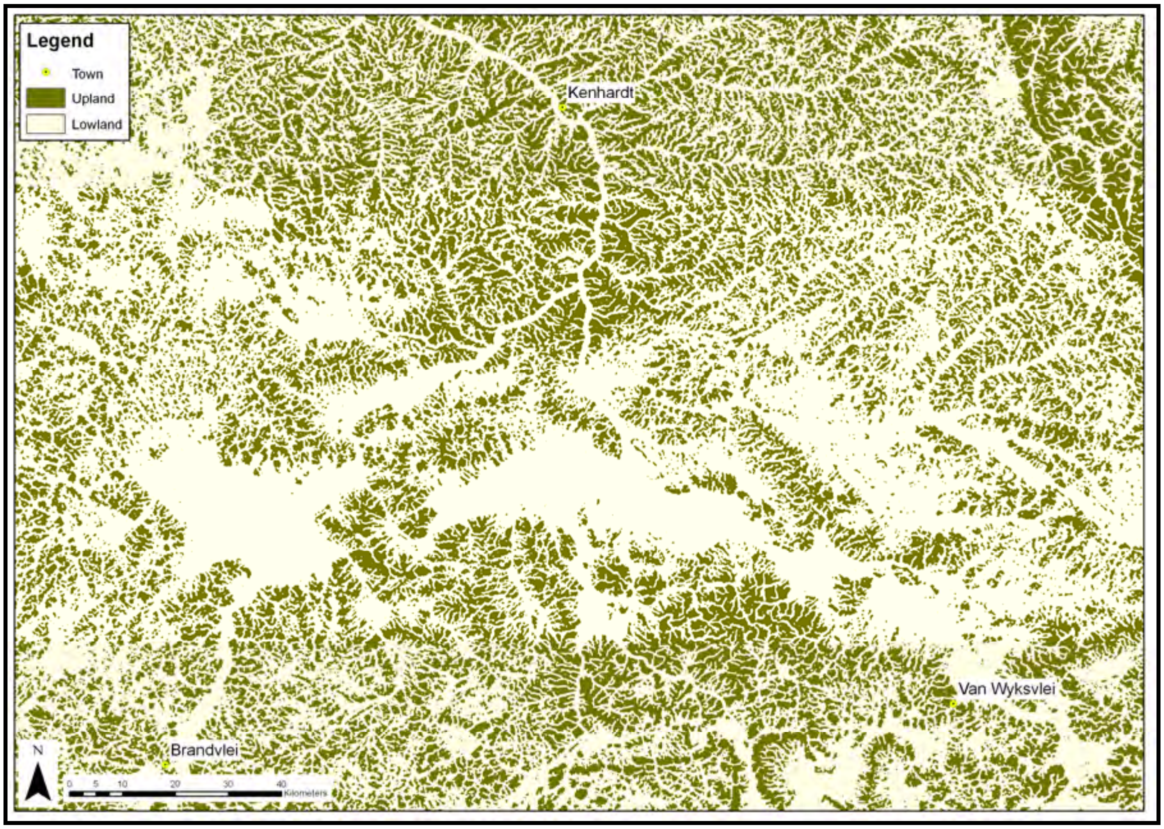


Figure 4.7: Detailed image of the improved uplands and lowlands dataset, after the filters were applied and the buffered flow paths merged with the terrain units. Derived from SRTM DEM (CGIAR, 2008).

4.3.3. Satellite Data

4.3.3.1. Pre-processing of coarse and medium resolution imagery

The NOAA/AVHRR NDVI 10 daily deciles for 1997 to 2000 (5) as well as the MODIS EVI 16 day composites for 2000 to 2009 (6) were extracted from the image archive at the ARC-ISCW. Using the batch command in ERDAS Imagine the 144 NOAA/AVHRR NDVI and 432 MODIS NDVI and EVI bands were imported and cut to the boundary of the province using vector mask (7). Data values were kept in unsigned 16-bit format and in Geographic/WGS84 projection for processing purposes.

4.3.3.2. Seasonal profiles

Training sites of different land cover classes were selected from the NLC2000 field data collection database. NOAA/AVHRR and MODIS images were analysed according to annual phenology patterns of *Prosopis* and other vegetation covers from the NLC2000 data to establish the best time of year to discriminate between *Prosopis*, woodlands, dense and open bushland, shrubland and cultivated fields (8).

NOAA/AVHRR NDVI Profiles.

Seasonal images were created using the 10 daily NOAA/AVHRR NDVI deciles from July to June of the next year of all available data from 1997 to 2000. Pixel values of each selected vegetation cover (8) were extracted using ERDAS and imported to Microsoft Excel. The median value at each point from four (4) growing seasons was calculated for each class and plotted against each 10 daily decile of a month (Figure 4.8). To eliminate the influences that rainfall has on the NDVI values as well as to compensate for outliers in the sample points the median instead of the average value over all years was used (Zoran and Stefan, 2006). The influence of higher and lower rainfall on NDVI values are illustrated in Figures 4.8 to 4.10. The rainfall gradient (9) from west to east of the study areas clearly influence the NDVI and vegetation type. The influence on NDVI of the higher average rainfall in 1997/1998 (215mm) can be seen in Figure 4.8 while the lowest rainfall occurred during the 1998/1999 (167mm) season (Figure 4.9), rainfall during the 1999/2000 season was average (207mm).

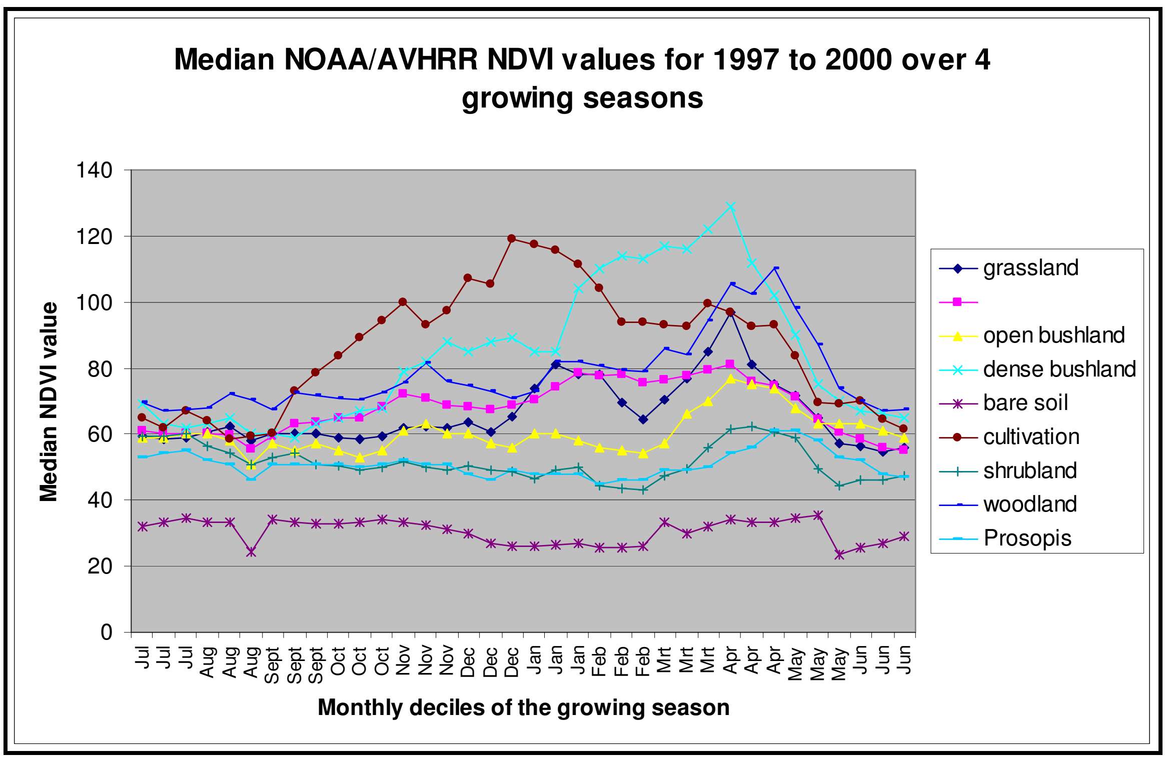


Figure 4.8: The median NOAA/AVHRR value per point (Y-axes) over four growing seasons was calculated for each vegetation cover class and plotted against each decile (X-axes).

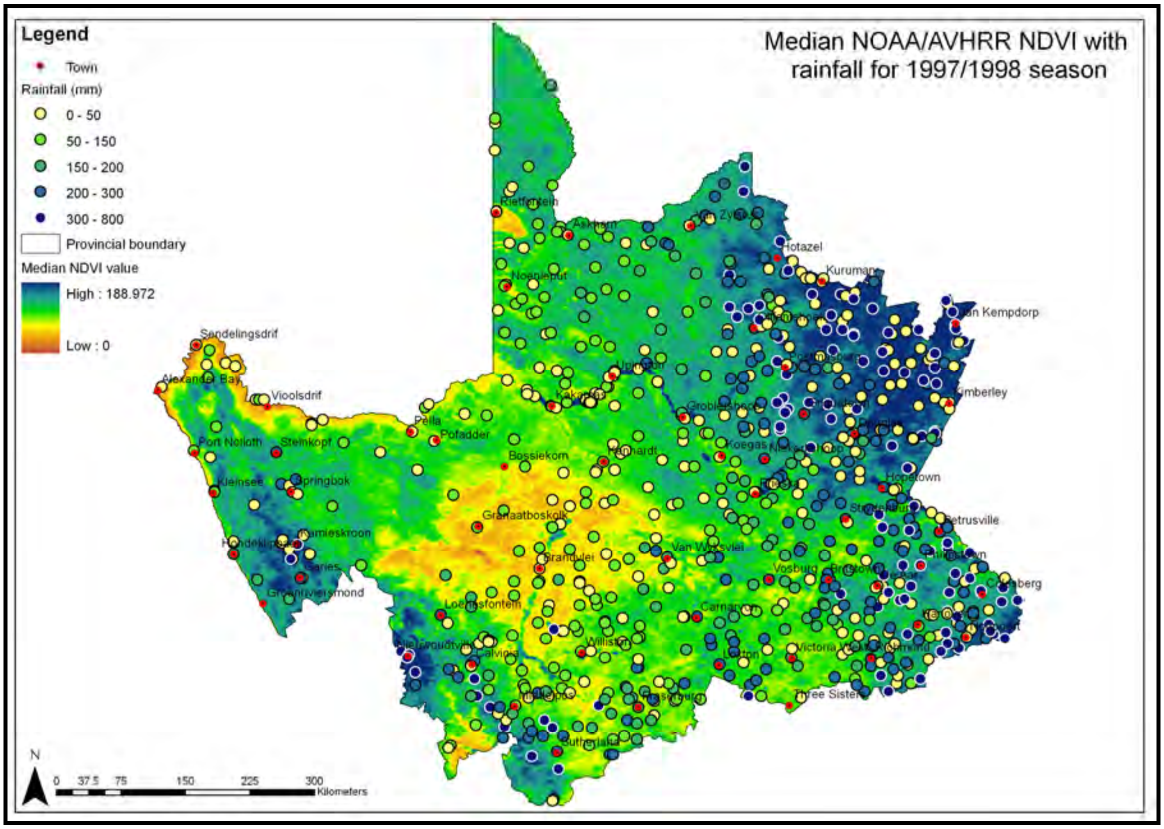


Figure 4.9: Mean NOAA/AVHRR NDVI with annual rainfall for the 1997/1998 season at available weather stations indicated by points (WEB2007, 2007).

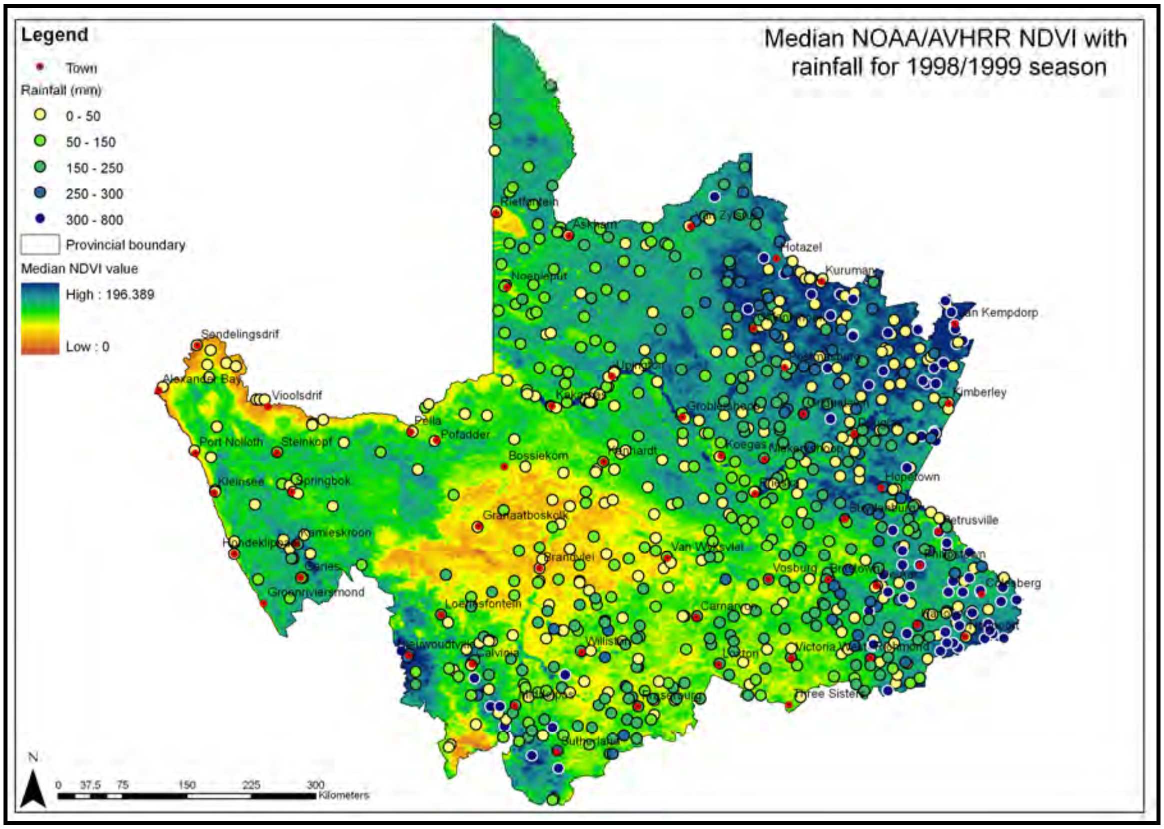


Figure 4.10: Mean NOAA/AVHRR NDVI with annual rainfall for the 1998/1999 season at available weather stations indicated as points (WEB2007, 2007).

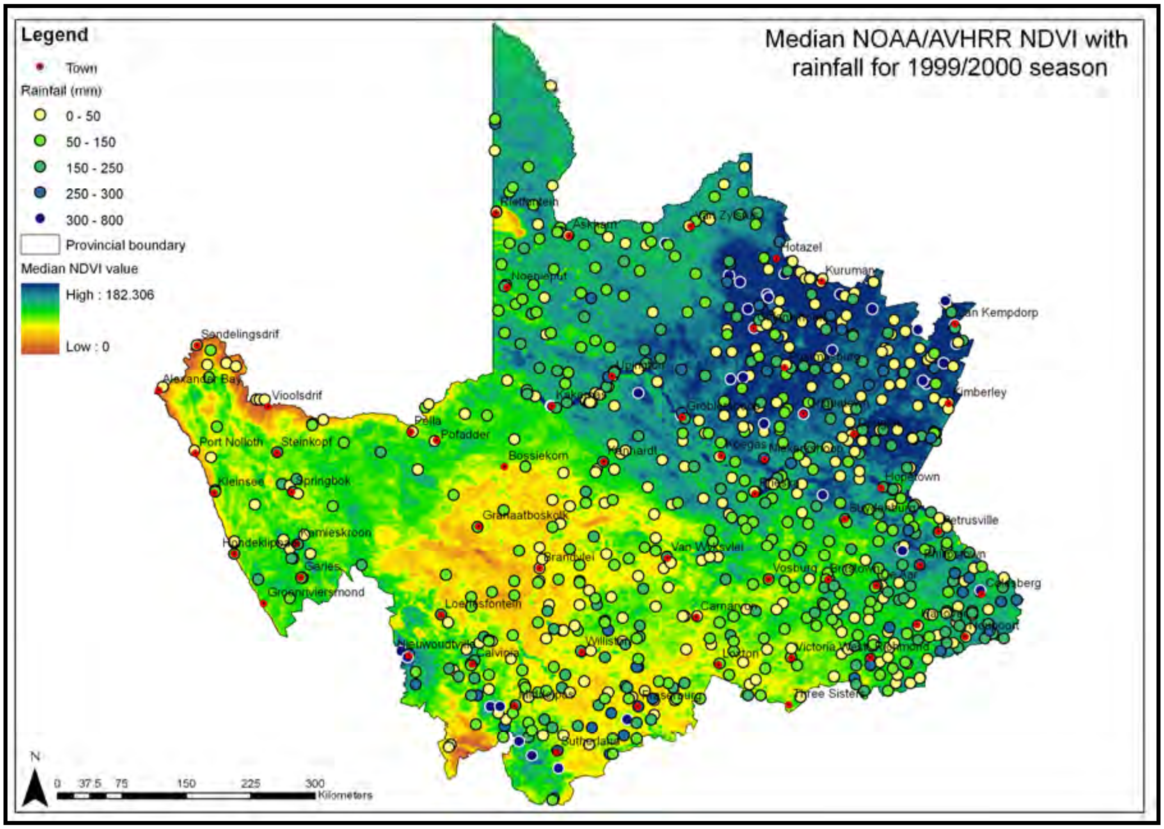


Figure 4.11: Mean NOAA/AVHRR NDVI with annual rainfall for the 1999/2000 season at available weather stations indicated as points (WEB2007, 2007).

MODIS EVI profiles

Seasonal images were created using the 16 day MODIS EVI Composites from July to June of the next year of all available data from 1997 to 2000. Pixel values of each vegetation cover point were extracted using ERDAS and imported to Microsoft Excel (8). The median value per point over nine growing seasons was calculated for each class and plotted against each 16 day composite (Figure 4.12). The median EVI value was used again instead of mean values, to eliminate the influence of rainfall as outliers in the sample points. The relationship between rainfall (9) and EVI values for *Prosopis* are evident when Figures 4.13 and 4.14 are compared.

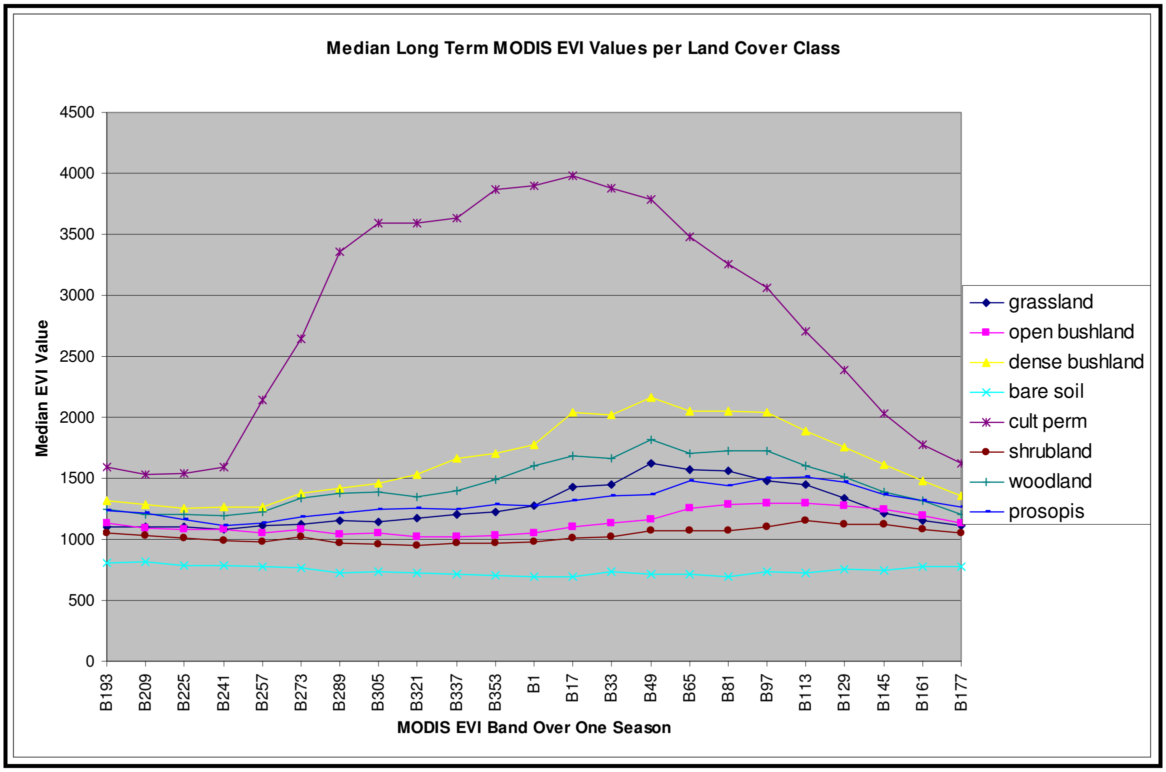


Figure 4.12: The median EVI values over nine growing seasons (Y-axes) plotted against the 16 day EVI bands (B) (X-axes) for each vegetation cover class.

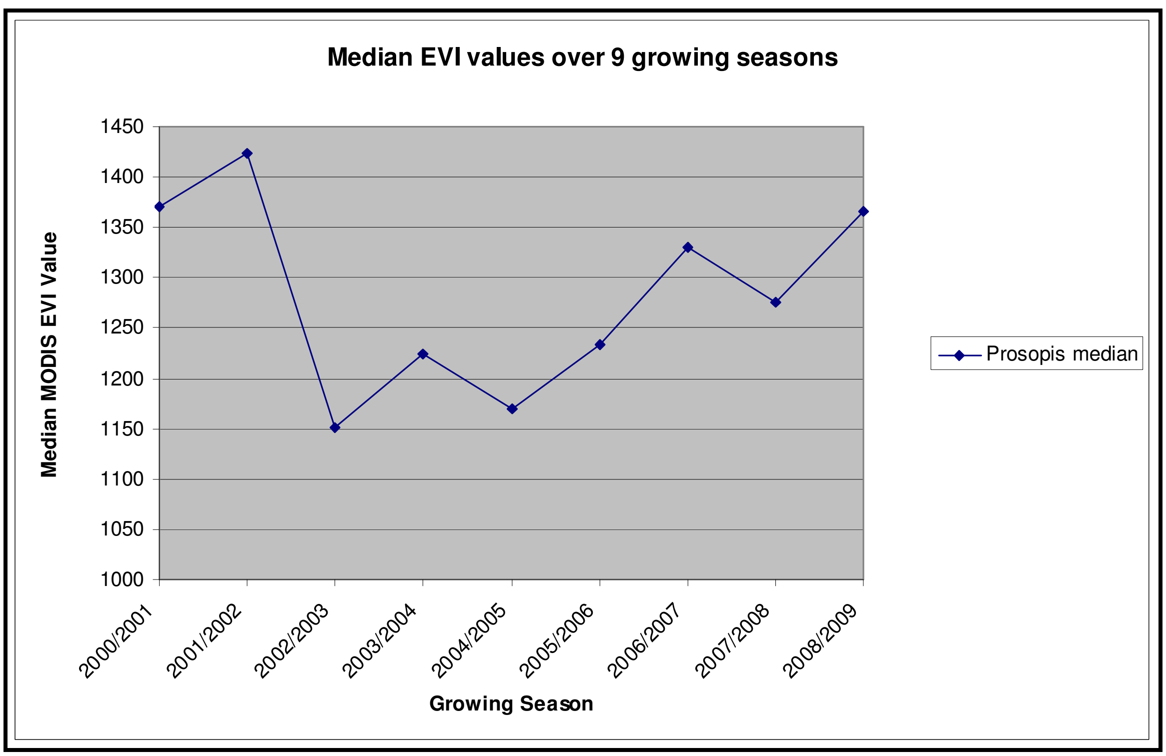


Figure 4.13: The median EVI values (Y-axes) for *Prosopis* over nine seasons (X-axes) from 2000 to 2009.

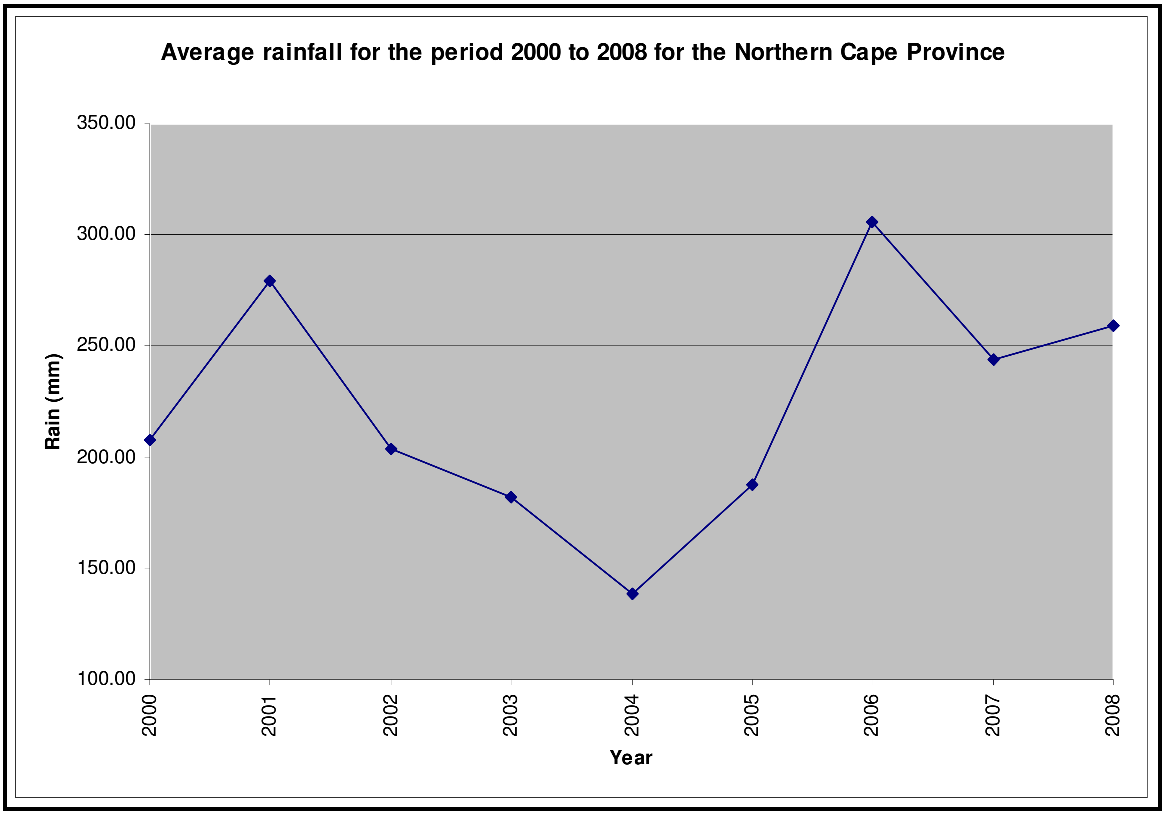


Figure 4.14: The average rainfall (Y-axes) for the period 2000 to 2008 (X-axes) for the Northern Cape Province.

