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Environmental Factors and Management Options for *Prosopis* Invasive Species: A Case Study in Botswana's Kgalagadi District



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Samuel Mosweu

Thesis submitted for the degree Doctor of Philosophy in Environmental Science at the Mafikeng Campus of the North-West University

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STATEMENT OF ORIGINALITY

This thesis presents research work undertaken and completed between January 2009 and June 2012 under the research permit number A34/6 XII (36) DPS (LS) issued by the Ministry of Agriculture in Botswana. This is original work except where due reference is given. It has not been and shall not be submitted for the award of any degree or diploma at any other institution of higher learning.

Author's Signature: _____ Date: 05/09/2012

ABSTRACT

Various species of *Prosopis* originate from South America, Central America and the Caribbean where they serve as major plant resources that provide raw materials for shelter as well as fodder and fuel wood in arid and semi-arid environments. Colonial administrators and seamen were responsible for the introduction of *Prosopis* species into the African continent. The introduction of the species in Africa started in the West African region around 1822, and into other parts of Africa including South Africa around 1880 and Botswana around 1980. The principal objective of the introduction of *Prosopis* species in various areas around the world including Botswana was to mitigate the environmental impacts of desertification and to harness a rapidly growing and robust fuel wood and fodder species that is capable of enduring environmental adversities. Most communities living in the areas where *Prosopis* has been introduced initially welcomed the species until the invasion of the species and its negative environmental impacts became prominent in their areas.

In Bokspits, Rappelspan, Vaalhoek and Struizendam (BORAVAST) villages located in the Kgalagadi Districts in Botswana, the introduction of the species was welcomed until around the year 2000 when the invasive impacts of the species on the environment and the livelihoods of the communities became evident. Since then, the communities living in the area have been in need of a solution to the invasion of *Prosopis*. Therefore, the aim of this thesis was to investigate the scale or spatial extent of the invasion of *Prosopis*, and environmental factors associated with the distribution of the species; and propose sustainable management options that could be implemented to control its spread in Botswana using a case study of the BORAVAST villages in Botswana's Kgalagadi District.

To study the interactions between *Prosopis* species and soil characteristics in the study area, the gradsect method was used to obtain data on the soils and vegetation characteristics. Vegetation sampling was conducted in 42 quadrats of 25 m x 25 m (625 m^2) and sub-quadrats of 5 m x 5 m (25 m^2) were used for sampling small shrubs. The quadrats were located along a transect established in the Nossob-Molopo riparian zone from Struizendam to Rappelspan. The plant canopy cover, plant height, species density and composition were determined. Soil samples were collected at the centre of the quadrats at the depth of 0-20 cm and 60-80 cm under *Prosopis* tree canopies and in the interspaces. Soil samples were analysed for pH, EC, Ca, Mg, K, Na, total N and organic carbon.

To study the relationship between soil characteristics and the growth stage of *Prosopis* species, *Prosopis* trees were categorized into three classes on the basis of height and canopy size. Soil samples were collected at 0-10 cm soil depth under class 1, class 2 and class 3 *Prosopis* tree canopies and subjected to analysis of pH, EC, Ca, Mg, K, Na, total N and organic carbon. *Prosopis* soil seed bank was investigated in the study area by obtaining soil samples at 0-5 cm and 5-10 cm soil depth under *Prosopis* tree canopies and in the interspaces followed by the determination of the number of *Prosopis* seeds in the soil samples. A questionnaire survey coupled with focused group discussions was used to obtain data on the perceptions of the communities about *Prosopis* species in the study area.

The results showed that soil organic carbon ($F = 2.68$, $P = 0.05$, $\alpha = 0.05$) and soil pH ($F = 44.81$, $P < 0.001$; $\alpha = 0.05$) were statistically significantly different between the under canopy and the inter-canopy soils. Ca, Mg, K, Na and N did not show statistically significant differences in the soils. *Prosopis* species appeared to be dominant over other tree species in the study area