4.3.3.3. Processing of coarse and medium resolution satellite data

NOAA/AVHRR

Results of the time series analysis of *Prosopis* cover (Figure 4.8) created from NOAA/AVHRR NDVI data, indicated that the peak time of plant activity for *Prosopis* is in May and that these deciles are more likely to help distinguish *Prosopis* from other vegetation cover types. The three deciles for each month of May were selected for the available four seasons and layer-stacked (10) as a thematic image with 12 bands, the median value of the 12 pixels (11) on top of each other were calculated and a thematic, unsigned 8-bit image created. The image was scaled (12) into five NDVI probability classes (Appendix 9), using visual interpretation, from low (class 1) to high (class 5), and a cultivation class (class 6).

MODIS EVI

Results of the time series analysis of *Prosopis* (Figure 4.12) created from MODIS EVI data indicated that the peak time of plant activity is during February (B33) to May (B129) and that these bands are more likely to help distinguish *Prosopis* from other vegetation cover. Two NDVI images for late February (B49) and beginning of March (B49) were selected to eliminate the overlap between the grassland and woodland classes, and to co-inside with the already available Landsat images. The two bands selected for each of the eight seasons were layer-stacked (13) into a thematic image with 16 bands. The median value of the 16 pixels (14) on top of each other was calculated and a thematic image created with unsigned 8-bit values. The image was scaled (15) using visual interpretation into five probability classes (Appendix 10), from low (class 1) to high (class 5), and a cultivation class (class 6).

4.3.4. Construction of *Prosopis* probability map

The final step in creating the *Prosopis* probability map was to integrate the satellite data with the soil information (16) and the improved upland and lowland data (17) created from the DEM. The NOAA/AVHRR NDVI (18) and MODIS EVI classifications (19) were masked with the soil classes and bottomlands and uplands datasets using the Model Builder (20) in ERDAS Imagine. The probability model is based on the presence and absence of *Prosopis* in the three input datasets. The lowlands and nine soil classes that were associated with *Prosopis* was coded one in the raster and the rest of the raster as zero for no association. The model returned the class value of the NOAA/AVHRR NDVI probability class (21) to a new raster when both of the values of the bottom lands and generalized soil patterns were one. This process was repeated for the MODIS EVI classification (22). The reliability of the probability classification was tested using the independently created Landsat 2007 *Prosopis* density classification (23). The two final raster products were re-projected (24) from the Geographic projection to Albers Equal Area projection to improve area calculations and vectorised for further analysis.

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

The flow chart in Figure 4.15 explains the process followed and the data used to create data on the historic and current extent of *Prosopi*s invasion in the Northern Cape Province. Only high spatial resolution Landsat images for five different years were used and processed using the same procedure. The circled numbers in the flow chart (Figure 4.15) are used for cross referencing between the flow chart and the explanation of the processing procedure in the text.

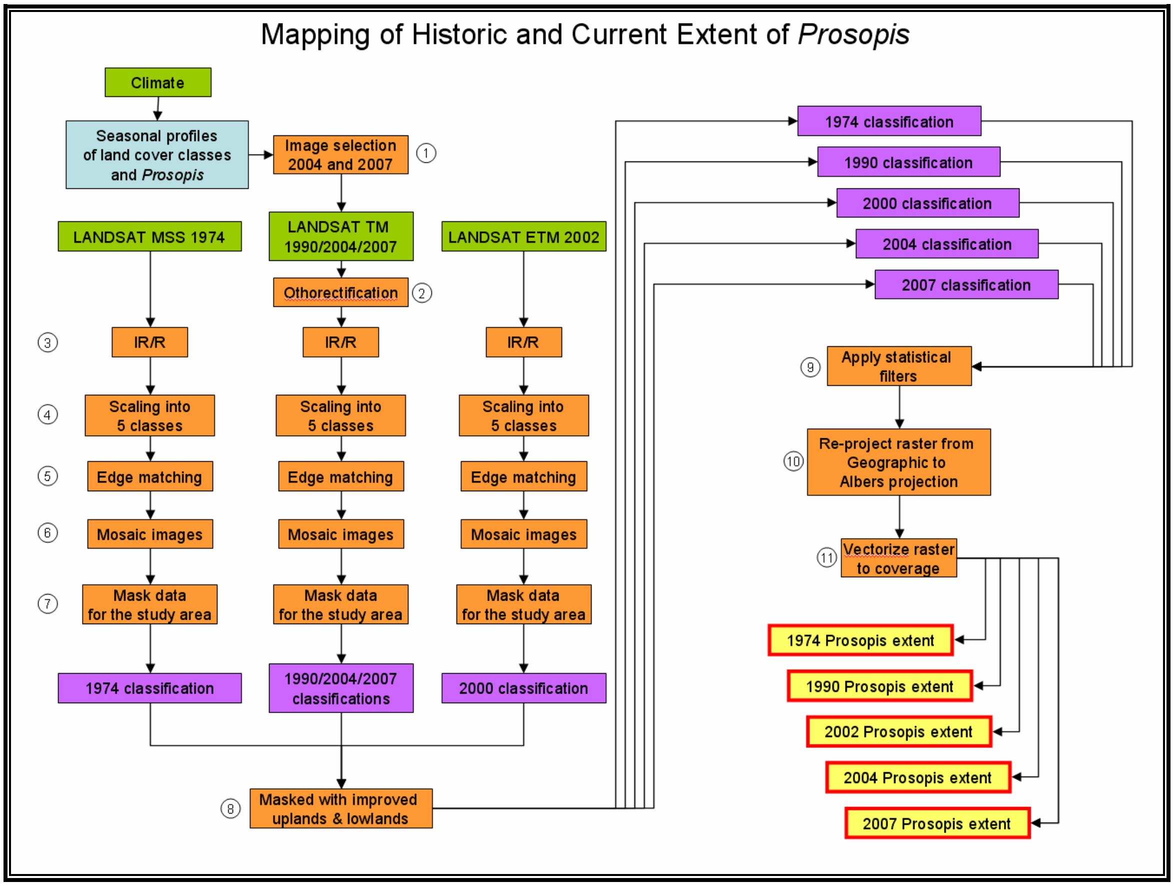


Figure 4.15: Flow chart of the process followed to create the data on the historic and current extent of *Prosopis* invasion. Green squares indicate the raw datasets used and purple squares the final raster datasets of the extent of *Prosopis*. Orange squares indicate the processing performed on the datasets. The final vector datasets are indicated by yellow squares with thick red outlines.

4.4.1. Pre-processing of imagery

The Landsat MSS (1970's), TM (1990) and ETM+ (2002) images were all pre-processed as part of the Global Land Cover Network (GLCN) initiative. These three datasets were imported to ERDAS Imagine and the projection was changed from Universal Transverse Mercator (UTM) World Geodetic System 84 (WGS84) to Geographic/WGS84. The two recent Landsat TM datasets (2004 and 2007) were provided by the Satellite Application Centre (SAC) in South Africa. The dates of these images were selected to match the older datasets. After initial analysis using the summer and winter datasets of the NLC2000 project and the spectral analysis of the MODIS data, it was conclusive that the late summer (February to April) images would be suitable to map *Prosopis* (1). The 2004 and 2007 images were orthorectified (2) using the SRTM DEM and 2002 Landsat dataset as base data. The new images were orthorectified using the original

UTM/WGS84 projection after which it was re-projected to the Geographic/WGS84 projection. Each Landsat TM and ETM+ dataset consisted of 31 images while the Landsat MSS dataset consisted out of 37 images. Data values of all datasets were kept as unsigned 8-bit.

4.4.2. Spectral Vegetation Indices

The large geographical extent and variation in vegetation and landscape demanded the use of a semi-automated technique for the mapping of *Prosopis*. A two stepped procedure was implemented to accomplish this. Firstly, all images were processed using the vegetation index Infrared/Red (IR/R) (3). The result was a continuous layer for each individual image with floating point data values. IR/R 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. 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. As expected, discrimination between *Prosopis* and other woody vegetation was not achieved completely, but the results were however much better than a normal unsupervised interactive self-organised clustering procedure (ISODATA) classification. The IR/R index did however discriminate between much of the dryer Savanna vegetation and open woodlands. The influence of background noise, like geology, was also eliminated by the index. The IR/R images could not be scaled according to fixed predetermined values for two main reasons, namely (i), the variation in image dates and (ii) the variation in rainfall over the study area. The images were therefore scaled manually (4) using visual interpretation, the field data points and expert knowledge into five density classes, as well as an agricultural class (Figure 4.16). The 2007 Landsat dataset could also be scaled using the 2007 SPOT 5 spatially enhanced multispectral dataset for South Africa. Unfortunately no SPOT 5 data for the other Landsat datasets were available for the province. Care was taken to correct the classification at the seams of adjacent images (5) in the mosaic. All images of each year were mosaiced (6) into one image and clipped to the extent of the province (7). The subsequent step was to remove the indigenous vegetation. This was achieved by masking the classification (7) with the Upland Bottomland dataset created for the probability map (Figure 4.17). The cultivated class was improved by adding the mapped cultivated fields available from the South African Agricultural Field Boundaries database (South African Agricultural

Field Boundaries, 2008) to all the classifications.

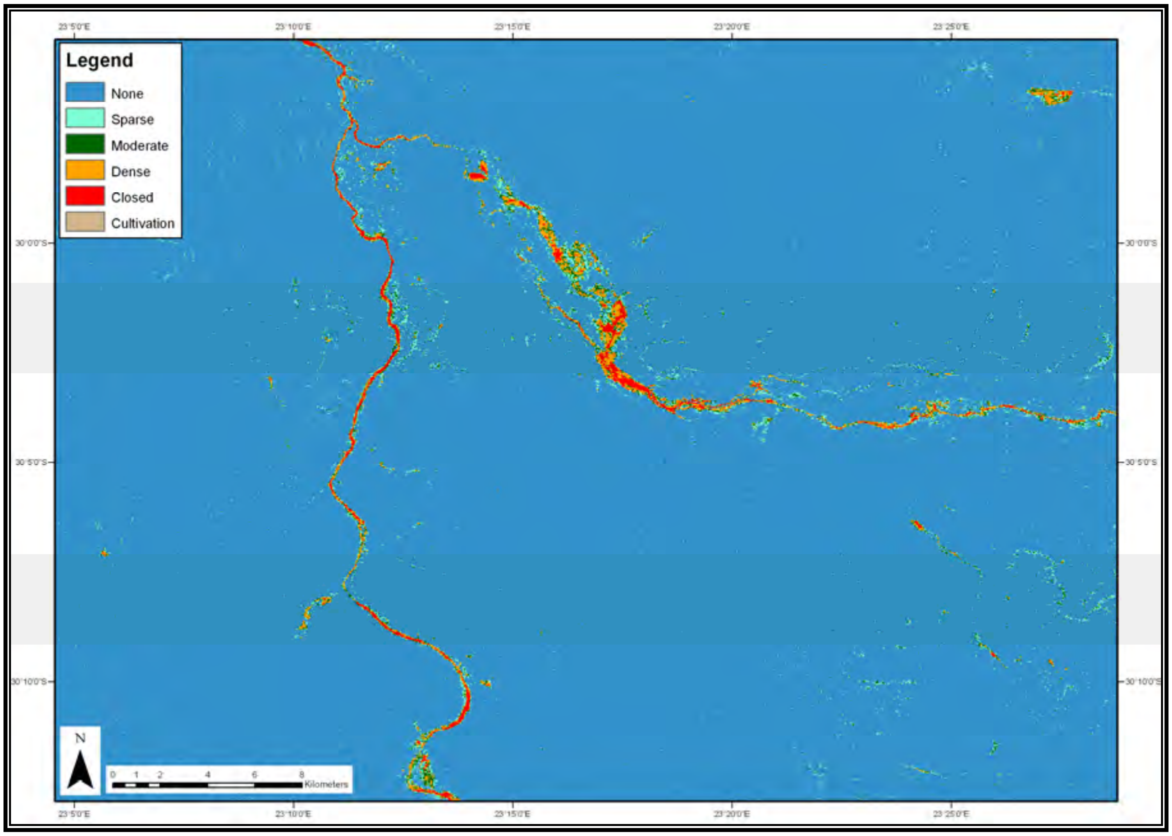


Figure 4.16: Scaled IR/R images with five *Prosopis* canopy density classes and a cultivation class.

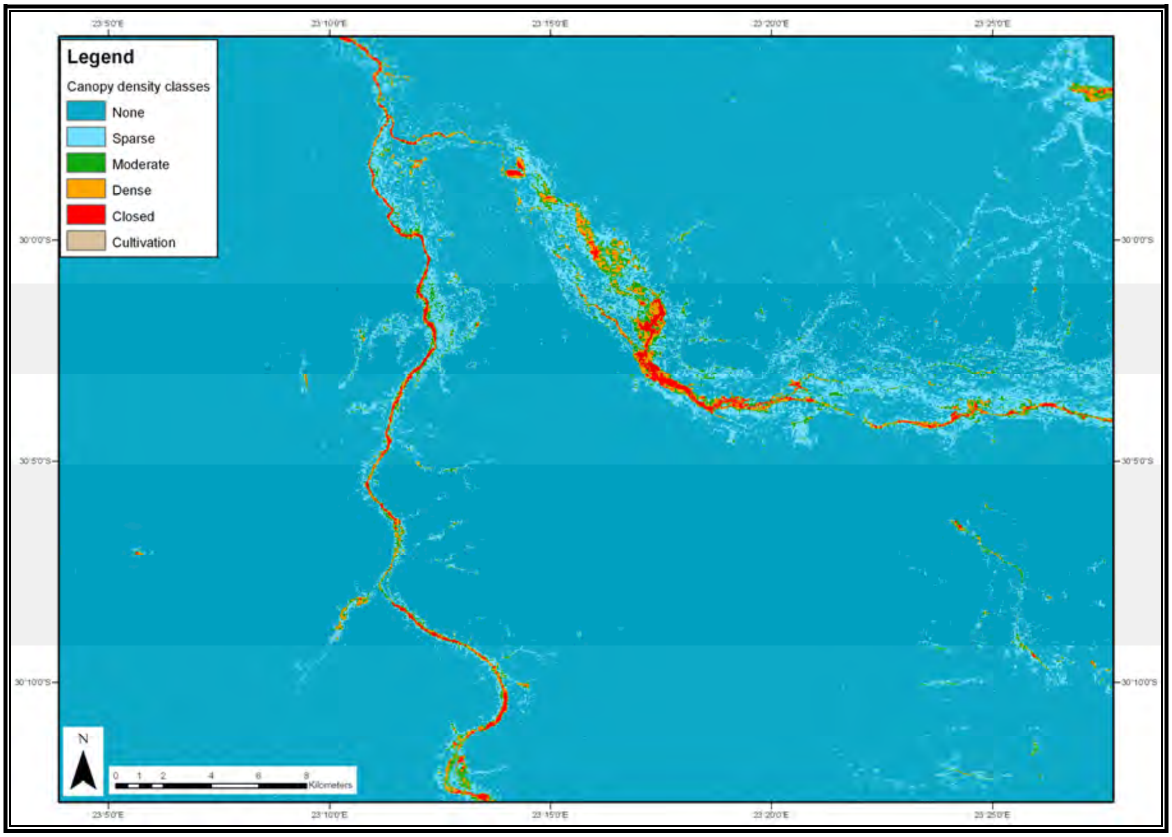


Figure 4.17: Classified and masked IR/R image with five *Prosopis* canopy density classes and a cultivation class.

Two statistical filters (9) were applied to the raster data (Figure 4.18). In these filters, the center 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 or areas with scattered *Prosopis* cover. Secondly a 5 x 5 median filter was applied to filter out very small areas which create a salt and pepper effect. The classifications were finally re-projected (10) to the Albers Equal Area Conic projection which produced a more accurate area and distance calculations than the Geographic projection for large areas (ERDAS Field Guide, 2008). These images were exported to ARCINFO coverage's (11) in ERDAS, imported in ARCINFO and exported to ARCINFO shape files. All area calculation and dataset intersections were done using ARCINFO software.

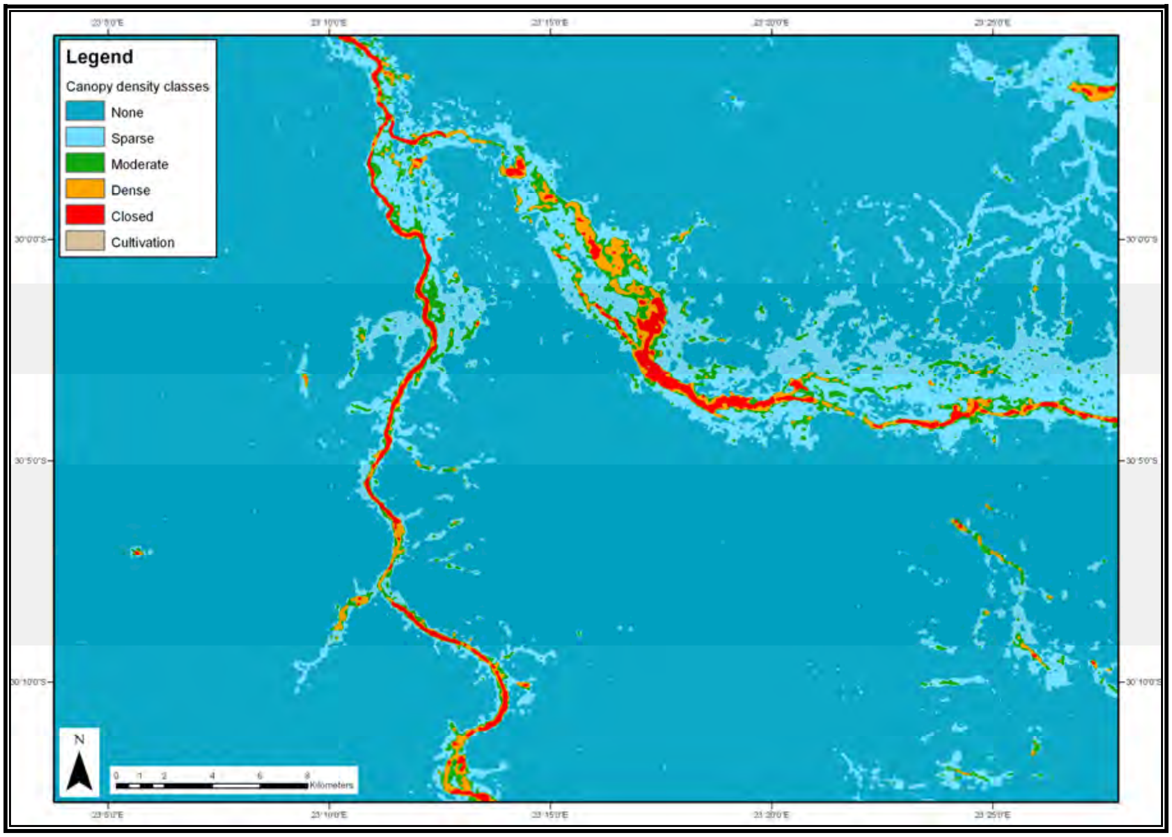


Figure 4.18: Classified IR/R images of *Prosopis* canopy density classes after the filters were applied.

4.5. Analysis of the extent of *Prosopis* using Landsat data

The flow chart in Figure 4.19 explains the use of the different historic (1) and current data (2) of the extent of *Prosopi*s invasion in the Northern Cape Province to perform different analysis on the classifications created from the different Landsat datasets.

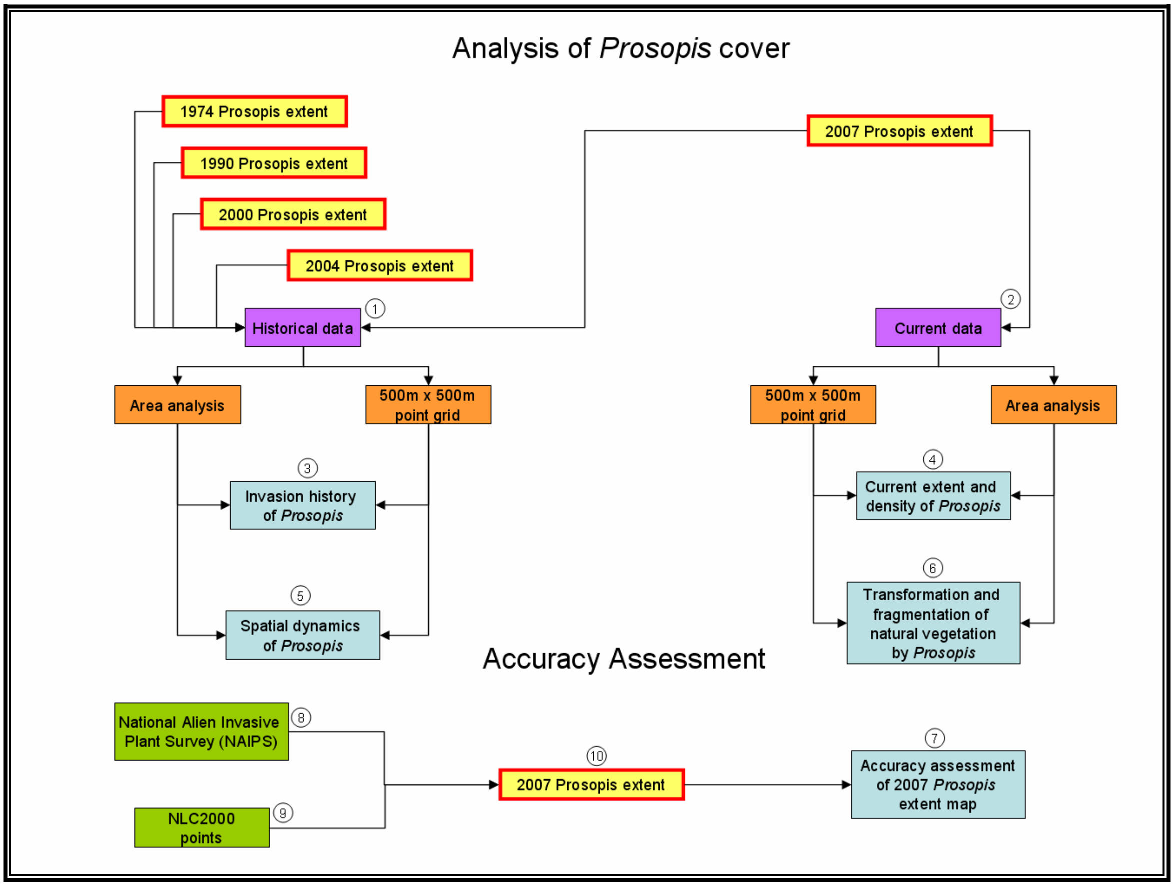


Figure 4.19: Flow chart explaining the use of the historic and current data of the extent of *Prosopis* to perform different analysis on the spatial data. The yellow squares indicate the datasets used for the analysis of the historic and current data (purple squares). Blue squares indicate the type of analysis done on the data. Green squares indicate raw datasets used for the study.

4.5.1. Invasion history of *Prosopis* as derived from satellite images

Two methods were used to describe the invasion history and change in *Prosopis* cover (3) since 1974. Firstly, an area comparison of cover and rate of change between 1974 and 2007 was done. The area of each polygon was calculated in ARCINFO and exported to an Access database where all calculations were carried out. The change was also analysed spatially by creating a 500m x 500m point grid over all five datasets (1974, 1990, 2002, 2004 and 2007). The point grid was intersected with the *Prosopis* density maps to extract density and presence/absence data values to visually display significant change throughout the time frame. A dataset representing the main rivers were created using class 3 to 10 flow paths, buffering them with between 50m for the smaller rivers and 200m for the main rivers to establish the extent of invasion in the riparian zones. The riparian dataset and point grid information was used to establish the dispersal pattern of *Prosopis* in the riparian as well as outside the riparian zone.

4.5.2. Current extent and density of *Prosopis*

The 2007 Landsat dataset was used to describe the current extent and canopy densities of *Prosopis* (4) in the Northern Cape Province. Total area per density class was calculated as well as the number of patches for each class. The extent of *Prosopis* invasion was also analysed to establish the extent of invasion of the quaternary water catchments and drainage lines in the province.

4.5.3. Spatial dynamics of *Prosopis*

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* (5) 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. In addition, histograms were prepared showing the size class distribution of patches since 1990.

4.5.4. Transformation and fragmentation of natural vegetation by *Prosopis*

The transformation and fragmentation (6) of natural vegetation by invasion poses one of the greatest threats to ecosystems services (Mack *et al*., 2000). The Northern Cape Province consists of five biomes and 20 vegetation types (Low and Rebelo, 1996). To establish the extent of fragmentation caused by *Prosopis* infestation the classified 2007 data were intersected with the vegetation type data of Low and Rebelo (1996).

4.6. Accuracy assessment of classifications

No classification is complete until the accuracy of the classification (7) has been assessed (Lillesand *et al*., 2004). The accuracy assessment data were collected from two independent datasets, the NLC2000 (Van den Berg *et al*., 2008) and National Alien Invasive Plant Survey (NAIPS) databases (8) (Kotze *et al*., 2009). The NLC2000 (9) project randomly collected 3263 field verification points for the Northern Cape Province (Appendix 2) between 2001 and 2003. At each sample site (200m x 200m) the land cover characteristics and any associated attributes were recorded. Part of the associated site attributes were the identification of alien vegetation species at genus level. The listing of these species however depended on what was visible and could be identified at a distance (100m) from the road site sample position. It was therefore anticipated that most of the identified invasive plants were the taller tree and shrub species like the *Prosopis* species as opposed to the smaller herbaceous plants. The NAIPS database points (Appendix 3) were produced using a stratification process, using NDVI and terrain unit classes, land cover and bioregion information. The survey was performed using a fixed wing aircraft, recording the overall density of invasive alien plant species, the three dominant invasive alien plant species and their densities as well as the size class and other relevant comments for a sampling plot of 100m x 100 m.

The accuracy assessment data for this study was compiled by merging the selected points from the above two datasets. The data from the NLC2000 dataset was primarily used to cover the areas not sampled by the NAIPS project, as this project gave preference to sampling the riparian zones. A sample of 20% of the NLC data was selected and 40% of the NAIPS dataset. The 1849 points (Figure 4.20) were used for accuracy assessment of the 2007 *Prosopis* classification (10) through establishing the presence and absence of *Prosopis* on the classified map. A buffer of 100m was placed around each sampling point, to compensate for the distance between the aircraft and the actual observation point and because the area sampled by the NAIPS project was not a homogeneous area as with the NLC2000 project. The presence of one or more of the density classes under the buffered point was noted as being an accurate classification. No field verification data were available for the period 1974 to 2004 and therefore no accuracy assessment was done on the classifications of the historic data.

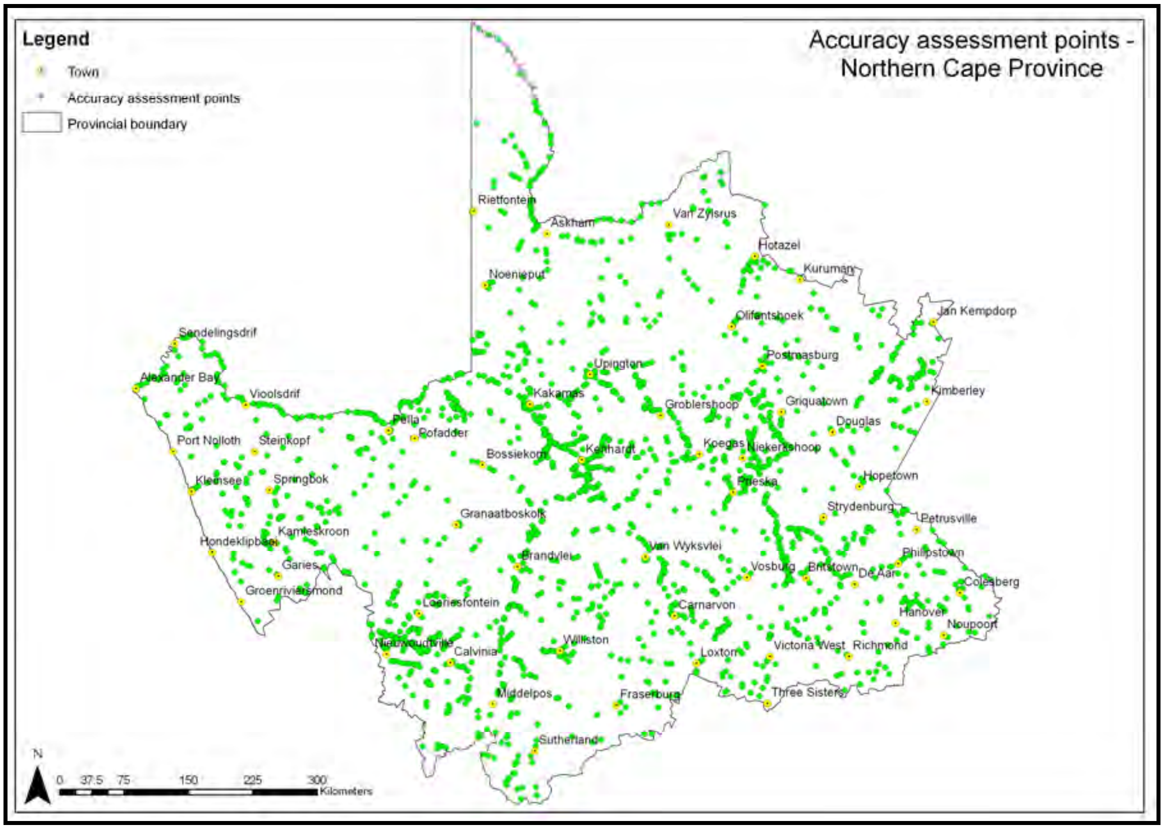


Figure 4.20: Distribution of the combined accuracy assessment points selected from the NLC2000 and NAIPS datasets.

CHAPTER 5: RESULTS AND DISCUSSION

5.1. Results

5.1.1. Areas susceptible to invasion

The relationship between terrain unit, flow path, and spectral vegetation response were used to create a map of possible *Prosopis* occurrence for the province. Both NOAA/AVHRR NDVI data (1997 – 2000) and MODIS EVI data (2000 - 2009) were processed using the same method. Two datasets with five probability classes were created using only the median pixel value of the NDVI and EVI, the NOAA/AVHRR data on 1km resolution (Appendix 9) and the MODIS data at 250m resolution (Appendix 10). The integration of the MODIS EVI spectral vegetation response and the ancillary data produced a good quality map (Appendix 11) of possible areas susceptible to *Prosopis* invasion. The integration of the NOAA/AVHRR data did, on the other hand, not produce a high-quality result. The NOAA/AVHRR NDVI did nevertheless provide, on a very broad scale, information regarding big homogeneous stands (2km x 2km) of dense to closed *Prosopis* stands prior to 2000.

Although the initial calculation of the possible area for *Prosopis* invasion are estimated at 12,131,656ha over all probability classes, the very low probability class (4,250,899ha) could be over-estimated due to the scale of the images and the influence of the spectral response of small patches of woody vegetation (Foxcroft *et al.*, 2007). The area of probability class 4 was adjusted using the percentage of correspondence between the 2007 density map and the probability map. An over estimation of 2,903,793ha in class four and five as a result of the Savanna vegetation in the north east of the study area also occurred. The figures for probability class 4 and 5 were therefore adjusted to more reliable figures (Table 5.1). It would therefore be safe to say that an area of approximately 4,976,964ha is susceptible to invasion by *Prosopis* (Appendix 11).

The reliability of the probability map was tested using the grid points of the 2007 Landsat density classification (Figure 5.1). Of the 58,760 points where *Prosopis* were present on the 2007 Landsat classification, a total of 44,308 or 75% of these points were also in one of the five probability classes (Table 5.2).

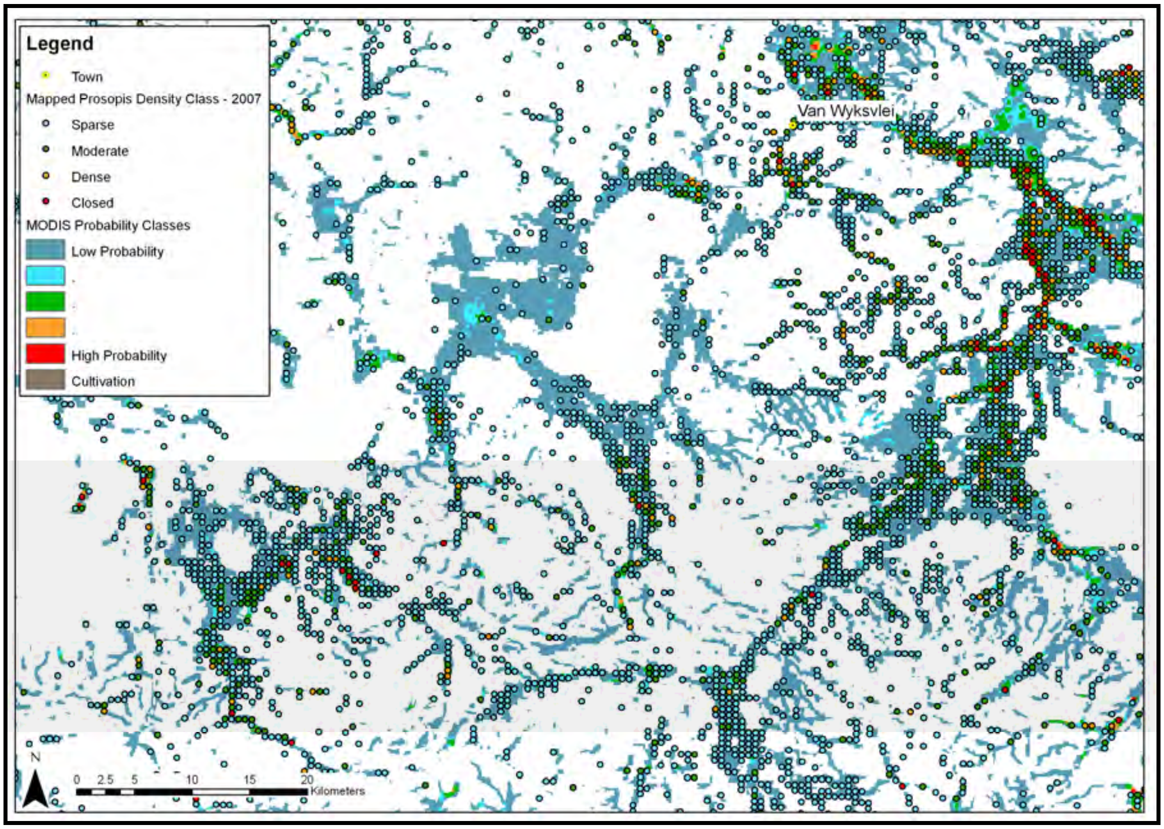


Figure 5.1: The distribution correspondence between the actually mapped density classes (points) of the Landsat 2007 data and the MODIS probability classes.

Table 5.1: Area estimations of MODIS probability map.

Probability class	Original figure (ha)	Adjusted figure (ha)
1 Very low probability	4,250,899	3,018,131
2	1,314,916	1,314,916
3	2,322,658	2,322,658
4	3,141,127	950,348
5 High probability	1,102,056	389,042
Total area	12,131,656	7,995,095

Table 5.2: Percentage correspondence between the Landsat classification using the 500m grid points and the MODIS probability map.

Density class	Points in Landsat density class	Points in probability map	Percentage correspondence (%)
1	40,456	28,625	71
2	11,850	9,065	76
3	3,894	3,100	80
4	2,560	1,793	70
Total	58,760	44,308	75

5.1.2. Invasion history of *Prosopis* from 1974 to 2007

Prosopis occupied 0.35% (127,820.96ha) of the province by 1974 (Table 5.3) and was already highly dispersed by this time (Figure 5.2; Appendix 12). Canopy cover was not uniform throughout the province, being much higher in the riparian area (4.13%) than the remaining lowlands and uplands (0.25%).

Table 5.3: 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 *Prosopis* 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

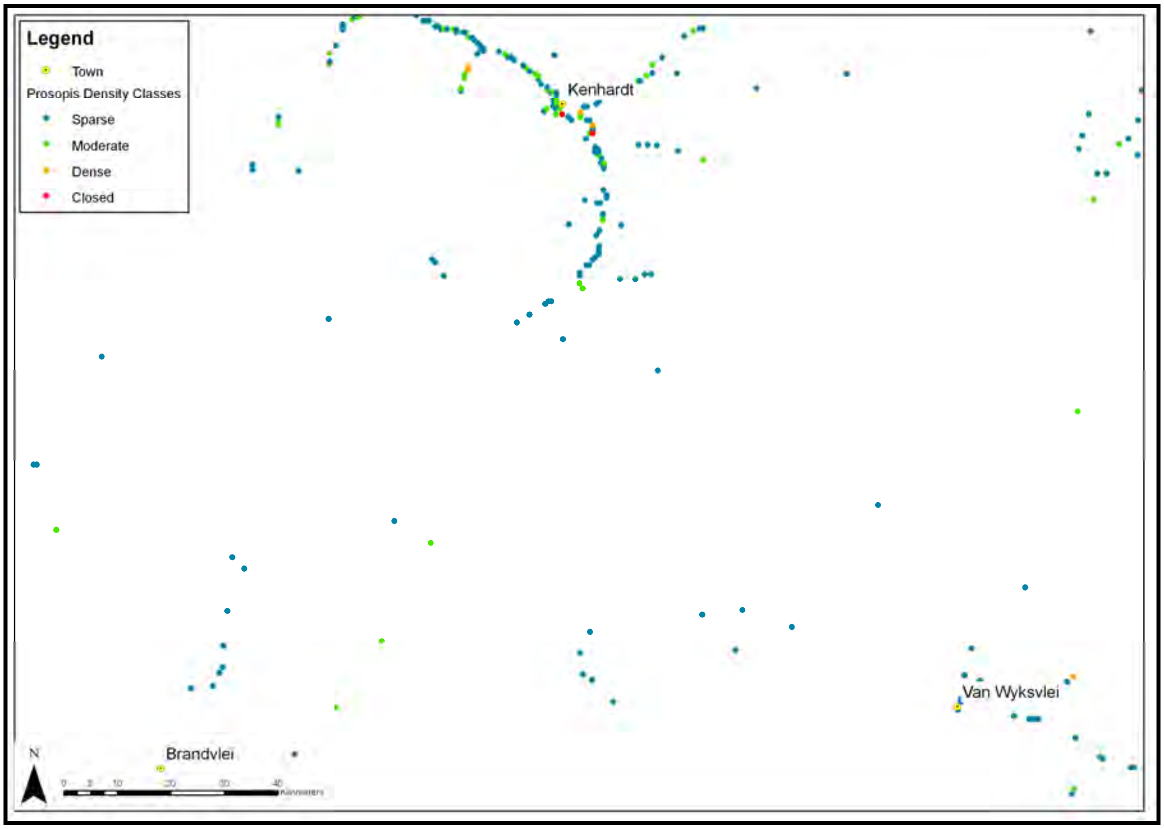


Figure 5.2: *Prosopis* cover during 1974 for an area between Kenhardt, Brandvlei and Van Wyksvlei is indicated by the amount and distribution of the points. The *Prosopis* density classes at the points are indicated by the different colours in the map legend.

Total *Prosopis* cover in 1990 (Appendix 13) was 0.87% (314,580ha) of the total land area of the Northern Cape Province and in 2007 4.06% (1,473,953ha), representing an increase of 146% over 16 years. The invasion by plants, is one of the main negative causes of the destruction of riparian habitats in Southern Africa (Richardson *et al*., 1997). 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 5.4). The increase in *Prosopis* distribution in 1990 (Figure 5.3) compared to 1974 in the riparian zone south of Van Wyksvlei are noticeable when Figure 5.2 and Figure 5.3 are compared.

Table 5.4: Percentage increase of *Prosopis* cover, in riparian zones and lowlands from one dataset to another

Year	1974 - 1990	1990 - 2002	2002-2004	2004-2007
Number of years	16	12	2	3
Change in total invaded area (%)	146	53	48	107
Change in riparian areas (%)	217	34	20	35
Change in lowlands (%)	116	64	63	135
Ratio of change (riparian:lowlands)	1:0.5	1:1.8	1:3.15	1:3.85

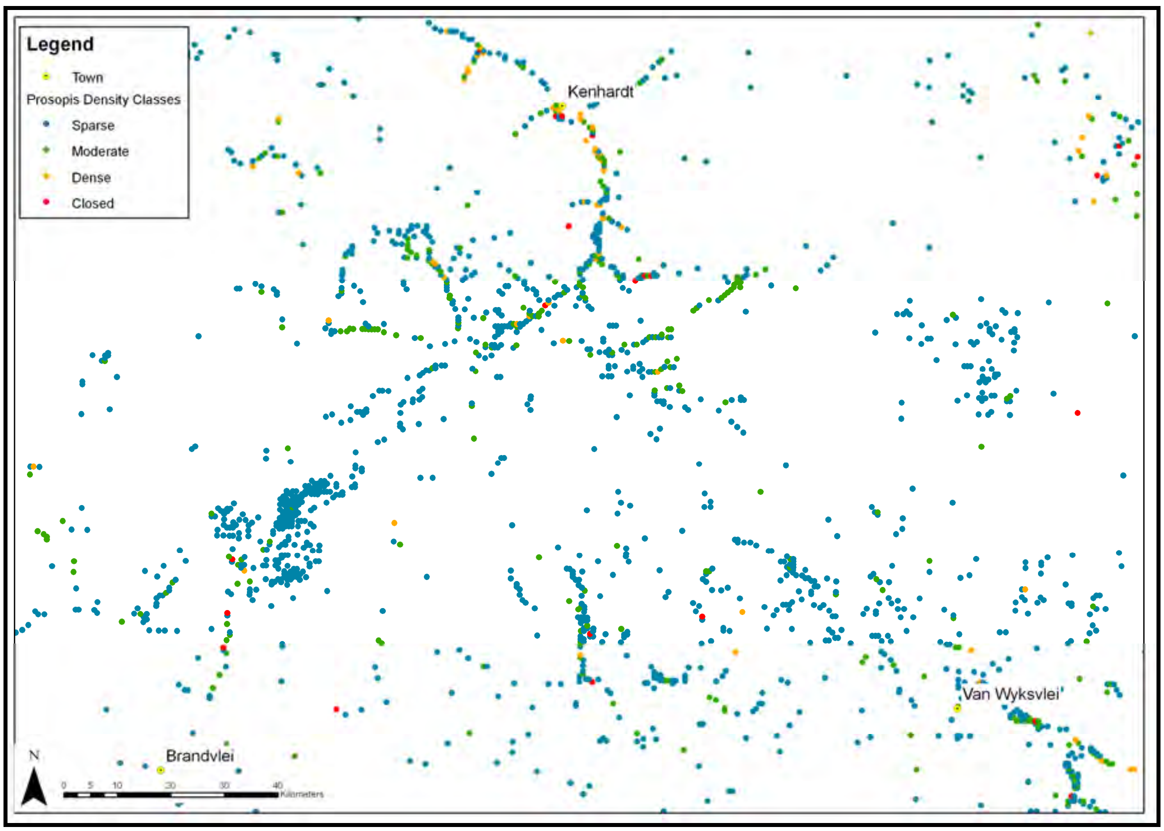


Figure 5.3: *Prosopis* cover during 1990 for an area between Kenhardt, Brandvlei and Van Wyksvlei is indicated by the amount and distribution of the points. The *Prosopis* density classes at the points are indicated by the different colours in the map legend.

During 2002 (Figure 5.4; Appendix 14) *Prosopis* occupied 1.32% (480,515ha) of the total land area of the province compared to the 4.06% (1,473,953ha) during 2007 (Figure 5.5; Appendix 16). This represents an increase in cover of 993,438ha over the last five years. The total riparian area invaded by *Prosopis* during 1990 was 121,894 ha compared to the 264,764 ha of 2007 (Table. 5.3; Appendix 17). The increase of riparian invasion between 1974 and 1990 was more rapid (217%) than the 116% in the lowlands (Table 5.4). The ratio of change in the riparian area compared to the lowlands has 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 presence/absence grid points in Figure 5.6 as well as by visually comparing Appendices 13 to 16. The rapid expansion of *Prosopis* infestation since 2002 is noticeable by the number of orange point visible in Figure 5.6.

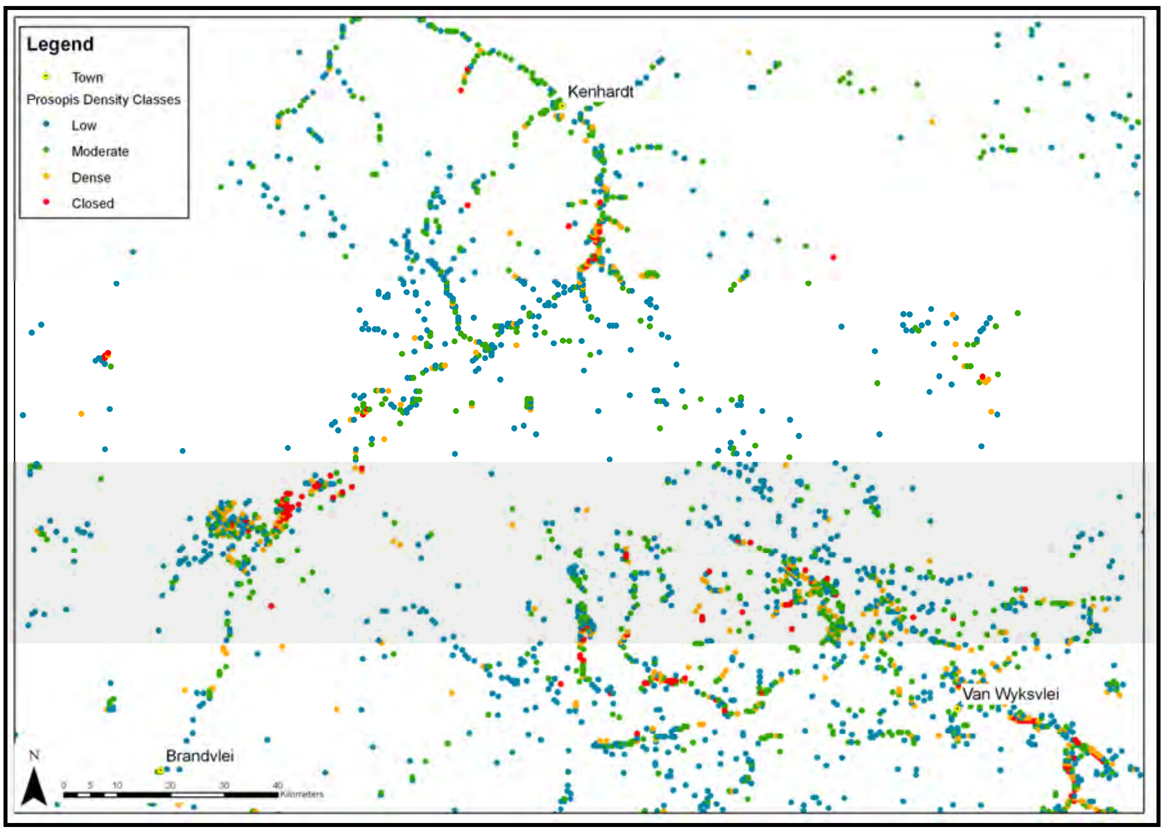


Figure 5.4: *Prosopis* cover during 2002 for an area between Kenhardt, Brandvlei and Van Wyksvlei is indicated by the amount and distribution of the points. The *Prosopis* density classes at the points are indicated by the different colours in the map legend.

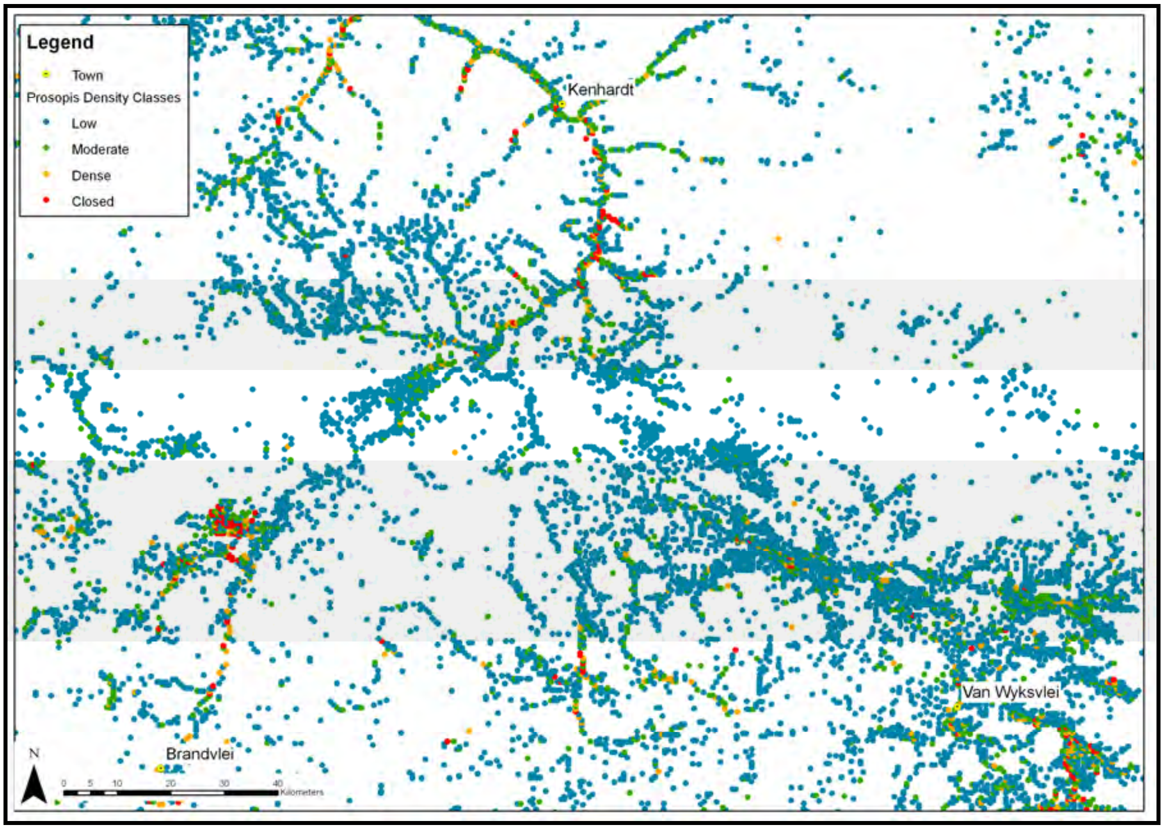


Figure 5.5: *Prosopis* cover during 2007 for an area between Kenhardt, Brandvlei and Van Wyksvlei is indicated by the amount and distribution of the points. The *Prosopis* density classes at the points are indicated by the different colours in the map legend.

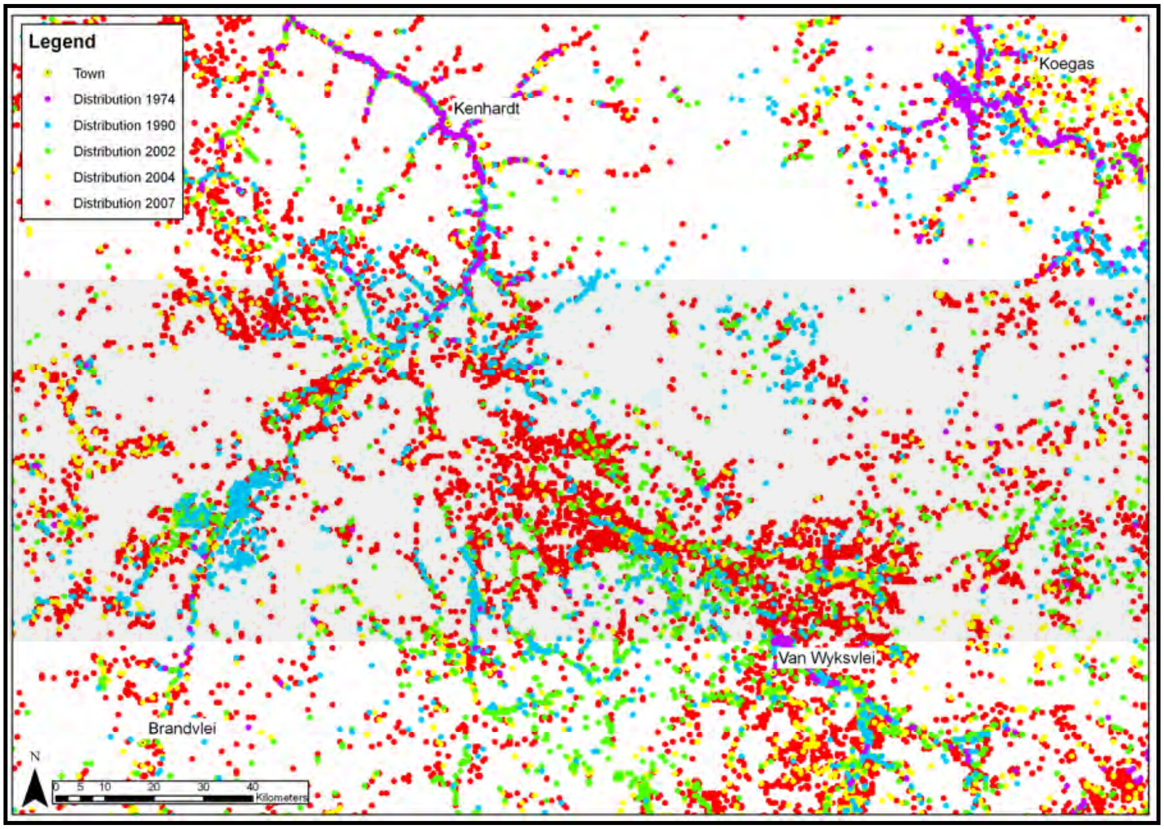


Figure 5.6: Expansion of *Prosopis* cover from 1990 to 2007 for an area between Kenhardt, Brandvlei and Van Wyksvlei, visually displayed by the 500m grid points indicating the presence of *Prosopis* using a different colour point for each year.

5.1.3. Extent and densities of *Prosopis* canopy cover for 2007

The extent of *Prosopis* cover in the Northern Cape Province (Appendix 17) reached 1.473 million hectare or 4% of the total land area during 2007 (Table 5.5). An area of 163,752ha is covered by dense and closed *Prosopis* stands consisting of a mixture of small and big multi-stemmed trees (Figure 5.7). The biggest area is covered by the moderate and sparse classes (1.310 million ha) consisting of many small or a few big trees with large canopies (Figure 5.8). Figure 5.9 shows the extent of the area covered by the different canopy density classes of *Prosopis* in the area between Van Wyksvlei and Carnarvon.

Table 5.5: Summary statistics of *Prosopis* cover during 2007

Total area invaded by *Prosopis* (ha)		1,473,953
Percentage *Prosopis* of 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
Number of patches per canopy density class	Sparse	372,597
	Moderate	164,138
	Dense	79,286
	Closed	24,232

Figure 5.7: A patch of closed *Prosopis* trees consisting of a mixture of small and big multi-stemmed trees.

Figure 5.8: A patch of sparse *Prosopis* trees consisting mostly of small multi-stemmed trees.

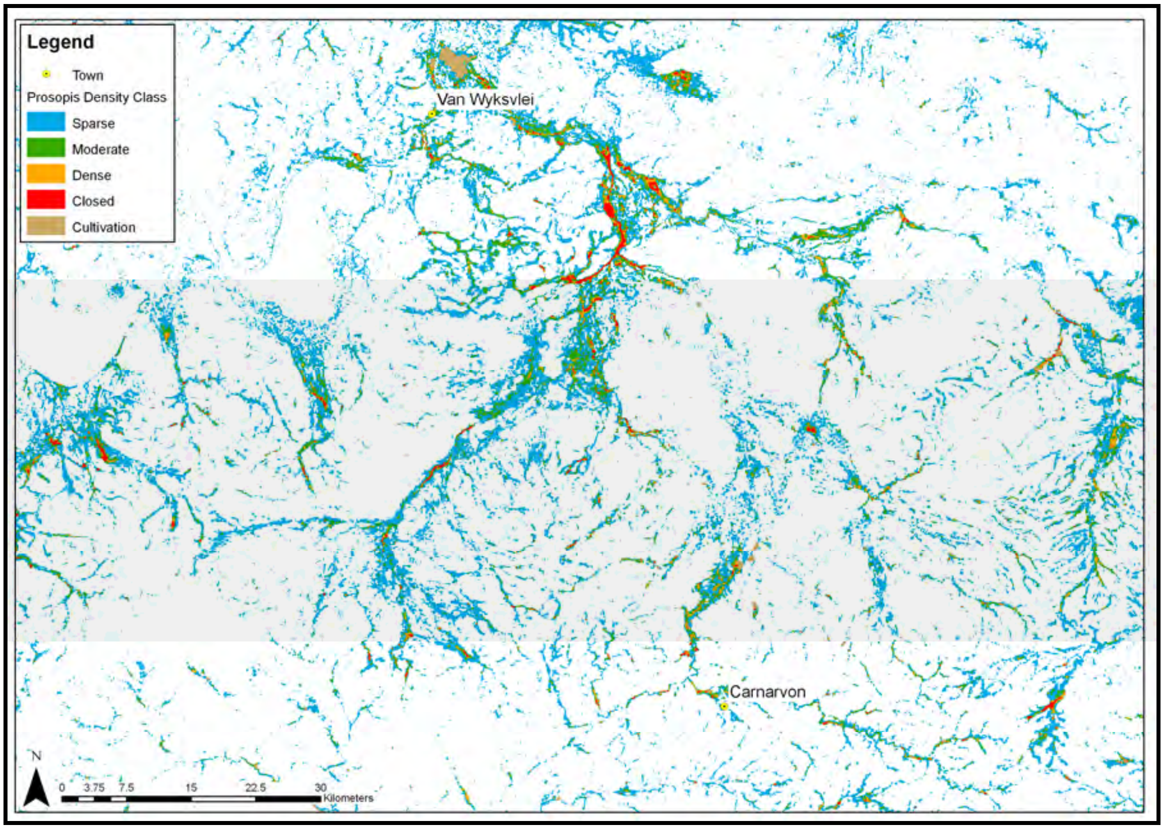


Figure 5.9: *Prosopis* cover during 2007 for an area between Van Wyksvlei and Carnarvon is indicated by the coloured areas on the map. The *Prosopis* density classes are indicated by the different colours in the map legend.

There are only 12 quaternary catchments in the Northern Cape that are not invaded by *Prosopis*. Most of the catchments in the interior of the province are invaded by more than 10% of the total catchment area (Appendix 18). Thirty-one catchments have no patches with canopy densities of 50% or more. The catchments which are the heaviest infested are also the areas with the largest areas of moderate and dense patches (Figure 5.10).

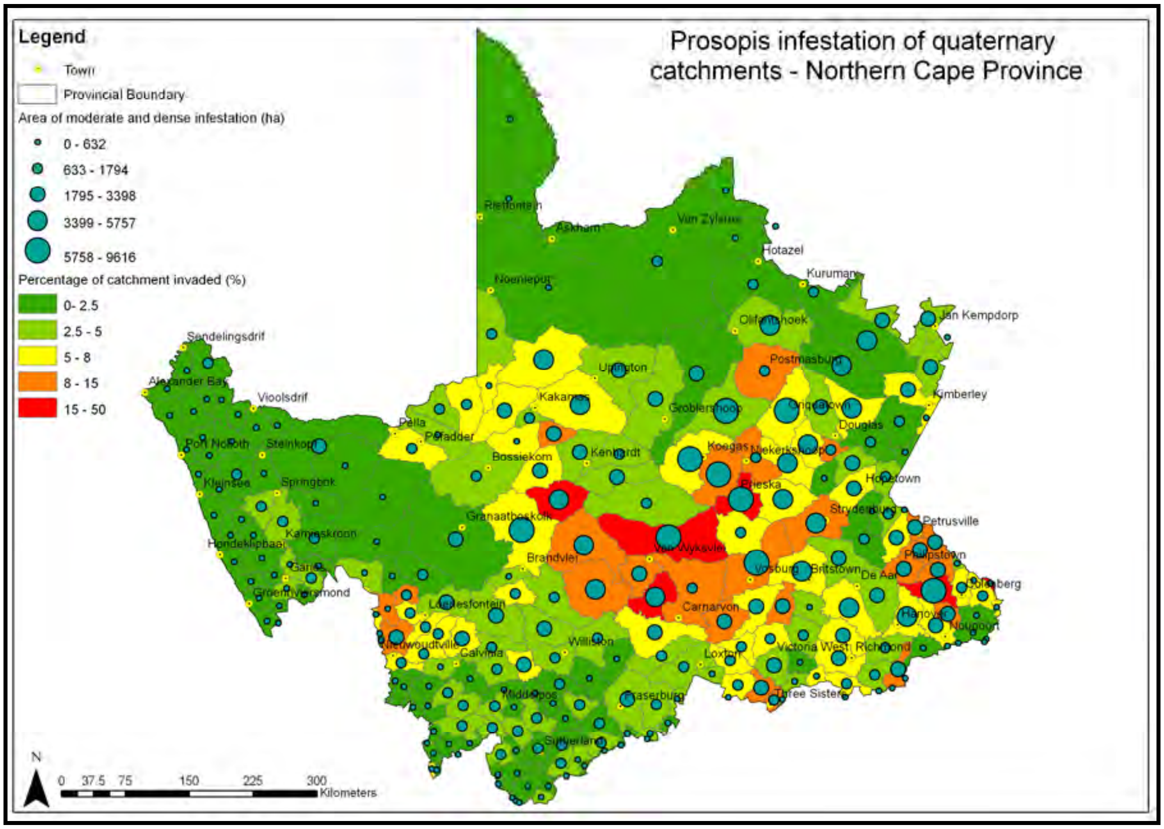


Figure 5.10: Comparison between percentage *Prosopis* invasion per catchment and area of moderately and dense infestation indicated by the size of the purple circles.

5.1.4. Spatial dynamics of *Prosopis* in the Northern Cape Province

The patch dynamics analysis was only performed on the Landsat data. It should be mentioned that the patch size for other sensors could be greater or smaller depending on the sensor characteristics. 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 5.6). *Prosopis* patches greater than 25ha were relatively uncommon in 1974 suggesting that coalescence was rare. The number of patches increased substantially between 1974 and 2007 in all density classes, demonstrating continued patch recruitment (Figure 5.11; Appendix 19). Median patch size increased from 0.15ha in 1990 to 3.0ha in 2007. The density of 808 grid 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 (Figure 5.12). The large number of patches greater than 25ha would have been partly the result of smaller patches coalescing to form dense thickets (Figure 5.13).

Table 5.6: 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
Largest patch (ha)	Sparse	982.67	2,278.06	505.74	3,338.18	11,753.10
	Moderate	302.28	843.11	218.20	286.34	774.82
	Dense	192.15	915.24	289.95	419.11	353.77
	Closed	110.14	169.56	344.67	530.12	528.89
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
Median patch size (ha)	Sparse	0.31	0.15	0.15	0.15	3.09

	Moderate	0.31	0.15	0.15	0.15	2.31
	Dense	0.23	0.15	0.16	0.15	1.54
	Closed	0.31	0.15	0.23	0.23	3.08
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

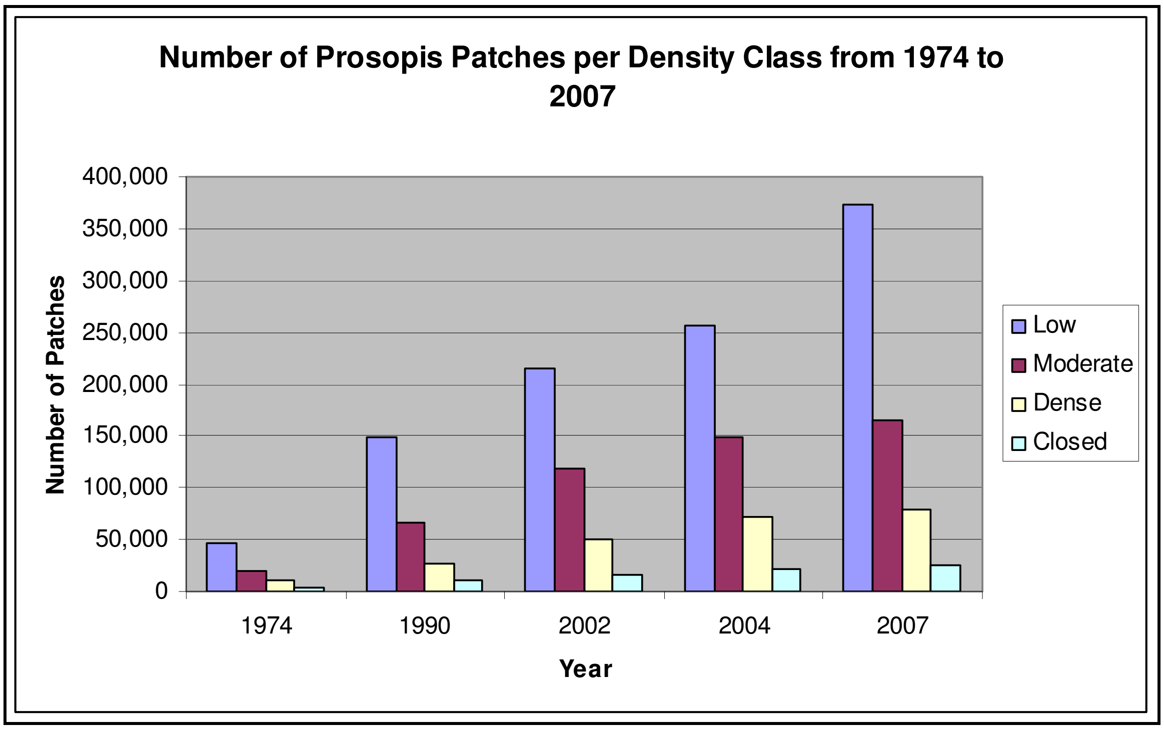


Figure 5.11: The increase in number of *Prosopis* patches per canopy density class from 1974 to 2007.

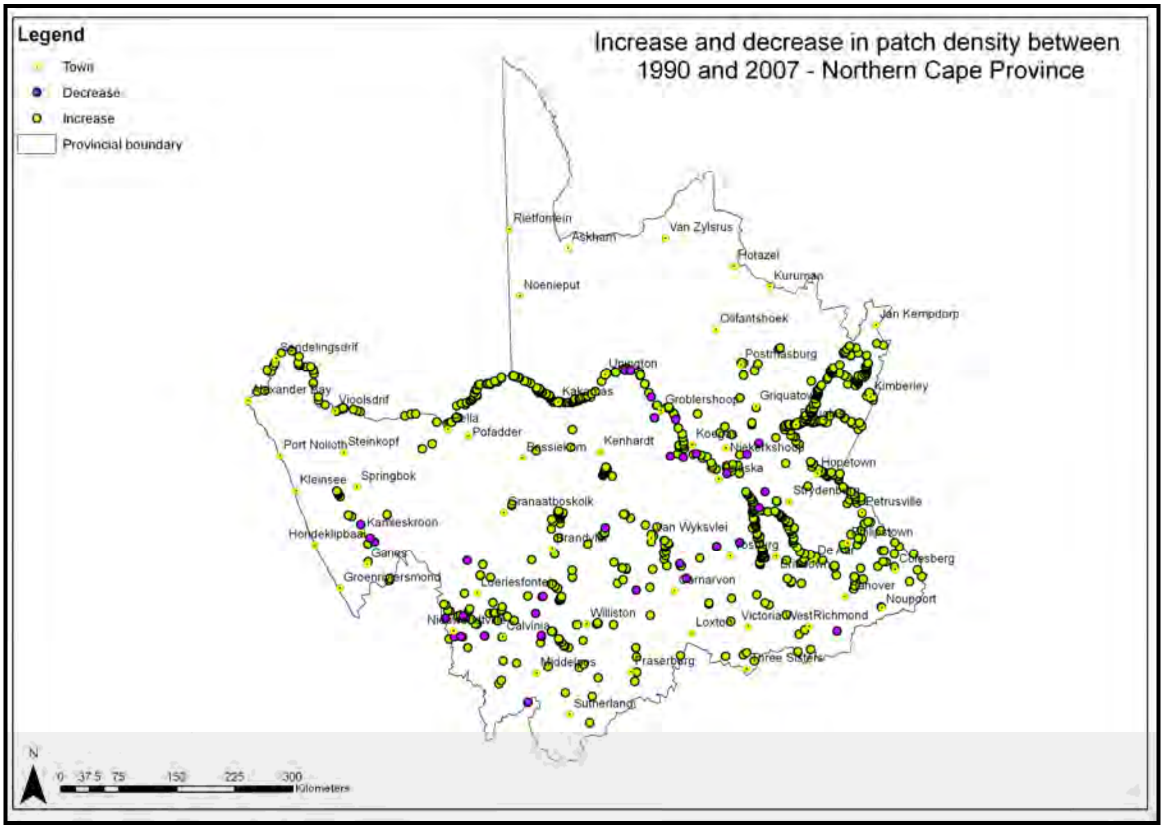


Figure 5.12: Increase and decrease in canopy density between 1990 and 2007. Green points indicate the points where the canopy density class has increased and purple where the canopy density has decreased.

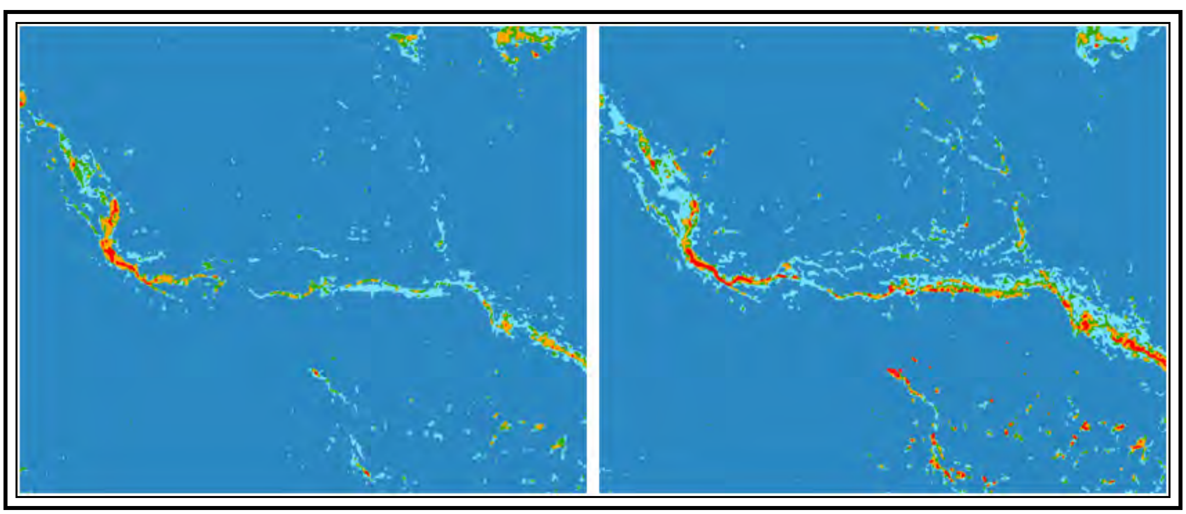


Figure 5.13: Coalescences of small patches with low canopy cover to large patches with higher density canopy cover.

5.1.5. Fragmentation of natural vegetation in the Northern Cape Province by *Prosopis*

Biodiversity is made up of three facets, namely functional, compositional and structural diversity of the biota in a certain area (Noss, 1990). Compositional diversity is most frequently accepted as a measure of biodiversity. However, functional (water provision, water filtering and cleaning, water retention, flood prevention) and structural diversity (physiognomy of herbaceous and woody layers) are an integral part of the systems dynamics, and are frequently altered by biological invasions (Foxcroft, 2002). One of the impacts of invasive alien plants is the replacement of diverse systems with single species stands of aliens (Cronk and Fuller, 1995). Invasion has already transformed 64,923ha of indigenous vegetation into mono typical stands of *Prosopis*. Four percent or more of nine vegetation types have already been invaded (Table 5.7; Appendix 20). The Bushmanland Nama Karoo is covered by 413,275ha of *Prosopis* (almost 5% of this Vegetation Type).

Table 5.7: Summary of *Prosopis* invasion as percentage (%) and area (ha) in the five biomes of the Northern Cape Province for the vegetation types according to the different canopy density classes in 2007(Low and Rebelo, 1996)

Biome	Vegetation Type	Sparse (ha)	Moderate (ha)	Dense (ha)	Closed (ha)	Invaded (%)	Invaded (ha)
Fynbos	Escarpment Mountain Renosterveld	5,550	2,100	625	175	2.05	8,450
	Mountain Fynbos	3,175	775	225	200	4.75	4,375
	North-Western Mountain Renosterveld	3,850	1,075	425	300	3.45	5,650
Grassland	South-Eastern Mountain Grassland	1,575	650	50	25	1.79	2,300
Nama Karoo	Bushmanland Nama Karoo	332,725	58,050	15,625	6,875	4.97	413,275
	Central Nama Karoo	650	275	125	50	9.09	1,100
	Eastern Mixed Nama Karoo	80,925	42,200	14,100	6,950	6.25	144,175
	Great Nama Karoo	550	100	125	75	6.85	850

	Orange River Nama Karoo	229,950	71,000	21,225	27,175	6.51	349,350
	Upper Nama Karoo	166,450	39,425	13,100	7,000	6.30	225,975
Savanna	Kalahari Mountain Bushveld	34,600	25,800	5,525	1,600	5.23	67,525
	Kalahari Plains Thorn Bushveld	13,650	4,175	750	50	1.49	18,625
	Kalahari Plateau Bushveld	9,800	6,825	1,650	275	1.49	18,550
	Karroid Kalahari Bushveld	14,725	5,675	850	250	1.15	21,500
	Kimberley Thorn Bushveld	21,350	12,175	11,100	6,500	4.81	51,125
	Shrubby Kalahari Dune Bushveld	575	100	0	0	0.02	675
	Thorny Kalahari Dune Bushveld	0	0	0	0	0.00	0
Succulent Karoo	Lowland Succulent Karoo	21,350	6,075	2,750	1,250	2.10	31,425
	Strandveld Succulent Karoo	1,125	450	250	0	0.86	1,825
	Upland Succulent Karoo	67,975	18,875	7,900	4,275	2.86	99,025

All five biomes in the Northern Cape Province are already invaded by *Prosopis* to some degree as indicated in Figure 5.14 and Appendix 20. Invasion mainly occurs in the Nama Karoo Biome with 1.1 million hectare (77%) of the total invaded area found in this biome (Table 5.8). The Savanna Biome can be divided into two regions, the mountainous bushveld to the east around Postmasburg and Griekwastad and the dune bushveld north of Upington. The majority of the *Prosopis* invasion (178,000ha) in the Savanna Biome occurs in the mountainous bushveld. As expected the highest patch density occur in the Nama Karoo. Even though the invaded are of the Savanna Biome are larger than that of the Fynbos and Succulent Karoo Biomes the density of the patches are lower suggesting that patch sizes in the Savanna Biome are much bigger.

Table 5.8: Transformation of biomes in the Northern Cape Province

Biome	Percentage Invaded (%)	Area Invaded (ha)	Number of Patches	Patch density relative to area	Percentage of Invasion (%)
Fynbos	3.44	18,475	3,204	0.005/ha	1.26
Grassland	1.79	2,300	461	0.003/ha	0.16
Nama Karoo	6.29	1,134,725	140,400	0.007/ha	77.41
Savanna	1.66	178,000	22,486	0.002/ha	12.14
Succulent Karoo	2.86	132,275	19,017	0.004/ha	9.02

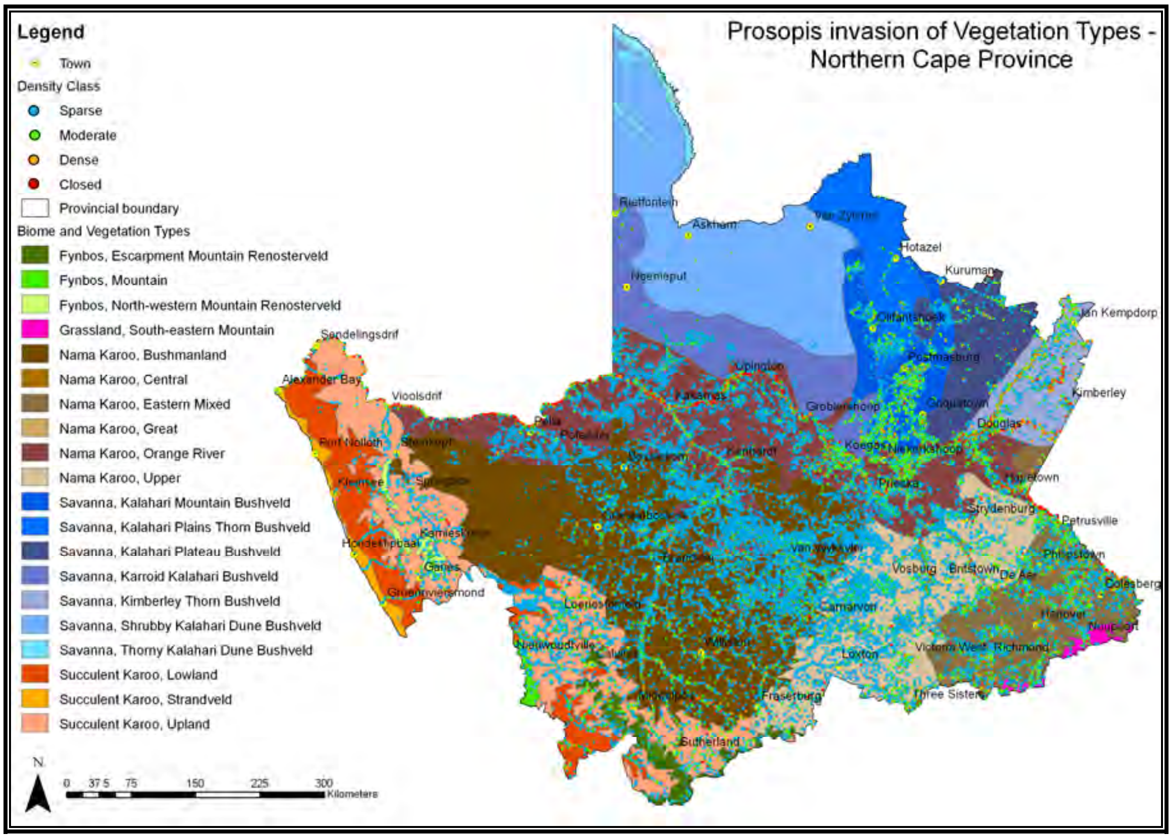


Figure 5.14: *Prosopis* invasion of biomes in the Northern Cape indicated by canopy cover points using different colours for each density class.

5.1.6. Assessment of classification accuracies

An 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. The error matrix lists the known points of *Prosopis* in the accuracy database against the pixels actually classified as *Prosopis*. The result is presented in Table 5.9.

Table 5.9: 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%			

Errors of omission and commission describe the errors in the classification (Table 5.10). The omission error (33%) describes the number of points that should have been classified as *Prosopis* but were omitted from the class. Errors of commission (22%), on the other hand describe 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* in 2007 using Landsat TM data.

Table 5.10: Errors of omission and commission describe the errors of the Landsat 2007 classification, based upon the results of the error matrix

Class	**Absent (1)**	**Present (2)**
Absent (1)	78%	22%
Present (2)	33%	67%

Quantification of the omission and commission errors in terms of density classes has been done using the density classification in the NAIPS database (Table 5.11). Analysis revealed the sparse class to be the main area of classification error, with 72% of all omission errors occurring in this class. Data on the commission error and density classes were however not sufficient for reliable analysis.

Table 5.11: Quantifying the omission and commission error of the Landsat 2007 classification

	Sparse	Moderate	Dense	Closed	No density available	Total
Omission Error	195	37	17	0	19	268
Commission Error	29	5	6	1	162	197

5.2. Discussion

5.2.1. Areas susceptible to *Prosopis* invasion

The attempt to map the actual and predicting the potential areas of distribution of *Prosopis* invasion turned out to be a great challenge with mixed results related to the size and diversity of the study area to the resolution of remotely sensed images. The fact that the NOAA/AVHRR probability map did not produce an accurate map can be linked to the resolution of the imagery and the pattern of occurrence of *Prosopis*. Although *Prosopis* often occurs over several kilometers along drainage lines, the width of the stands is generally less than the spatial resolution of the satellite (1km x 1km). The signal is therefore not saturated by *Prosopis* alone, but also affected by other features on the ground such as soil. Although the importance of resolution, spectral characteristics and temporal scale are highlighted, it is clear that for more accurate mapping of invasive species, the phenological stages of the plant has to be considered when selecting remotely sensed data. Rainfall variability over the province, as well as over the season, induces change in the growth and composition of vegetation and can lead to changes in the spectral signature of the land surface. Using the long term median NDVI and EVI values, instead of only a single image, prove to be successful in eliminating the seasonal effect as well as errors and the occasional spike in the data. The correlation (75%) between the MODIS probability map and the actual spatial extent mapped by the 2007 Landsat classification suggests that there are some relationship between spectral vegetation response and habitat characteristics such as soil types and the position in the landscape. Although some association exists between environmental factors, no clear pattern has however emerged. The main reason for the creation of a probability map is to focus the attention of managers and their efforts of eradication and control programs on those areas at risk of being invaded. The use of such a predictive map, that can be updated on an annual basis, provide a valuable tool in focusing resources towards the effective management of a labour and money intensive project, which in the case of the Northern Cape Province reduce the area to a possible 4,250,899 ha instead of more than 36 million hectare.

5.2.2. Invasion history of *Prosopis* from 1974 to 2007

The use of remote sensing imagery allowed us the rare opportunity to examine current and historic distribution of *Prosopis* in the Northern Cape Province. There is a distinct difference in canopy cover density, number and size of patches, and spatial distribution across the five datasets since 1974. The images showed a steady increase in *Prosopis* canopy cover, number of patches and density. The canopy density of only 37 grid points have decreased since 1990 while 808 of the points that were present in 1990 showed an increase in density over the 33 years.

5.2.3. Extent and densities of *Prosopis* canopy cover for 2007

Prosopis had spread throughout the Northern Cape Province, occupying an area of more than 1.4 million hectare in 2007. Several studies on the influence of invasions on water use and biodiversity has until now estimated the cover of *Prosopis* using interpolated data or combining data of different scales and studies (Holmes *et al*., 2005; Le Maitre *et al*., 2000). For the first time a quantitative estimation of the extent of *Prosopis* invasion for the whole Northern Cape Province on a minimum scale of 1:50 000 was provided. *Prosopis* showed a strong preference for riparian habitats in the Northern Cape Province as reflected by the higher percentage invasion of these areas. Most quaternary catchments in the arid central part of the Northern Cape Province are severely degraded by *Prosopis* invasions. These invasions reduce water yields in the catchments and affect riverine functioning and biodiversity, thereby destroying riparian ecosystems and increasing water use (Blignaut *et al*., 2007; Holmes *et al*., 2005). Many of the invasions has not yet reached dense and closed canopy cover densities, and therefore managers should focus and deploy resources in these areas while it is still more manageable and cost effective to remove.

5.2.4. Spatial dynamics of *Prosopis*

According to the classifications tree canopy density increased earlier than spatial extent, this might be due inability of the spatial resolution of the satellite sensor to detect small scattered trees. In this study, results have shown that the rates of increase became more rapid between 2004 and 2007. This may also be ascribed to the fact that higher resolution SPOT 5 images were used for the scaling of the vegetation indices. SPOT 5 data were unfortunately not available for the earlier years, but once again illustrate the value of higher resolution imagery. Harsher environmental conditions and less available moisture for the establishment of young plants, as well as the absence of grazers and browsers due to the poor availability of fodder might also be an explanation of the relatively slow increase in patches and patch sizes on the bottomlands. Number of patches, size and density did however increase dramatically since 2004. This change may be as a result of the inaccessibility of the riparian zones through the dense stands of *Prosopis*. During the field observations, it was observed, that some dense patches of *Prosopis* were fenced off by farmers in an effort to prevent seeds being dispersed by animals feeding on the seeds.

5.2.5. Quantifying the spread of *Prosopis* spp. in the major natural vegetation types

All biomes in the Northern Cape Province are invadable when faced with an aggressive introduced species such as *Prosopis* but the Nama Karoo seems to be more sensitive for invasion than others. The main drivers behind the establishment and spread of *Prosopis* in the Nama Karoo might be both natural and socio-economical. Natural drivers include favorable environmental conditions such as climatic and soil type as well as the presence of many seasonal drainage lines and pans. Socio-economic drivers emerge directly from human activities such as the disturbance caused by agriculture along the Orange River, mining along the west coast, domestic animals feeding and spreading the seeds, higher population density and historic invasive alien plant management.

The ecological impacts of invasion on ecosystems vary significantly depending upon the invading species, the extent of the invasion, and the vulnerability of the ecosystem being invaded (Ciruna *et al.*, 2004). Degradation of natural vegetation due to invasive alien species cause major alterations to physical habitat, influencing animal populations and migration patterns of birds, water quality and quantity and essential agricultural rangeland. These impacts can vary in terms of the lapse of time between the initial introductions when only a few patches of trees occurred to the subsequent spread and invasion where more than 4% of the vegetation in the Northern Cape Province are transformed. Conservation efforts should therefore be directed and prioritized to protect the more vulnerable biomes using the available spatial information on the extent of the degradation of the biomes in the Northern Cape Province.

5.2.6. Assessment of classification accuracies

While none of the image classification or probability maps can be considered as 100% accurate representations of *Prosopis* canopy density and spatial distribution, it provides a reliable tool to map and monitor large areas not possible with traditional methods. Uncertainty in the maps include: (i) the possibility of non-*Prosopis* tree patches occurring within patches mapped as continuous areas mapped only as *Prosopis*, and (ii) small, isolated *Prosopis* plants and patches not mapped because of the spatial resolution of the satellite image being to coarse, in this instance 30 meters. The patch size therefore needs to be at least 90m x 90m or 3 x 3 pixels to be classified.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1. Summary

Invasive *Prosopis* trees pose significant threads to biodiversity and ecosystem services in the Northern Cape Province of South Africa. Several estimates have been made in the past of the spatial extent of alien plant invasion in South Africa. A rapid reconnaissance in 1996/97 suggested that about 10 million hectares of SA has been invaded. However, the rate and spatial extent of *Prosopis* has previously never been accurately quantified in the Northern Cape Province. The objective of the study was therefore to use remote sensing and GIS techniques to i) determine the invasion history of *Prosopis* species in the Northern Cape Province in South Africa over the past 30 years ii) describe the current extent and densities of *Prosopis* spp. in the Northern Cape Province iii) reveal the spatial dynamics of *Prosopis* spp. spread and the areas susceptible to future invasion, and iv) quantify the spread of *Prosopis* spp. in the major natural vegetation types in the Northern Cape Province using remotely sensed data.

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. 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, soil, and terrain units. Multi-temporal Landsat images and a 500m x 500m point grid enabled the statistical analysis of vector and raster data to quantify the change in distribution and density, as well as the spatial dynamics of *Prosopi*s since 1974. Transformation, fragmentation and change of natural vegetation was quantified using the extent of all canopy cover density classes, calculating patch density per unit (ha) for each biome in the Northern Cape Province.

6.2. Conclusions

The historical datasets were a valuable resource of information by providing important data on the invasion history of *Prosopis* in the Northern Cape Province.

Over the past 30 years the extent of *Prosopis* has increased from 127,821ha to 1,473,953ha in the Northern Cape Province, which is 4.06% of the total study area (363 203km^2). Invasion of riparian areas have increased from 38,460ha (4.13%) in 1974 to

264,764ha (28.45%) in 2007. The invasion of *Prosopis* outside the riparian zone increased from 89,360ha (0.25%) in 1974 to 1,209,188ha (3.33%) in 2007. The number of *Prosopis* patches for all density classes, mapped from the Landsat images, increased from 79,578 in 1974 to more than 640,000 in 2007. The extent of the closed and dense canopy cover classes of *Prosopis* during 2007 were 463,752ha of the total study area, while the moderate and sparse density classes covered 293,169ha and 1,017,030ha respectively, occupying most of the low lying areas around the riparian zones. As mentioned, the highest increase in density and cover occurred in the riparian zone, putting enormous pressure on the water resources of the Province.

When the 1990 and 2007 datasets were analysed using the 500m x 500m standard grid points, it could be observed that the canopy cover densities of 808 grid points have increased since 1990 from sparse to close density classes in 2007. Only 37 of the grid points showed a decrease in plant density, suggesting an increase in woody species. Through personal observation and field work over a number of years it was noted that *Prosopis* mainly occur in the Northern Cape Province (Nama Karoo Biome and Succulent Karoo Biome) contributing to the main increase in the dense and closed classes. Bush encroachment of indigenous species such as *Acacia mellifera* occur mainly in the Savanna Biome. The comparison between the phenological behaviour of the different vegetation types and the selection of the appropriate image dates accordingly, helped to distinguish *Prosopis* more accurate from other occurring woody species. The assumption is therefore made that most of the increase in canopy density is probably because of the increase in *Prosopis* spp. It also indicates that *Prosopis* is a relatively long-lived plant, or that dead trees are being replaced by re-growth or new seedlings after control measures have been applied.

The GIS analysis of the polygon sizes of *Prosopis* patches indicated that only 500 patches were bigger than 25ha in 1974 compared to the 7,780 in 2007. The large number of patches greater than 25ha could have been partly the result of smaller patches coalescing to form dense thickets. The average patch size in 1990 was 1.07ha compared to 21.10ha in 2007.

The combination of the MODIS EVI classification, soil and terrain unit data, as well as the flow path information, resulted in a good quality probability map, highlighting the possible relationship between habitat and *Prosopis* invasion. The area susceptible to invasion by *Prosopis* is estimated to be 4,976,964ha, which include the 4 classes

(classes 2 to 5) of the probability map where *Prosopis* is most likely to occur. The reliability of the *Prosopis* probability map was established using the 500m x 500m grid points of the 2007 Landsat density classification. A total of 75% of the grid points where *Prosopis* was mapped on 2007 imagery corresponded with one of the five probability classes.

From all the data and results obtained by this study, it is evident that *Prosopis* is an aggressive invader, spreading rapidly over different land types once it gets established in a region. This species however prefers the riparian zones and alluvial lowlands rather than more steep rocky areas, putting pressure on the water table in the moist, lower lying areas of the arid- and semi-arid regions of South Africa and replacing and fragmenting natural vegetation at a rapid rate. Invasion has already transformed 64,923ha (area of closed canopy cover) of indigenous vegetation into mono typical stands of *Prosopis.* Invasion mainly occurs in the Nama Karoo Biome with 1.1 million hectare (77%) of the total invaded area found in this biome followed by 12.14% or 178,000ha in the Savanna Biome

Based on the results of the study, the following conclusions can be made about the remotely sensed data and methods used:

The spatial resolution (1km x 1km) of NOAA/AVHRR imagery is too coarse for mapping small and medium sized mixed stands of *Prosopis* accurately and was therefore not used in further studies of developing the probability maps in this study.

The temporal resolution of MODIS EVI data are a suitable tool to identify phenological growth patterns for *Prosopis* and therefore has the potential to be used as a monitoring tool. The spatial resolution (250m x 250m) of MODIS is suitable to detect *Prosopis* stands of moderate size and can therefore be used to report and continuously monitor the distribution of *Prosopis* on a national and international scale.

Landsat MSS, TM and ETM images with higher spatial resolution provided a more accurate classification for detecting and quantifying *Prosopis* in the Northern Cape Province, but the processing of the data are far more time consuming and expensive than the moderate resolution MODIS images.

The use of data with the same spatial resolution is crucial when attempting any change analysis. The use of the historical Landsat archive therefore provided a good platform to determine the invasion history of *Prosopis* over the past 30 years.

Maps produced on moderate resolution Landsat images can be up-scaled to use for reporting on national and global scale.

Image date selection is crucial to maximize feature identification and hence classification accuracy e.g. phenological differences between different plant species during a certain season (Acacia vs. *Prosopis*).

The use of the IR/R vegetation index discriminated well between possible *Prosopis* vegetation patches and other woody vegetation

Although the methodologies, including the results and conclusions of this study are mainly applicable to the invasion of *Prosopis* in the Northern Cape Province, they can easily be used to evaluate the invasion of alien species in other arid and semi arid areas e.g. invaded areas in Namibia.

This study indicates that a cost effective national *Prosopis* monitoring system is now technologically possible.

6.3. Limitations of the data

Woodcock and 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 and future studies, using different resolution satellite images, the extent in *Prosopis* cover in the Northern Cape Province could possibly differ. This is the result of the fact that so called "*Prosopis* areas" are generally not the dominant cover within a large (250 x 250m) cell due to their linear shape (e.g. along drainage lines) but are more dominant in a high (25m x25m) to very high (5mx5m) resolution cell. Various scales of data will therefore render different results and should not be abused and used beyond their minimum mapping scale.

6.4. Recommendations

Analysis of MODIS EVI data on an annual or bi-annual level might prove to be a valuable monitoring tool giving the good correlation between the actual mapped areas of *Prosopis* and the predicted areas as observed by satellite imagery. The same data can be used to report on the state of the environment on a regional and national scale.

The scaling of the MODIS EVI and Landsat data could be one of the most problematic aspects of such a study. Creating a fixed index to scale the classification values, by using the relationship between long term annual rainfall and vegetation indices, will improve the results of future change analysis between images of different years, making the data more reliable. The repeatability of future studies will be easier if such an index can be used which eliminates the interpreter's errors, which can then be further used to create an effective long-term monitoring tool.

Further research with regard to the ecology and biology of *Prosopis* spp. will facilitate a better understanding of the invasion, spread, range, and distribution of *Prosopis*. Increased data collection, soil analysis and better spatial resolution of soil data, is more than likely to benefit future research regarding rates of spread of *Prosopis,* as well as predicting habitat suitability for the early detection, and eradication programs such as the WfW program.

A long standing problem of managers and ecologist is the differentiation between alien and indigenous vegetation in mixed stands. With multi-spectral data becoming less expensive, the use of these images should be promoted, although some testing still has to be carried out. Appropriate sites for such a detailed study, using multi-spectral data, can be selected using the results of this study, if such projects are carried out in future.

Research opportunities exist with the availability of an annual SPOT 5 imagery dataset for South Africa (since 2008), to continue the change analysis detection and monitoring of the spatial dynamics and clearing programs of *Prosopis* invasion.

Digital spatial data analysis is a powerful tool for any manager or decision maker and should be used effectively to manage and protect the natural resources. It is however advised that the most recent data be used in such studies. The regular updating or maintenance of datasets is therefore essential.

It is recommended to extent studies like these to other regions of the country, not only to test the methodology in more temperate climate regions, but also to establish the extent of *Prosopis* invasion on a national level using similar techniques and data.

REFERENCES

Admasu, D. 2008. Invasive plant and food security: the case of *Prosopis juliflora* in the Aftar region of Ethiopia. FARM-Africa for IUCN. http://cmsdata.iucn.org/downloads/invasive_plants_and_food_security_final.pdf. Accessed on 17 September 2009.

AFDbases. 2004. World Agroforestry Centre. AgroForestyTree database. http://worldagroforestry.org. Accesses on 10 May 2006.

AMU. 2006. Aligarh Muslim Universilty. Department of geology. Remote Sensing in geology and geomorphology. India. http://www.cps-amu.org/sf/notes/msc.htm. Accesses on 10 August 2010.

Anderson, L., van Klinken, R.D. and Shepherd, D. 2007. Aerially surveying mesquite (*Prosopis* spp.) in the Pilbara. Pilbara mesquite management committee. Karratha. WA.

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

ARC-PPRI. 2006. Legislation on weeds and invasive plants in South Africa. Agricultural Research Council-Plant Protection Research Institute. Pretoria. http://www.arc.agric.za/home.asp?pid=1031. Accessed on 10 March 2010.

ARC-PPRI. 2007. What are invasive alien plants? Agricultural Research Council -Plant Protection Research Institute (ARC-PPRI). http://www.arc.agric.za/home.asp?pid=1030. Accessed on 13 Sept 2009

Avery, T.E. and Berlin, G.L. 1992. Fundamentals of Remote Sensing and Airphoto Interpretation**.** 5th edition. Upper Saddle River, Prentice-Hall, Inc.

Berhanu, A. and Tesfaye, G. 2006. The *Prosopis* dilemma, impact on dryland biodiversity and some controlling methods. *Journal of Dryland*. 1(2):158-164.

Blignaut, J.N., Marais, C. and Turpie, J.K. (2007). Determining a charge for the clearing of invasive alien plant species to augment water supply in South Africa, *Water SA*. 33(1):27-34.

Boone, R. B. and Calvin, K. A. 2000. Generalizing El Nino effects upon Maasai livestock using hierarchical clusters of vegetation patterns. *Photogrammetric Engineering* and

Remote Sensing. 66(6):737-744

Burrough, P.A. 1993. Geographical information system techniques for linking remote sensing images with other spatial data. *In Buiten, H.J. and Clevers, J.G.P.W. (eds) Land observation by remote sensing: theory and applications*, 323-336. Paris: Gordon and Breach Science Publishers.

Bredenkamp, G., Granger, J.E. and van Rooyen, N. 1996. State of the environment report (SOER). Department of Environmental Affairs and Tourism, Pretoria. http://www.environment.gov.za/soer/nsoer/Data/vegrsa/vegmenu.htm. Accessed on 29 July 2009.

Brutch, M.O. and Zimmermann, H.G. 1993. The prickly pear (Opuntia ficus-indica [Cactaceae]) in South Africa: utilization of the naturalised weed, and of cultivated plants. *Economic Botany*. 47:154-162.

CGIAR-CSI. 2008. SRTM 90m Digital Elevation Data. The CGIAR Consortium for Spatial Information (CGIAR-CSI). Web: http://srtm.csi.cgiar.org/. Accessed on 13 February 2008

Chen, D. and Brutsaert, W. 1998. Satellite-sensed distribution and spatial patterns of vegetation parameters over a tall grass prairie. *Journal of the Atmospheric Sciences.* 55(7):1225-1238

Ciruna, K.A., Meyerson, L.A. and Gutierrez, A. 2004. The ecological and socio-economic impacts of invasive alien species in inland water ecosystems. Report to the Conservation on Biological Diversity on behalf of the Global Invasive Species Program, Washington, 47 D.C. pp:34.

Coops, N.C., Wulder, M.A. and Iwanicka, D. 2009. Large area monitoring with MODIS-based disturbance index (DI) sensitive to annual and seasonal variations. *Remote Sensing of Environment*. 113:1250-1261.

Council for Geoscience. 2006. Simplified Geology of the Northern Cape Province. Council for Geoscience. Pretoria. http://www.geoscience.org.za/index.php. Accessed on 9 May 2007.

Cronk, Q.C.B. and Fuller, J.C. 1995. Plant invasions: the threat to natural ecosystems. Chapman and Hall, London

Csurhes, S. 1996. Mesquite in Queensland. Pest Status Review. Department of

Natural Resources and Mines. Queensland Government.

Cullis, J.d.S., Görgens, A.H.M. and Marias, C. 2007. A strategic study of the impact of invasive alien plants in the higher rainfall catchments and riparian zones of South Africa on total surface water yield. *Water SA*. 33(1):35-42.

Dean, W.R.J., Anderson, M.D., Milton, S.J. and Anderson, T.A. 2002. Avian assemblages in native Acacia and alien *Prosopis* drainage line woodland in the Kalahari, South Africa. *Journal of Arid Environments*. 51:1-19

DWAF. (1999). State of the environment report: Summary of environmental conditions in South Africa. http://www.environment.gov.za/soer/nsoer/GENERAL/summary.htm. Accessed on 14 September 2009.

Enright, W.D. 2000. The effect of terrestrial invasive alien plants on water scarcity in South Africa. *Phys. Chem. Earth*. 25 (3):237-242

ERDAS Field Guide. 2008. ERDAS Field Guide, Vol 1. ERDAS Software. ERDAS Inc. Georgia. USA

Essa, S. Dohai, B. and Ksiksi, T. 2006. Mapping dynamics of invasive *Prosopis juliflora* in the Northern Emirates of the UAR: An application of remote sensing and GIS. ISPRS Commission VII Mid-term symposium "Remote Sensing: from pixel to processes". Enschede, the Netherlands. 8-11 May 2006.

Fairbanks, D.H.K., Thompson M.W., Vink D.E., Newby T.S., Van den Berg H.M. and Everard D.A. 2000. The South African Land Cover Characteristics Database: a synopsis of the landscape. *South African Journal Science*. 96:69-82

Foxcroft, L.C. 2002. Impact of Invasive Alien Species on Biodiversity. Kruger National Park. Skukuza, South Africa.

Foxcroft, L.C., Hoffman, J.H., Viljoen, J.J. and Kotze, J.J. 2007. Environmental factors influencing the distribution of *Opuntia stricta,* an invasive alien plant in the Kruger National Park, South Africa. *South African Journal of Botany*. 73:109-112

Geesing, D., Felker, P. and Bingham, R.L. 2000. Influence of mesquite (*Prosopis glandulosa*) on soil nitrogen and carbon development: Implications for global carbon sequestration. *Journal of Arid Environments*. 46:157-180.

Goslee, S.C., Havstad, K.M., Peters, D.P.C., Rango, A. and Schlesinger, W.H. 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.

Groom, M.J., Meffe, G.K. and Carrol, C.R. 2006. Principles of Conservation Biology. 3rd Edition. Sinauer Associates, Inc. Sunderland

Hamada, Y., Stow, D.A., Coulter, L.L., Jafolla, J.C. and Hendricks, L.W. 2007. Detecting Tamarsisk species (*Tamarix* spp.) in riparian habitats of South California using high spatial resolution hyper spectral imagery. *Remote Sensing of the Environment*. 109:237-248.

Harding, G.B. and Bate, G.C. 1991. The occurrence of invasive *Prosopis* species in the north-western Cape, South Africa. *South African Journal of Science*. 87:188-192.

Henderson, L. 1998. South African Plant Invaders Atlas (SAPIA). *Applied Plant Science*. 12:31-32

Henderson, L. 2001. Alien weeds and invasive plants. A. Complete guide to declared weeds and invaders in South Africa. Plant protection research institute handbook no. 12. Arc-Plant Protection Research Institute, Pretoria.

Higgens, S.T., Turpie, J.K., Costanza, R., Cowling, R.M., Le Maitre, D.C., Marais, C. and Midgley, G.F. 1997. An ecological economical simulation model of mountain fynbos ecosystems dynamics, valuation and management. *Ecological Economics*. 22:155-169.

Hoffman, M.T., Todd,S. Ntshona, Z. and Turner,S. 1999. Land degradation in South Africa. Report, National Botanical Institute, Kirstenbosch.

Holmes, P.M., Richardson, D.M., Esler, K.J., Witkowski, E.T.F. and Fourie, S. 2005. A decision-making framework for restoring riparian zones degraded by invasive alien plants in South Africa. *South African Journal of Science*. 101:553-564.

Huete A.R., Didan K., Miura T., Rodriguesz E.P., Gao X. and Ferreira L.G. 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*. 83:195-213

ISSG. 2006. *Prosopis* spp. IUCN/SSC Invasive Species Specialist Group (ISSG). Global Invasive Species Database. http://www.issg.org/database/species/ecology.asp?si=433 andfr=1 andsts= andlang=EN. Accessed on 17 August 2007.

Itholeng, K.B. 2008. The indigenous knowledge of the local community towards weeds and alien invasive plants in the Dinokana area, North-West Province, South Africa.

North West University: NWU. (Dissertation – M.Sc.)

Jordaan, F. 2009. *Prosopis glandulosa* Torrey. Enkele probleemplante wat in die Noord-Wes Provinsie voorkom. Department: Agriculture, Conservation and Environment. North West Provincial Government. Republic of South Africa

Joshi, C. De Leeuw, J. and Van Duren, I.C. 2003. Remote Sensing and GIS applications for mapping and spatial modelling of invasive species. Department of natural resources, International Institute for Geo-information Science and Earth Observation. ITC. http://plone.itc.nl/agile_old/Conference/estoril/papers/93_Chudamani%20Joshi.pdf. Accessed on 3 July 2008.

Kanmon, R. and Harari-Kremer, R. 1999. Studying long-term vegetation dynamics using digital processing of historical aerial photographs. *Remote Sensing of Environment*. 68:164-176.

Kidane, D.K. 2004. Rule-based land cover classification model: expert system integration of image and non-image spatial data. Stellenbosch University. Stellenbosch. (Dissertation – M.Sc.)

Kolar, C.S. and Lodge, D.M. 2001. Progress in invasion biology: Predicting invaders. Trends in ecology and evolution. 16:199-204.

Kotze, I., Beukes, H. and Newby, T. 2009. National Alien Invasive Plant Survey (NAIPS). Report GW/A/2009/76. Agricultural Research Council – Institute for Soil, Climate and Water. Pretoria. South Africa.

Laliberte, A.S., Rango, A., Havstad, K.M., Paris, J.F., beck, RF., McNeely, R. and Gonzalez, A.L. 2004. Object-orientated image analysis for mapping shrub encroachment from 1937 to 2003 in southern New Mexico. *Remote Sensing of Environment*. 93:198-210.

Landsat Program. 1999. Landsat Program. National Aeronautics and Space Administration (NASA). http://geo.arc.nasa.gov/sge/landsat/. Accessed on 14 August 2007.

Land Type Survey Staff. 1972-2006. Land Types of South Africa (Digital Map- 1:250 000 scale) and Soil Invertory data bases. Agricultural Research Council-Institute for Soil Climate and Water.

Le Maitre, D.C., Versveld, D.B. and Chapman, R.A. 2000. The impact of invading alien plants on surface water resources in South Africa: A preliminary assessment. *Water SA*. 26(3):397-408.

Le Maitre. D.C., Van Wilgen, B.W., Gelderblom, C.M., Bailey, C., Chapman, R.A. and Nel, J.A. 2002. Invasive alien trees and water resources in South Africa: case studies of costs and benefits of management. *Forest Ecology and Management*. 160:143-159.

Levine, J.M. 2008. Biological Invasion. *Current Biology*. 18 (2):57-60.

Lillesand, T. M., Kiefer R.W. and Chipman J.W. 2004. Remote Sensing and image interpretation. 5th Edition. New York. Wiley and Sons, Inc.

Lloyd J. W., Van den Berg E. C., and Badenhorst N.C., 2002. Mapping the spatial distribution and biomass of *Prosopis* in the Northern Cape Province, South Africa, with the aid of Remote Sensing and Geographic Information Systems. Report GW/A/98/68. Agricultural Research Council-Institute for Soil Climate and Water. Pretoria. South Africa.

Lodge, D. M., Williams, S., MacIsaac, H.J., hayes, K.T., Leung, B., reichard, S., mack, R.N., Moyle, P.B., Smith, S., Andow, D.A., Carlton, j.T. and McMichael, A. 2006. Biological Invasions: recommendations for U.S. policy and management. *Ecological Applications*. 16(6):2035-2054.

Lopez-Portillo, J., Montana, C. and Ezcurra, E. 1996. Stem demography of *Prosopis glandulosa* var. *torreyana* in vegetation arcs and associated bare areas. *Journal of Vegetation Science*. 7:901-910.

Low, A.B. and Robelo, A.G. 1996. Vegetation of South Africa, Lesotho and Swaziland. Pretoria: Department of Environmental Affairs and Tourism. Land Type Survey Staff. 1972-2006. Land Types of South Africa (Digital map 1:250 000 scale) and soil inventory data base. Agricultural research Council – Institute for Soil, Climate and Water. Pretoria. South Africa. Web: www.agis.agric.za/agisweb/landtypes.html. Accessed on 7 October 2007.

LP DAAC. 2008. MODIS Overview. Land Processes Distributed Active Archive Centre. Web: http://edcdaac.usgs.gov/modis. Accessed on 14 December 2009

Mack, R.N., Simberloff, D., Lonsdale, W.M., Evans, H. Clout, H. and Bazzaz, F.A. 2000. Biotic invasions: causes, epidemiology, global consequences, and control.

Ecological Applications. 10:689-710.

Mampholo, R.K. 2006. To determine the extent of bush encroachment with focus on *Prosopis* species on selected farms in the Vryburg district of North West Province. North West University: NWU. (Dissertation – M.Sc.).

Musina, L. and Rutherford, M.C. 2006. The vegetation of South Africa, Lesotho and Swaziland. Strelitzia 19. South African National Biodiversity Institute. Pretoria.

Mwangi, E. and Swallow, B. 2005. Invasion of *Prosopis juliflora* and local livelihoods: Case study from the lake Baringo area of Kenya. ICRAF Working Paper –no. 3. Nairobi: World Agroforesty Centre. 2007. http://www.issg.org/database/species/reference_files/progla/Mwangi and Swallow_2005.pdf. Accessed on 17 September 2009.

NOAA. 2007. The National Oceanic and Atmospheric Administration/ Advanced Very High Resolution Radiometer (NOAA/AVHRR) satellite system. http://en.wikipedia.org/wiki/Advanced_Very_High_Resolution_Radiometer. Accesed on 14 August 2007.

NOSS, R.F.1990. Indicators for monitoring biodiversity: a hierarchical approach. Conservation biology, 4:355-364.

Pasiecznik, N. 1999. *Prosopis* – pest or providence, weed or wonder tree? European Tropical Forest Research Network. Newsletter. 28:12-14. http://www.etfrn.org/ETFRN/newsletter/nl28_oip.htp. Accessed on 17 September 2009.

Pasiecznik, N. 2002. *Prosopis* (mesquite, algarrobo): invasive weed or valuable forest resource? HDRA – the organic organisation. Coventry. UK

Preston, G. 2003. Invasive alien plants and protected areas in South Africa. World Parks Congress, Durban, South Africa.

Richardson, D.M. 1998. Forestry trees as invasive aliens. *Conservation Biology*. 12:18-26.

Richardson, D.M. and Van Wilgen, B.W. 2004. Invasive alien plants in South Africa: how well do well do we understand the ecological impacts? *South African Journal of Science*. 100: 45-52.

Robinson, T.P., Van Klinken, R.D. and Metternicht, G. 2008. Spatial and temporal rates and patterns of mesquite (*Prosopis* species) invasion in Western Australia. *Journal of*

Arid Environment. 72:175-188.

Roura-Pascual, N., Richardson, D.M., Krug, R.M., Brown, A., Chapman, R.A., Forsyth, G.G., Le Maitre, C.L., Roberson, M.P., Stafford, L., Van Wilgen, B.W., Wannenburg, A. and Wessels, N. 2009. Ecology and management of alien plant invasion in South African Fynbos: Accommodating key complexities in objective decision making. Biological Conservation. 142:1595-1604.

SANParks. 2010. Formal_Protected_Areas_and_Informal_Conservation_Area_System" [ESRI shapefile]. Created by Park Planning and Development, Conservation Services, SANParks. Using ArcView 9.2, from a compilation of national and provincial protected area layers. (http://library.mcmaster.ca/maps/mapcite.htm).

SEES. 2003. Studying Earths Environment from Space (SEES). Center for Coastal Physical Oceanography. http://www.ccpo.odu.edu/SEES. Accessed on 15 September 2009.

Schmidt, H. and Karnieli, A. 2000. Remote sensing of the seasonal variability of vegetation in a semi-arid environment. *Journal of Arid Environment.* 45(1):43-60.

South Africa. 1983. Conservation of Agriculture Resources Act (CARA), Act, No 43 of 1993. Pretoria: Government Printer.

South Africa. 1998. National Water Act, No 36 of 1998. Pretoria: Government Printer.

Stefanov, W.L., Ramsey, M.S. and Christensen, P.R. 2001. Monitoring urban land cover change: an expert system approach to land cover classification of semiarid to arid urban centres. *Remote Sensing of Environment.* 77:173-185.

Soil Classification Working Group. 1991. Soil classification: a taxonomic system for South Africa. Memoirs of the Natural Resources of South Africa. 15:1-257.

South African Agricultural Field Boundaries. 2008. South African Agricultural Field Boundaries. Geoterraimage. Pretoria. South Africa. Digital Map.

Spot Image. 2009. Spot Images SPOT: Product Information. http://www.spotimage.com/web/en/172-spot-images.php. Accessed on 14 December 2009.

Thomas, V., Moll, E. and Grant, R. 2008. Sappi tree spotting; Cape from coast to Kalahari. First Edition. Jacana Media. Johannesburg. South Africa. 2008.

Thompson, M.W. 1996. A standard land cover classification scheme for remote sensing applications in South Africa. *South African Journal of Science*. 92:34-42.

UNESCO. 1977. Handbook of precision agriculture: Principles and applications. Ancha Srinivasa. Howarth press. 2006.

USDA. 2009. National Invasive Species Information Centre (NISIC). United States Department of Agriculture. Web: http://www.invasivespeciesinfo.gov/whatis.shtml. Accessed on 14 Sept 2009.

USGS. 2009 (a). Landsat Multispectral Scanner (MSS) Data. Earth Resources Observation and Science (EROS) Centre. http://eros.usgs.gov/#/Guides/landsat_mss. Accessed on 14 December 2009.

USGS. 2009 (b). Landsat Thematic Mapper (TM) Data. Earth Resources Observation and Science (EROS) Centre. http://eros.usgs.gov/#/Guides/landsat_tm. Accessed on 14 December 2009.

USGS. 2009 (c). Landsat Enhanced Thematic Mapper Plus (ETM+). Earth Resources Observation and Science (EROS) Centre. http://eros.usgs.gov/#Find_Data/Products_and_Data_Available/ETM. Accessed on 14 December 2009.

Van den Berg, E.C., Plarre, C., Van den Berg, H.M. and Thompson, M.W. 2008. The South African National Land Cover 2000. Agricultural Research Council-Institute for Soil, Climate and Water. Pretoria. (Report No. GW/A/2008/86).

Van der Merwe, J.P.A. 2005. Spatial monitoring of natural resource condition in Southern Africa. Stellenbosch University. Stellenbosch. (Dissertation – M.Sc.)

Van Wilgen, B.W., Little, P.R., Chapman, R.A., Görgens, A.H.M., Willems, T. and Marais, C. 1997. The sustainable development of water resources: History, financial cost, and benefits of alien plant control programs. *South African Journal of Science*. 93:404-411.

Van Wilgen , B.W., Richardson, D.M., Le Maitre, D.C., Marais, C. and Magadlela, D. 2001. The economic consequences of alien plant invasion: examples of impact and approaches to sustainable management in South Africa. Environment, Development and Sustainability. 3:145-168.

Van Wilgen, B.W., De Wit, M.P., Anderson, H.J., le Maitre, D.C., Kotze, I.M., Ndala, S., brown, B. and Rapholo, M.B. 2004. Cost and benefits of biological control of invasive alien plants: case studies from South Africa. *South African Journal of Science*. 100:113-122.

Van Wilgen, B.W., Reyers, B., Le Maitre, D.C., Richardson, D.M. and Schonegevel, L. 2008. A biome-scale assessment of the impact of invasive alien plants on ecosystem services in South Africa. *Journal of Environmental Management*. 89:336-349.

Verling, E., Ruiz, G.M., Smith, L. D., Galil, B., Whitman Miller, A. and Murphy, K.R. 2005. Supply-side invasion ecology: characterizing propagule pressure in coastal ecosystems. *Proceedings of the Royal Society.* 272:1249-1257.

Versveld, D.B., Le Maitre, D.C. and Chapman, R.A. 1998. Alien invading plants and water resources in South Africa: A preliminary assessment. WRC report no. TT99/98 CSIR no ENV/S-C07154.

Visser, N. 2004. Potensiële beheermaatreëls vir *Prosopis* in die ariede en semi-ariede dele van die Karoo –'n literatuuroorsig. The Department of Agriculture: Western Cape. *Elsenburg Journal*. ISSN: 0250-1538. http://www.elsenburg.com. Accessed on 13 Sept 2009.

WEB2007. 2007. Web climate databank. Institute for Soil, Climate and Water. Agricultural Research Council

Weeds in Australia. 2003. Mesquite (*Prosopis* species) weed management guide. Department of the Environment and Heritage and the *CRC* for Australian Weed Management. http://www.weeds.gov.au/publications/guidelines/wons/prosopis.html. Accessed on 10 March 2010.

Wild. A.J. and Du Plessis, C.G. 2007. Information sheets: *Prosopis*. Department of Agriculture: Western Cape. http://www.elsenburg.com/info/els/043/043e.html. Accessed on 14 Sept 2009.

WIP. 2006. Weeds and Invasive Plants: Version 2.00. Agricultural Geo-Referenced Information System. Agricultural Research Council and National Department of Agriculture. http://www.agis.agric.za/wip. Accessed on 25 September 2009.

Woodcock, C.E. and Strahler, A.H. 1987. The Factor of Scale in Remote Sensing. *Remote Sensing of the Environment*, 21: 311-332.

Zimmerman, H., 2005. Realistic approach to the management of *Prosopis* species in

South Africa. HDRA - the Organic Organization. http://www.gardenorganic.org.uk/pdfs/international_programme/SouthAfrica*Prosopis*Brief.pdf. Accessed on 14 Sept 2007.

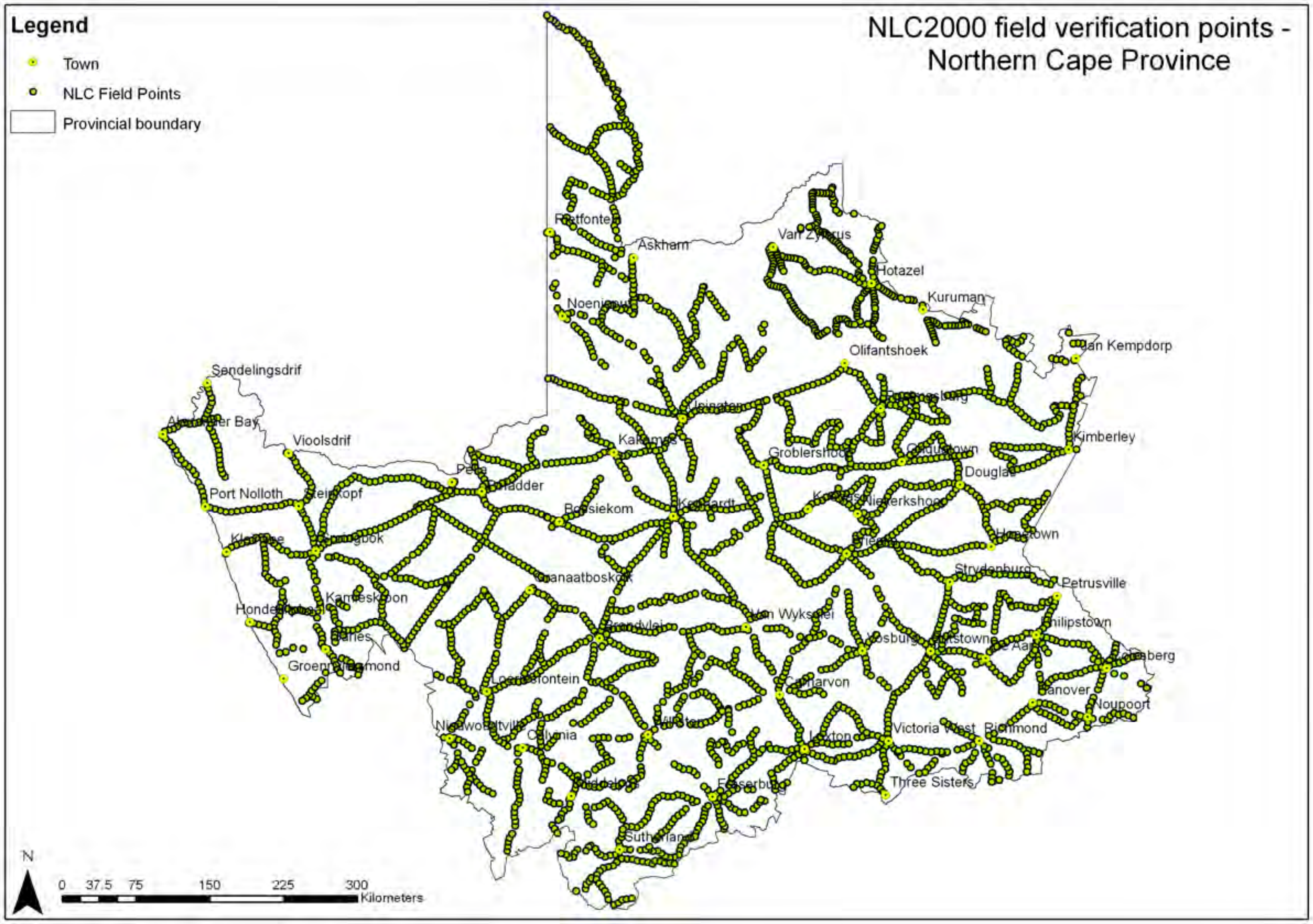
Zoran, M. and Stefan, S. 2006. Climate Changes Effects on Spectral Vegetation Indices for Forested Areas Analysis from Satellite Data. Proceedings of the 2nd Environmental Physics Conference, 18-22 Feb. Alexandria, Egypt.

APPENDICES

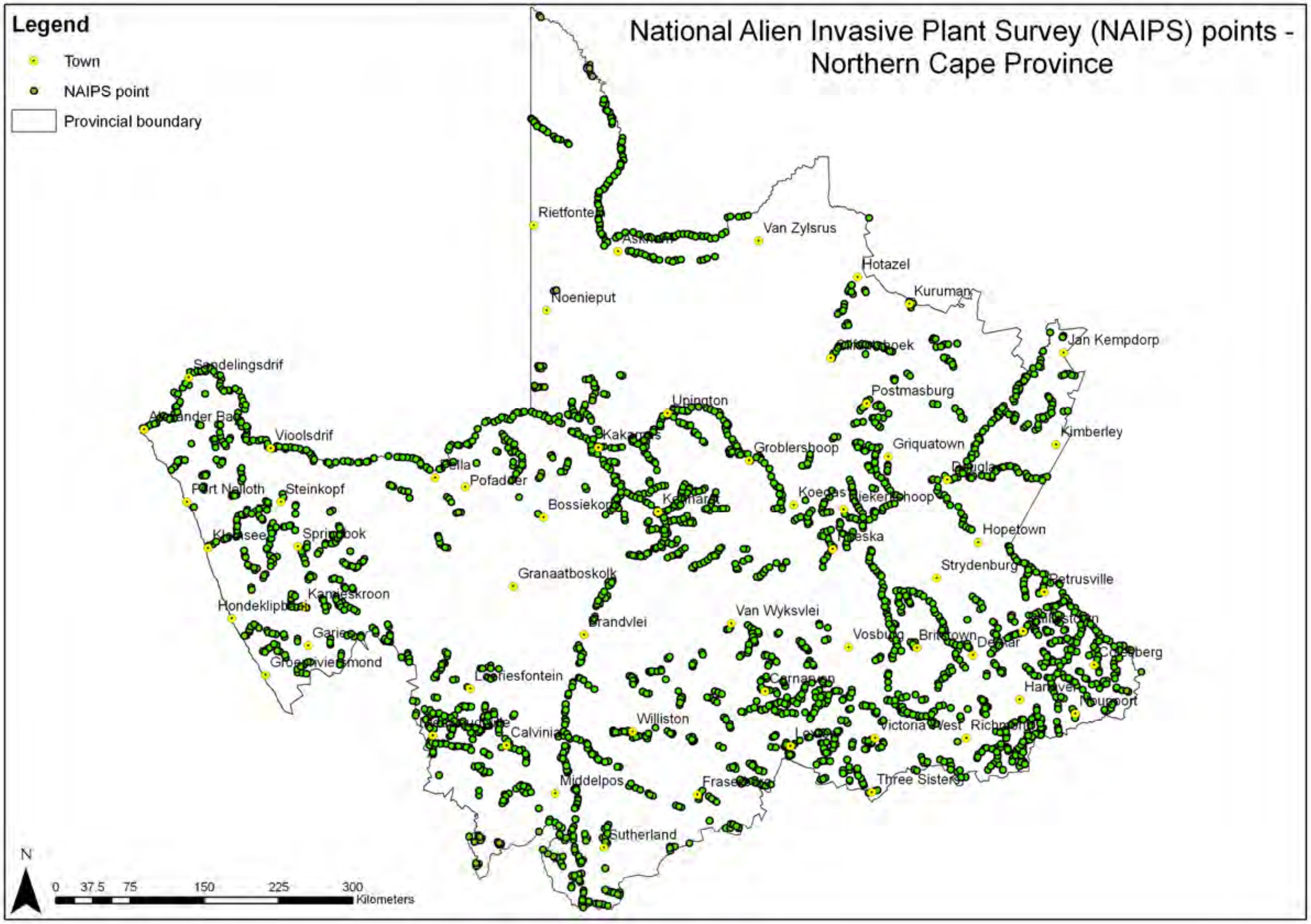
Appendix 1: Field data collection sheet used to capture descriptive information of actual *Prosopis* occurrence. The information was used to create a spatial layer in a GIS to assist with the analysis of satellite images and other spatial data.

***Prosopis* field data collection information sheet.**					
Point Number		**Date**			
Photo Number					
Soil					
Soil Sample No					
Colour	Yellow	Red	Grey	Dark	
Dunes	Yes	No			
Type	Sand	Loam	Mixed		
Lime on surface	Yes	No			
Prosopis					
Density class	Closed	Dense	Moderate	Sparse	
Tree Height	<2m	2- 4m	>4m		
Stems	Single	Multi			
Terrain unit	1	3	4	5	
Patch Size (m)	> 250	100-250	50-100	< 50	
Compilation of tree size %	> 4m		2- 4m		<2m
% of Total Vegetation					
Other species					
Name					
Height	<1m	1-2m	2-4m	>4m	
Density class	Closed	Dense	Moderate	Sparse	
Stems	Single	Multi			
% of Total Vegetation					
Name					
Height	<1m	1-2m	2-4m	>4m	
Density class	Closed	Dense	Moderate	Sparse	
Stems	Single	Multi			
% of Total Vegetation					
Signs disturbances / Other comments					

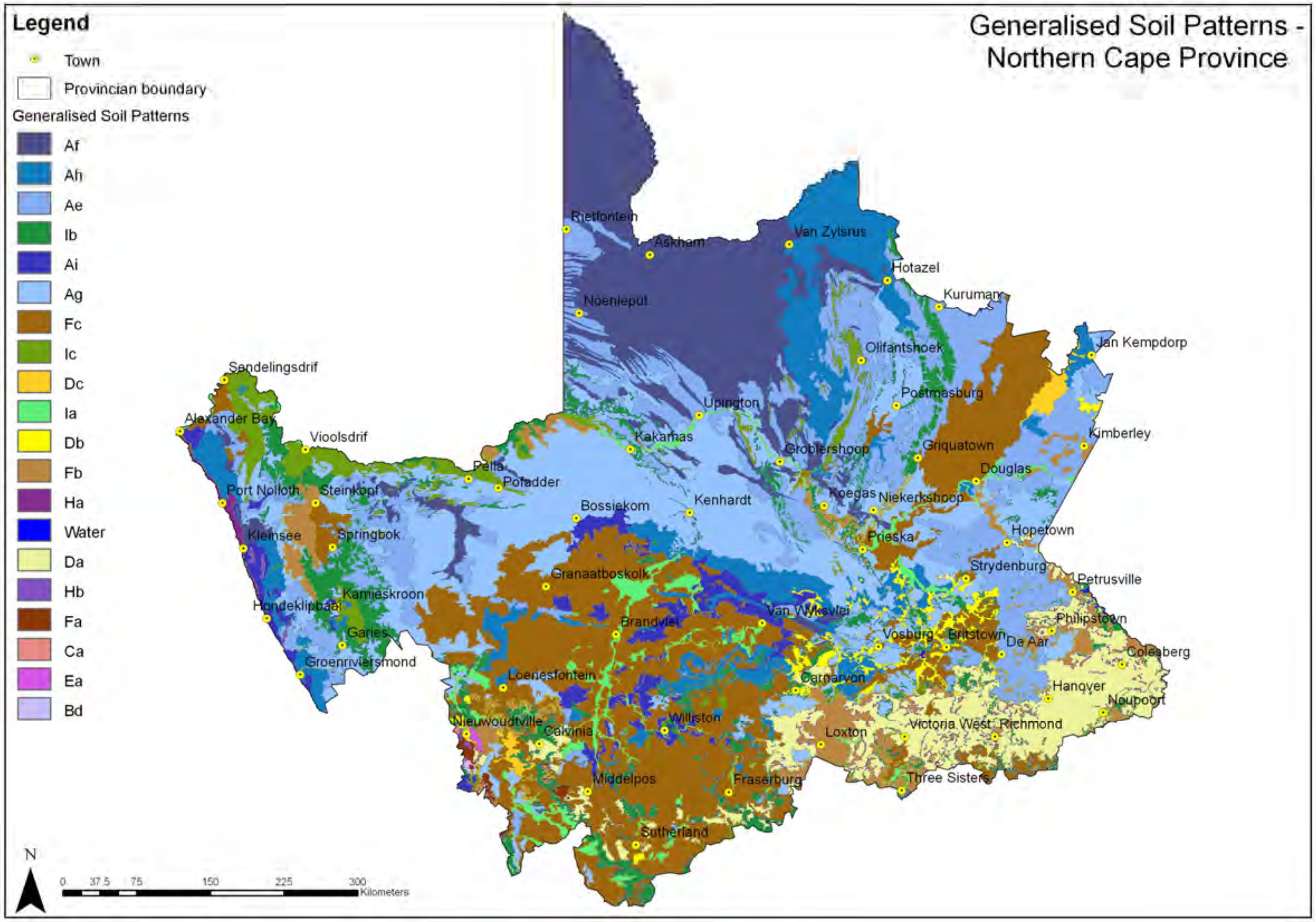
Appendix 2: NLC2000 field verification points for the Northern Cape Province (Van den Berg *et al.*, 2008).



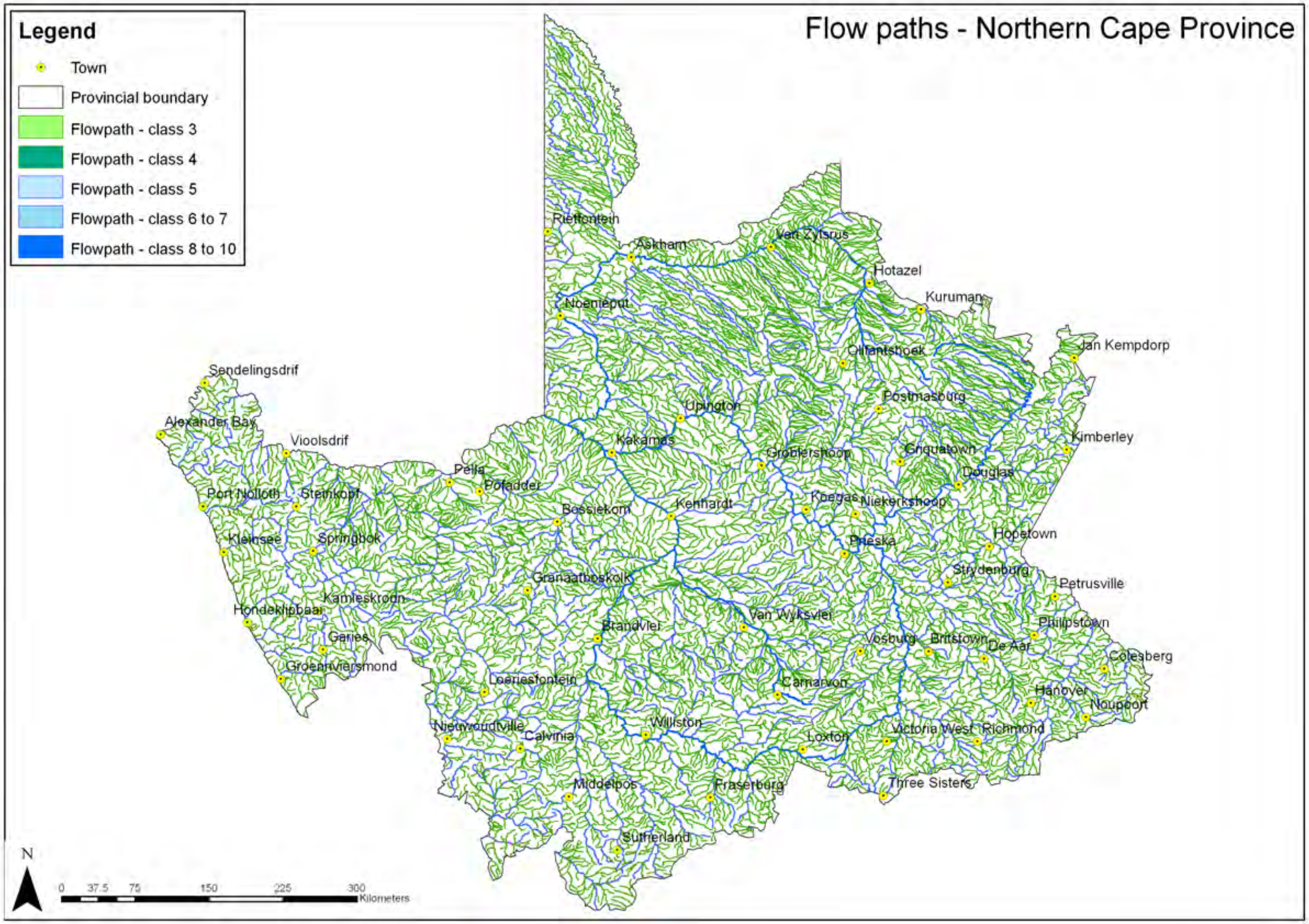
Appendix 3: National Alien Invasive Plant Survey (NAIPS) points for the Northern Cape Province (Kotze *et al.*, 2009).



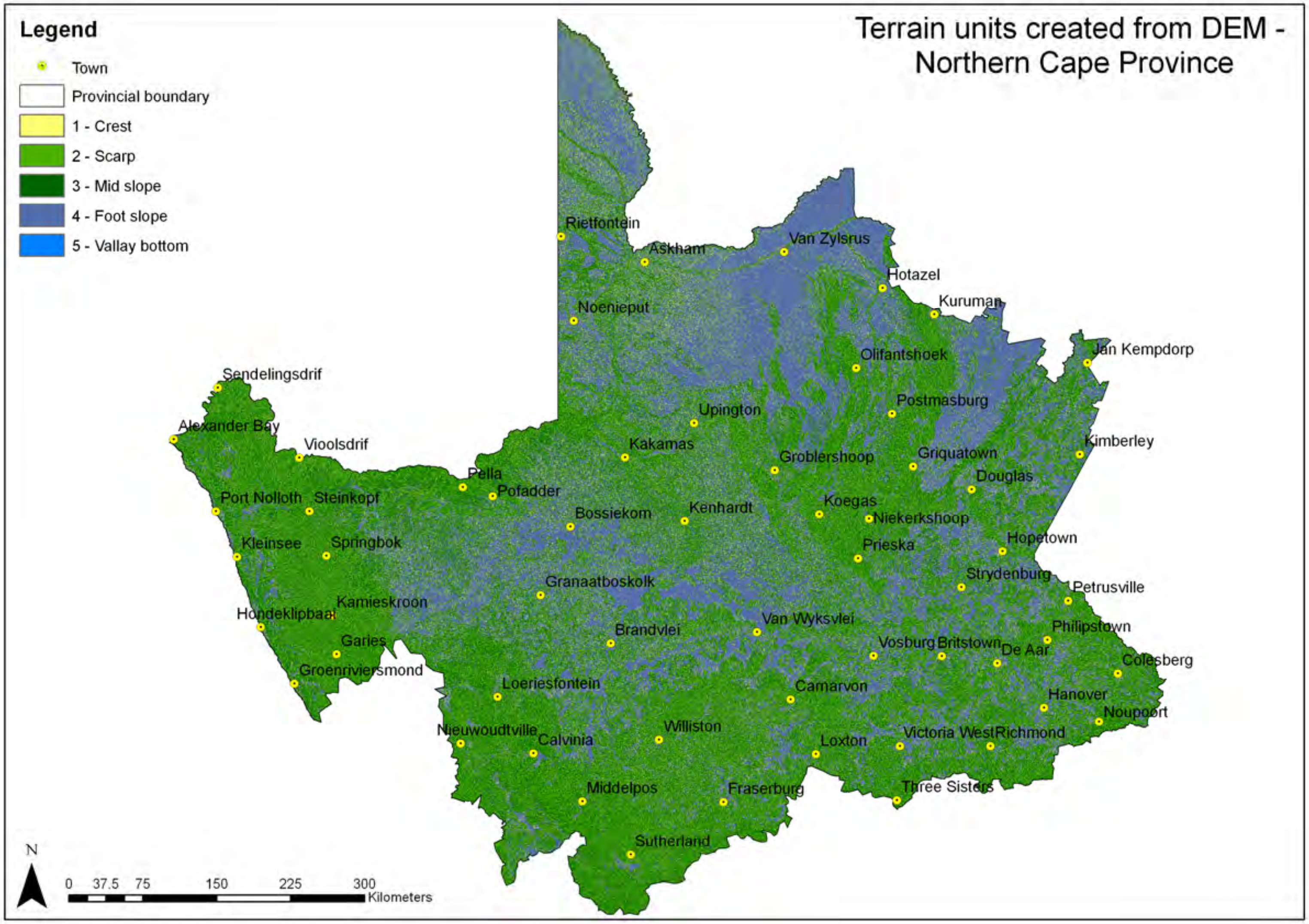
Appendix 4: Generalised Soil Patterns of South Africa for the Northern Cape Province (Land Type Survey Staff, 1972 – 2006).



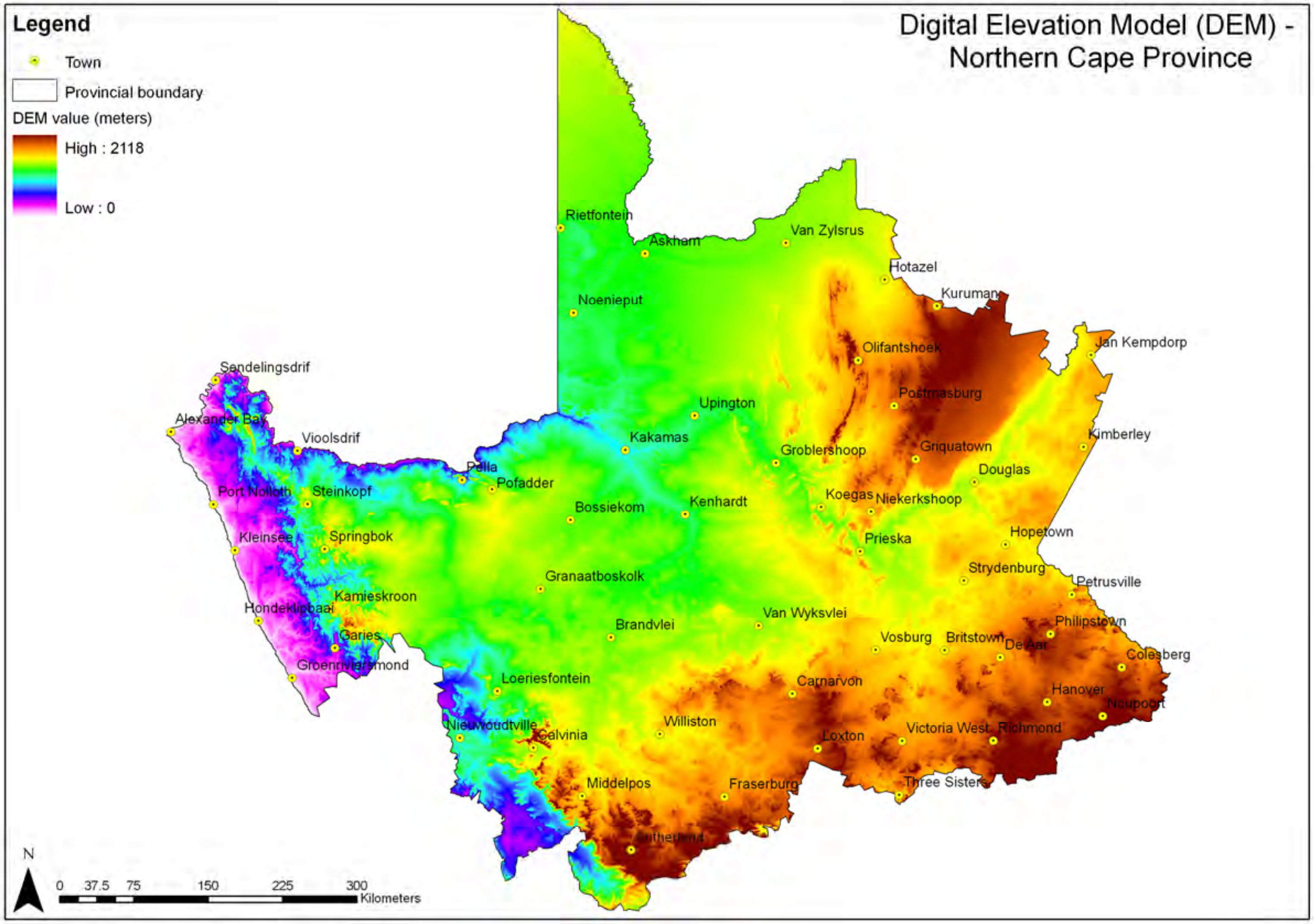
Appendix 5: Flow paths for the Northern Cape Province. Derived from SRTM DEM (CGIAR, 2008).



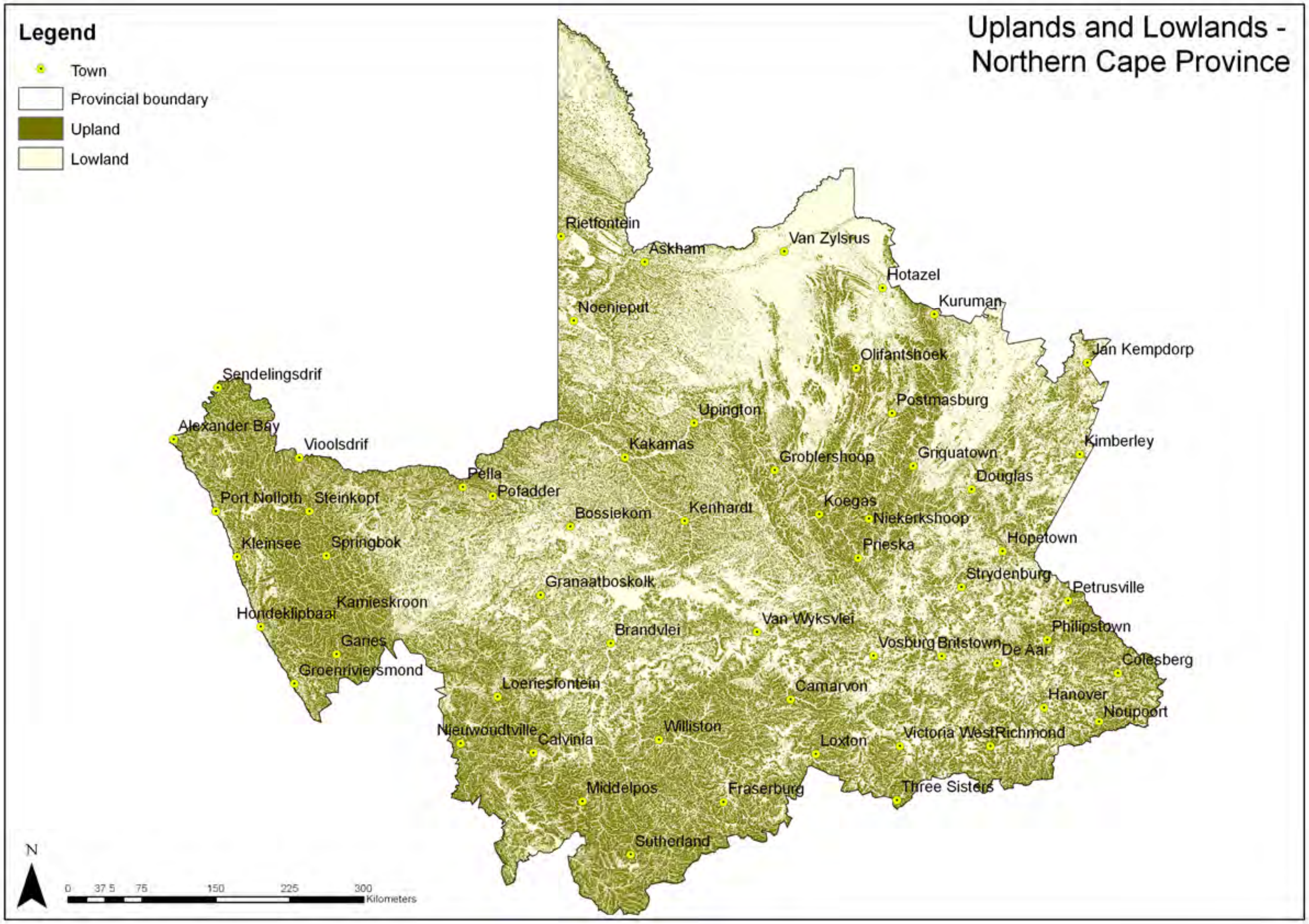
Appendix 6: Terrain units for the Northern Cape Province. Derived from SRTM DEM (CGIAR, 2008).



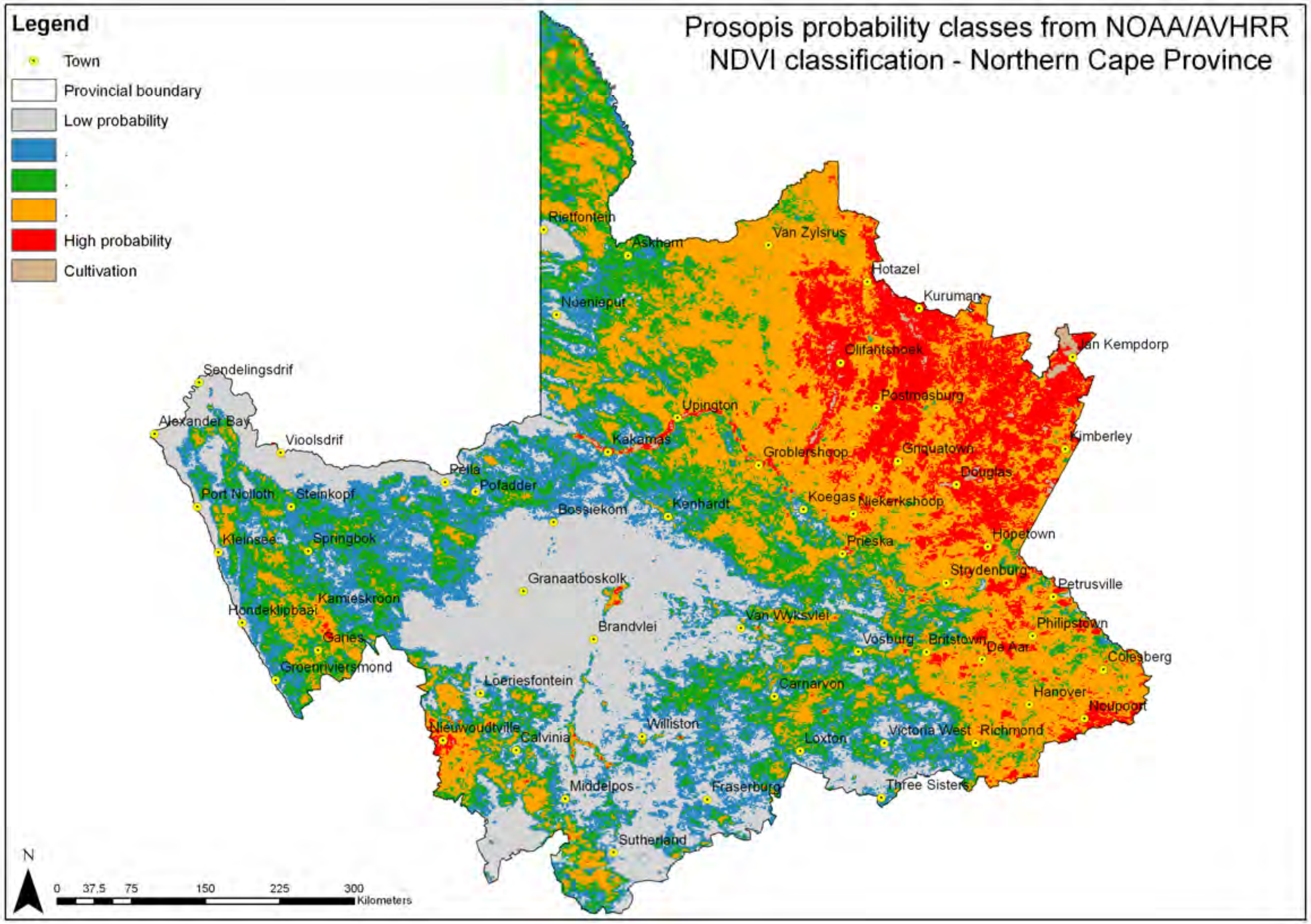
Appendix 7: Digital Elevation Model (DEM) for the Northern Cape Province (CGIAR, 2008).



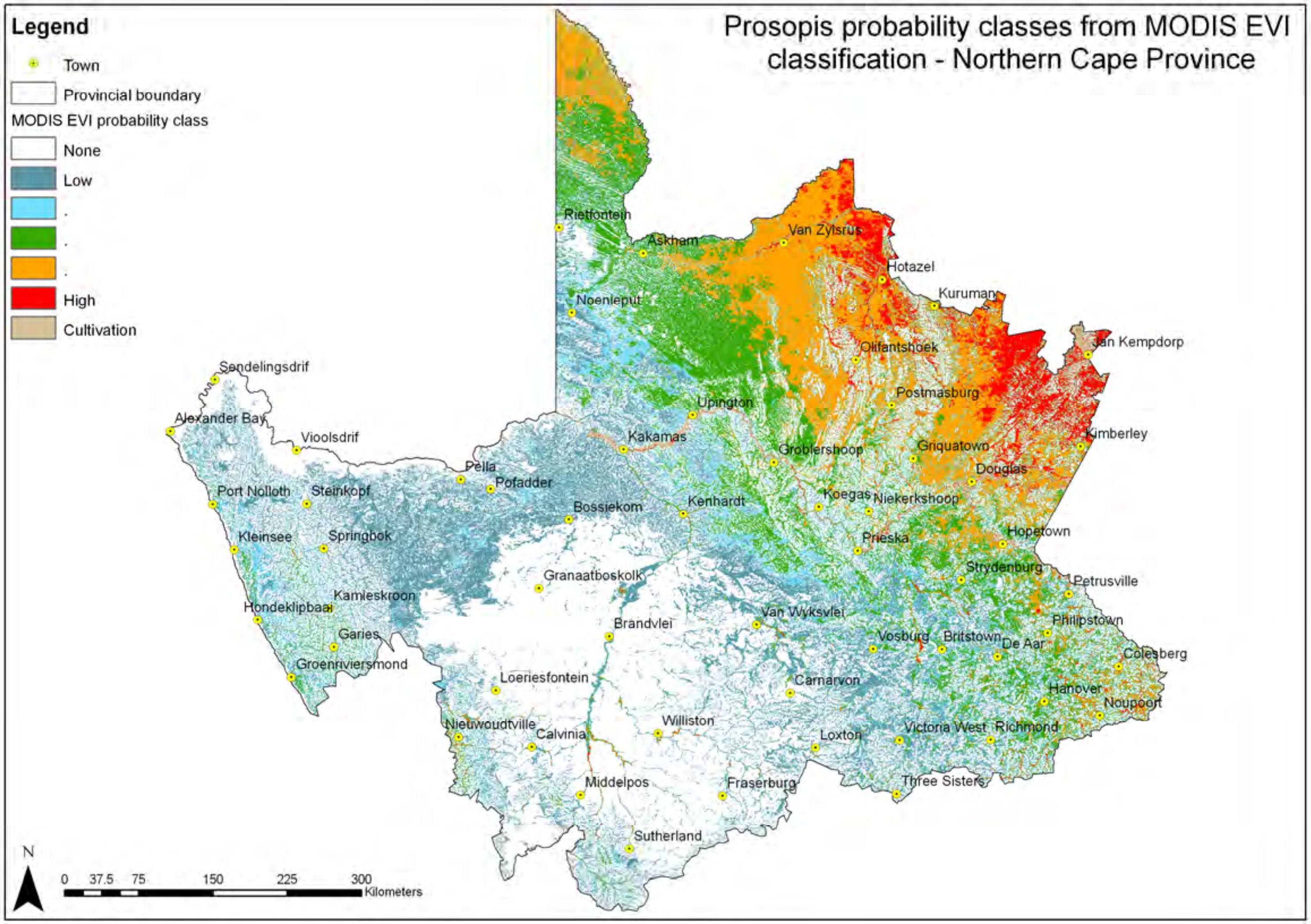
Appendix 8: Uplands and Lowlands for the Northern Cape Province. Derived from SRTM DEM (CGIAR, 2008).



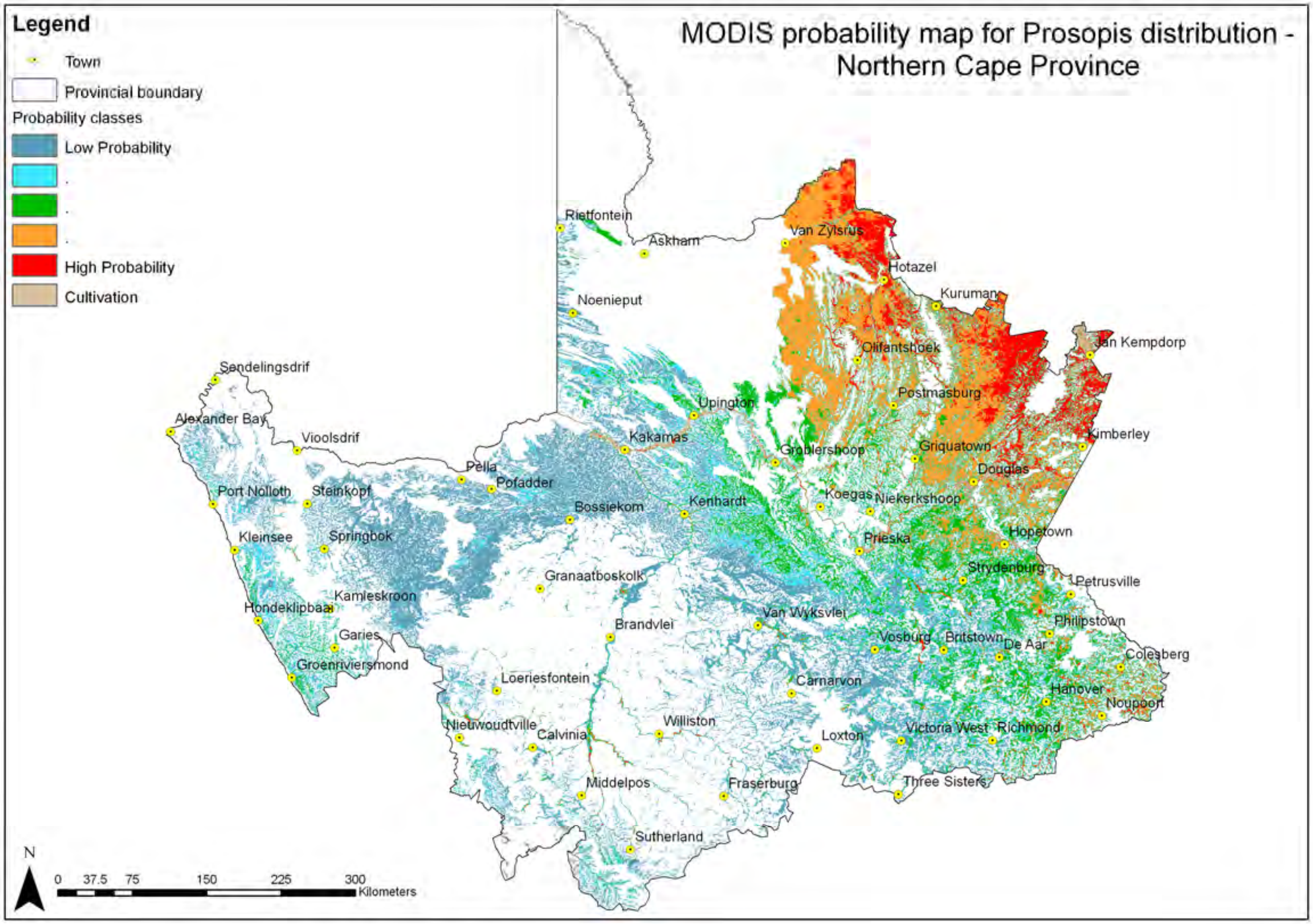
Appendix 9: NOAA/AVHRR NDVI generated *Prosopis* probability classes with 1km resolution and five probability classes for the Northern Cape Province.



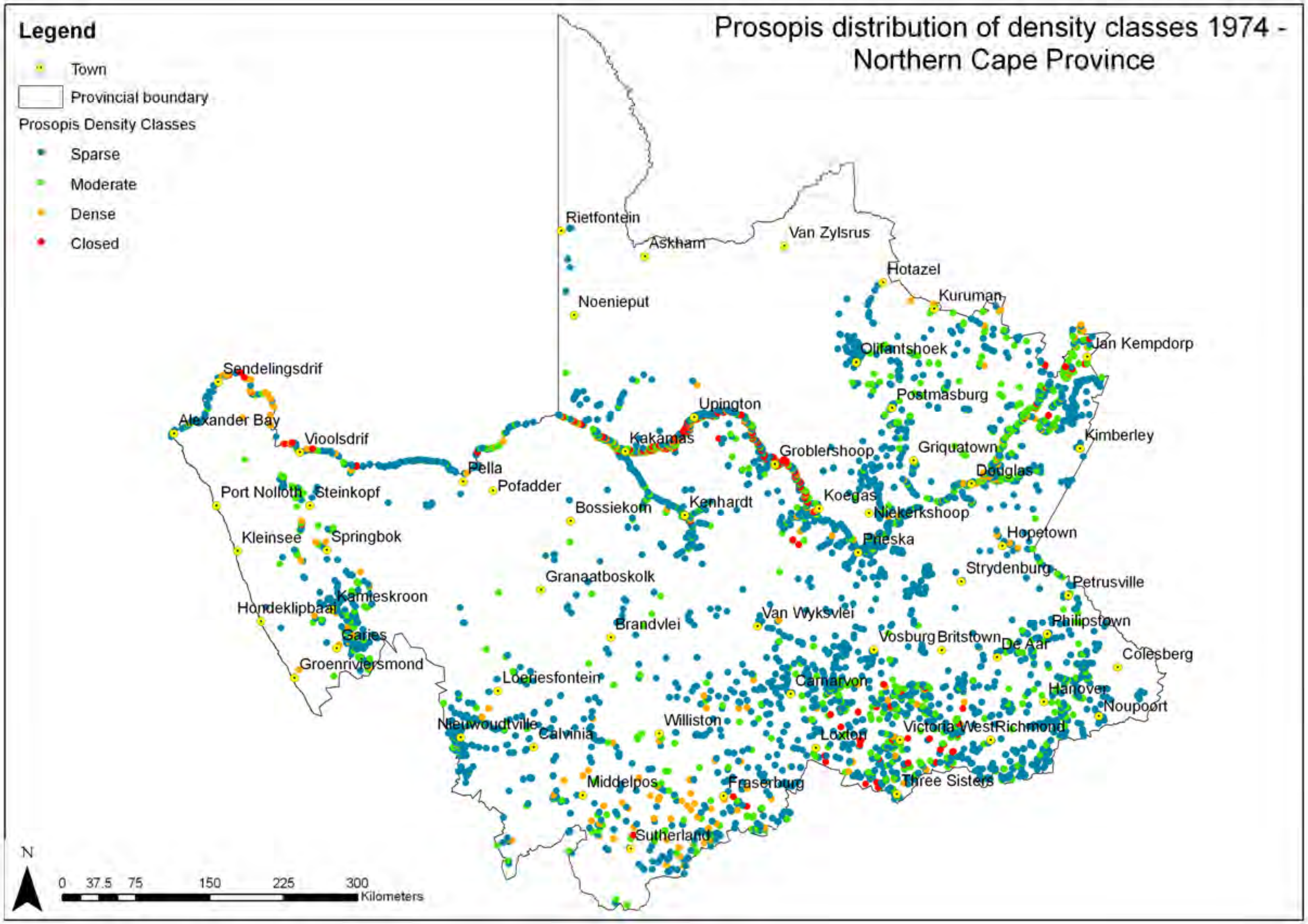
Appendix 10: MODIS EVI generated *Prosopis* probability classes with 250m resolution and five probability classes for the Northern Cape Province.



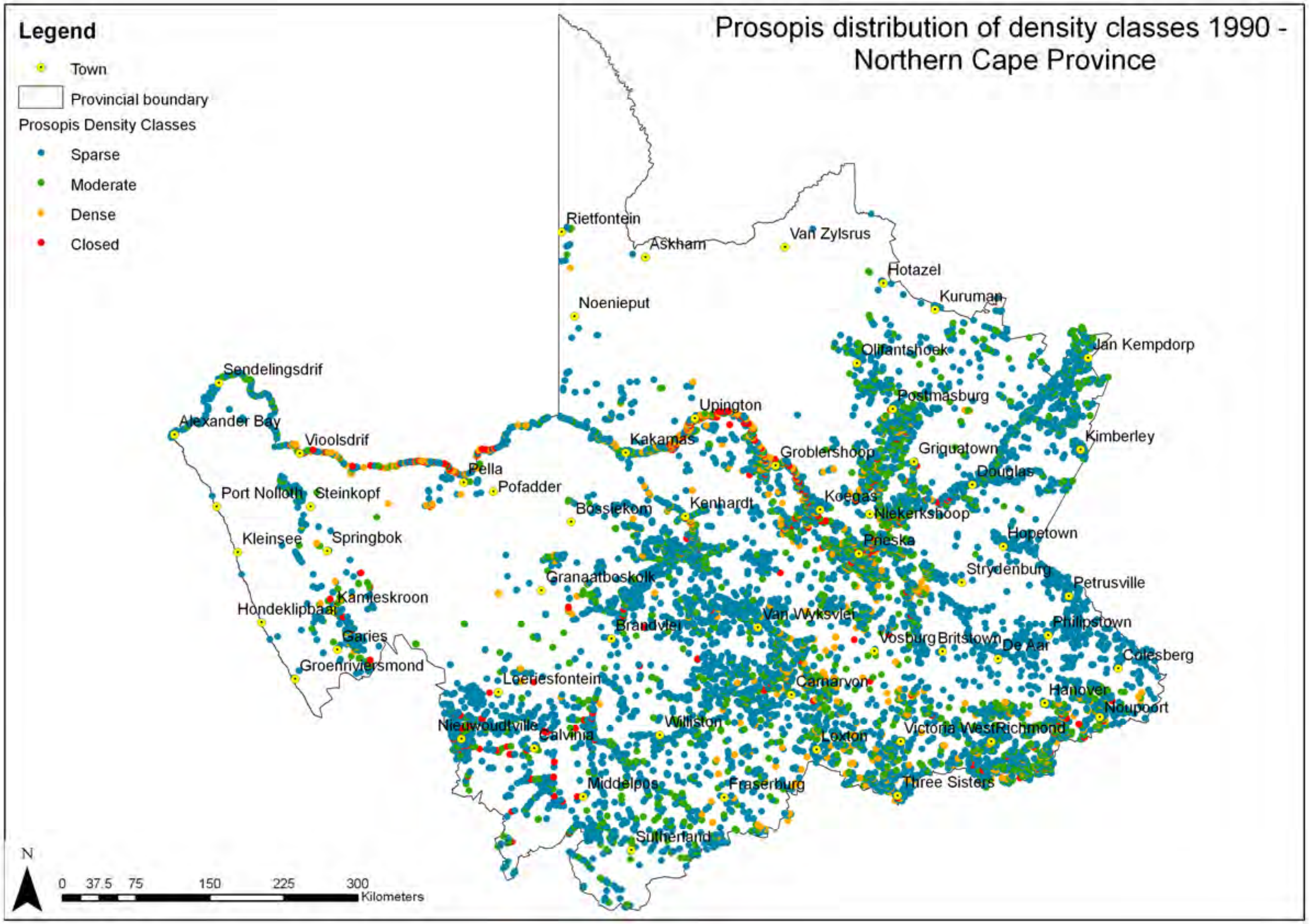
Appendix 11: MODIS probability map for *Prosopis* distribution for the Northern Cape Province. (Details can be seen on attached CD-Rom)



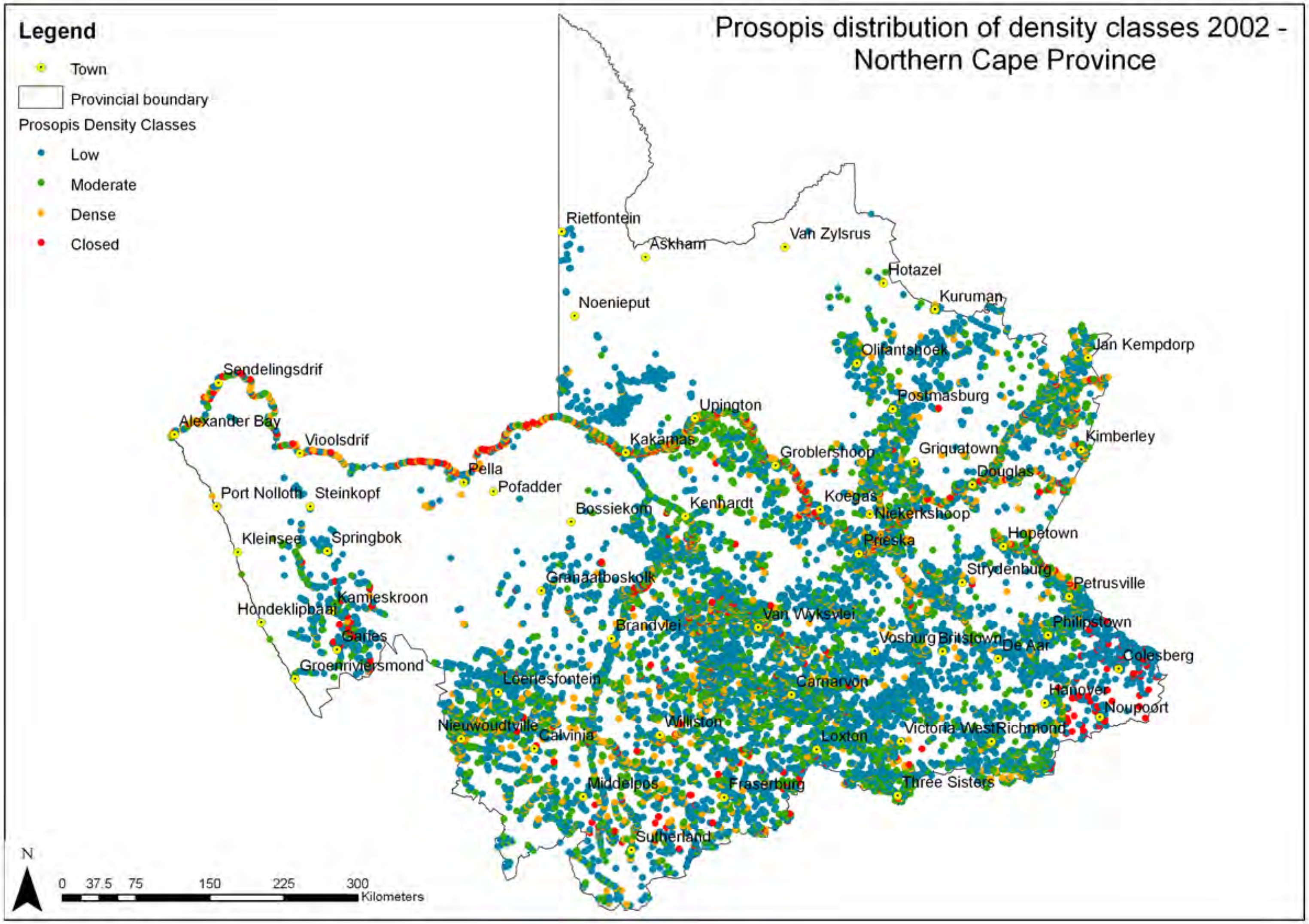
Appendix 12: *Prosopis* distribution and density classes in 1974 for the Northern Cape Province.



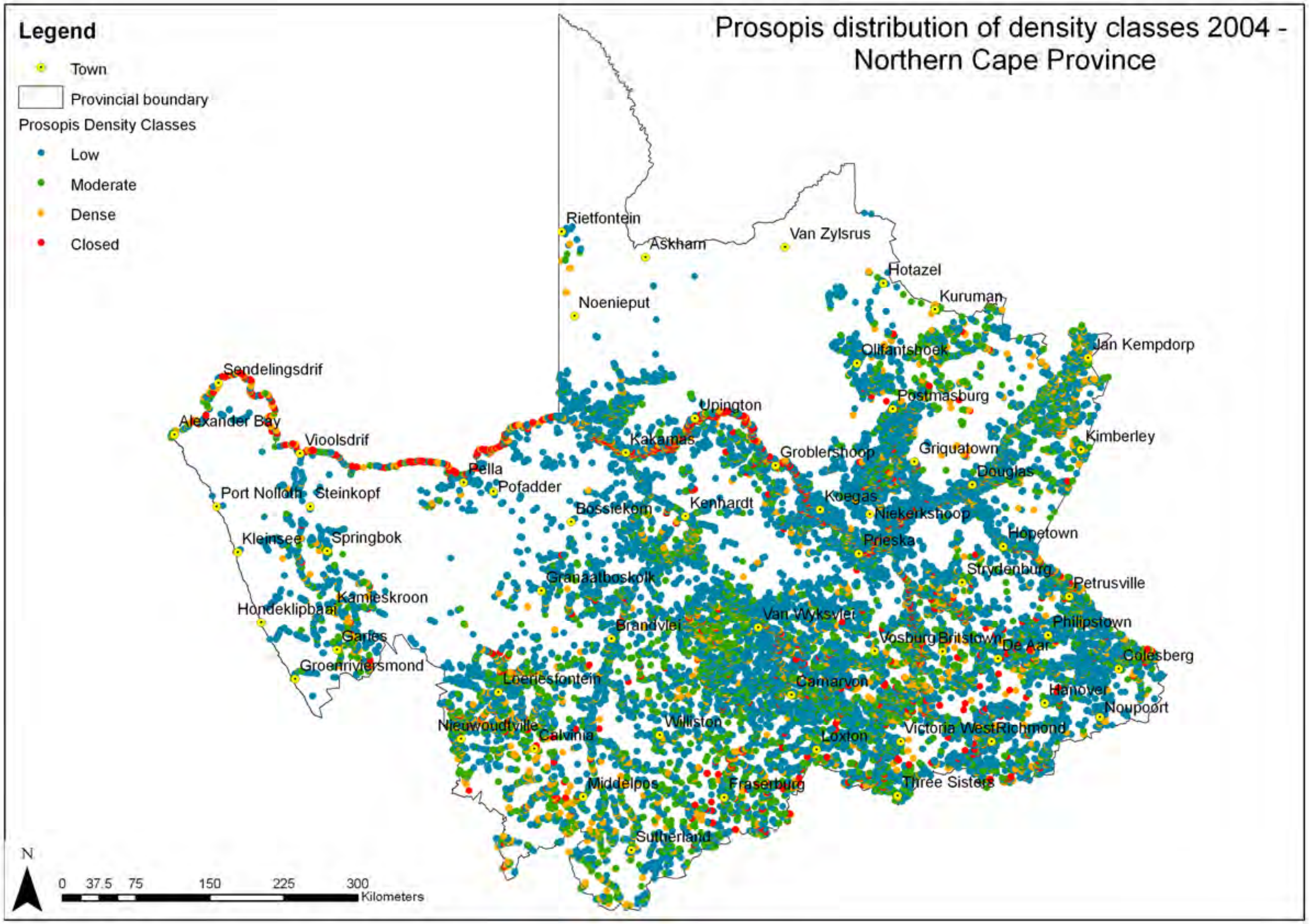
Appendix 13: *Prosopis* distribution and density classes in 1990 for the Northern Cape Province.



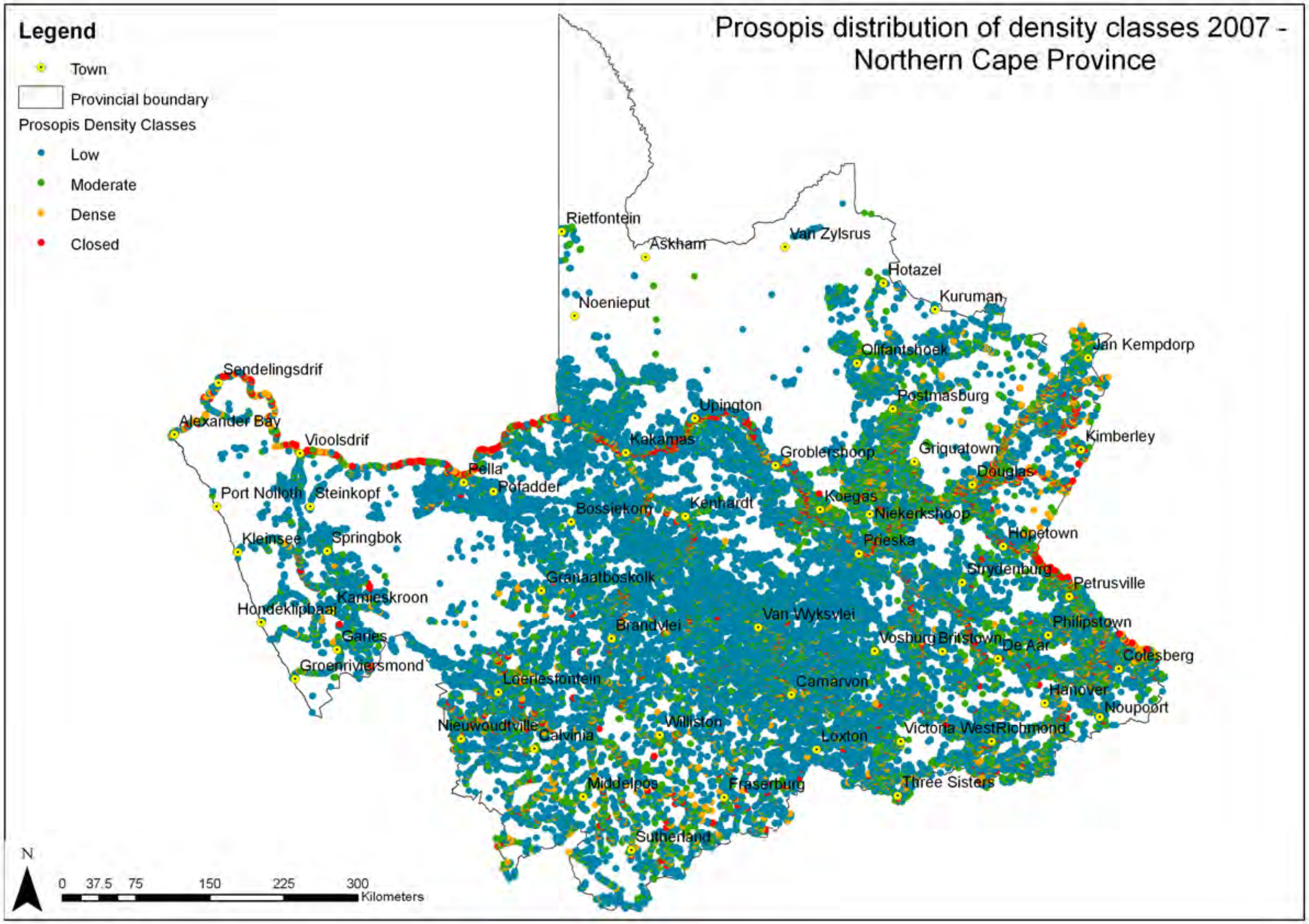
Appendix 14: *Prosopis* distribution and density classes in 2002 for the Northern Cape Province.



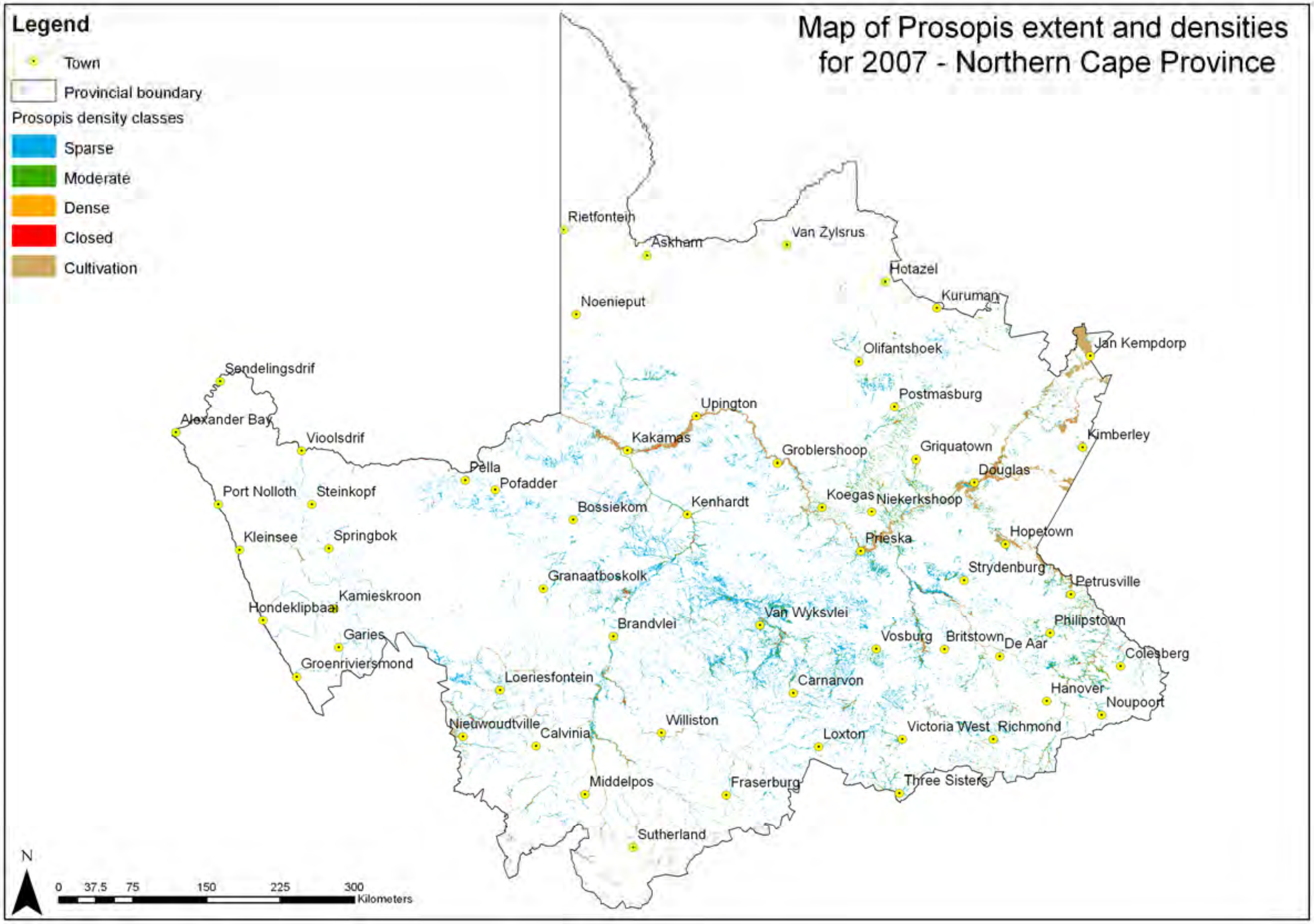
Appendix 15: *Prosopis* distribution and density classes in 2004 for the Northern Cape Province.



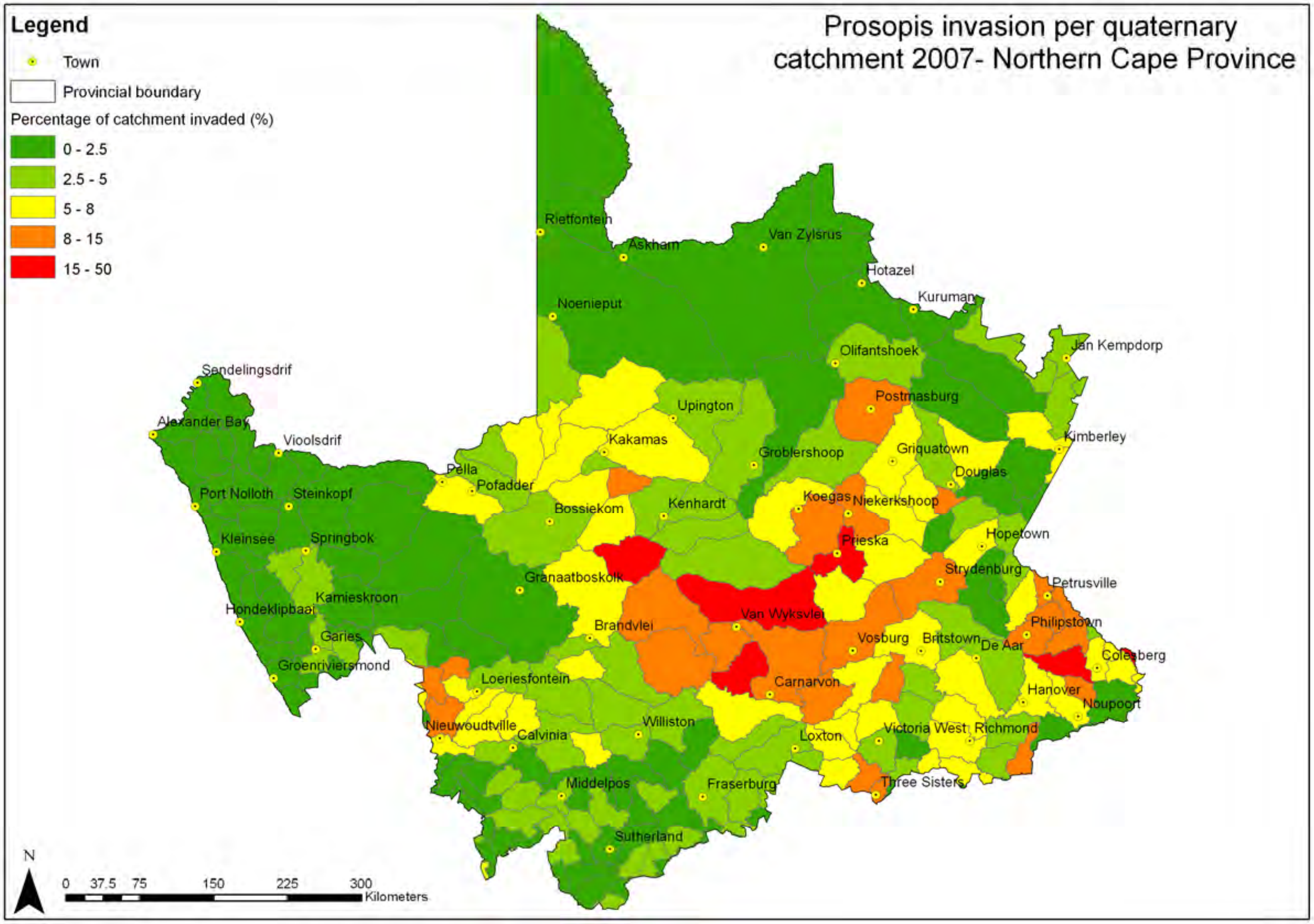
Appendix 16: *Prosopis* distribution and density classes in 2007 for the Northern Cape Province.



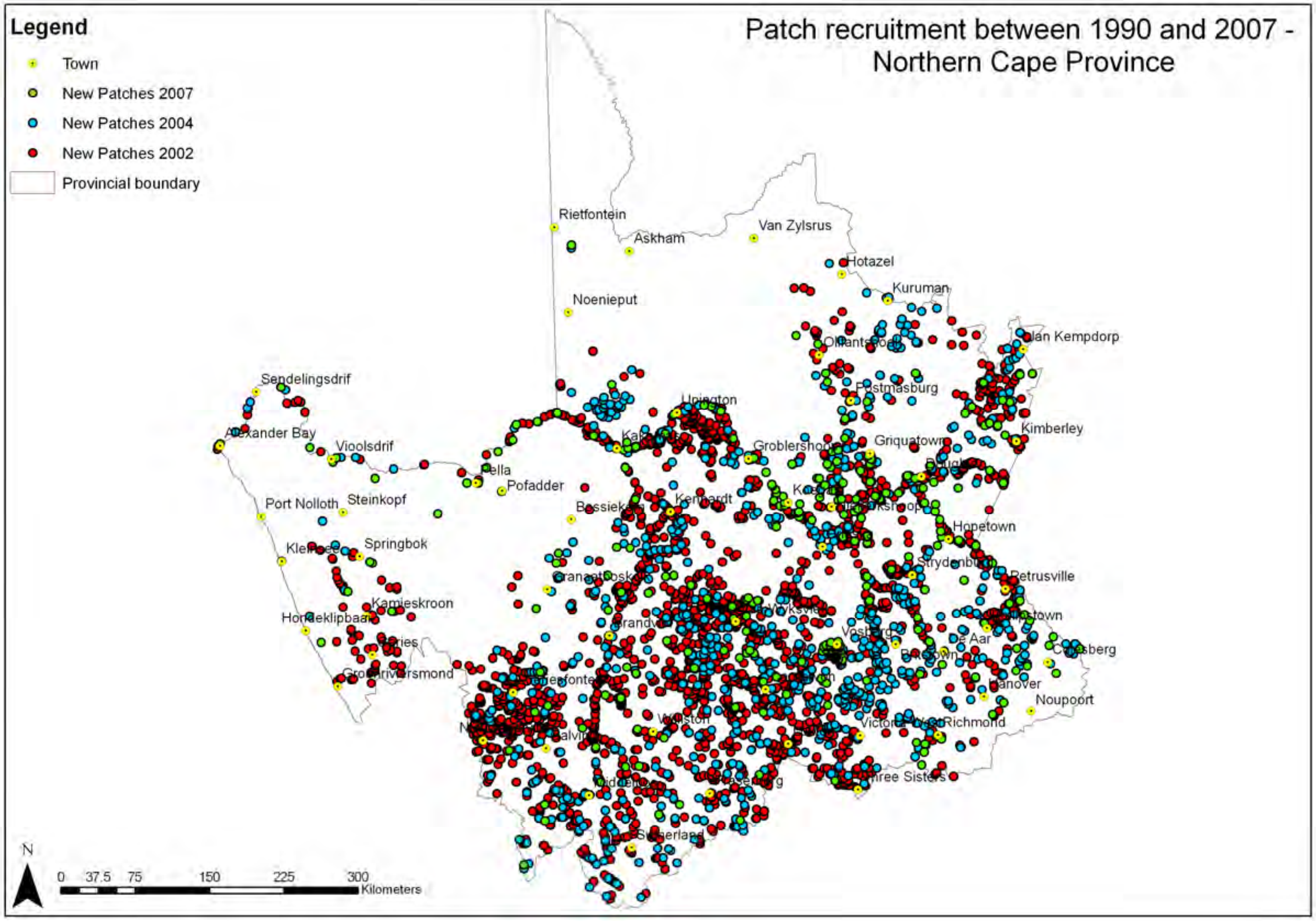
Appendix 17: Map of the extent and densities of *Prosopis* in 2007 for the Northern Cape Province. (Details can be seen on attached CD-Rom)



Appendix 18: *Prosopis* infestation per quaternary catchment in 2007 for the Northern Cape Province.



Appendix 19: Prosopis patch recruitment between 1990 and 2007 for the Northern Cape Province.



Appendix 20: Percentage *Prosopis* invasion of vegetation types in 2007 for the Northern Cape Province.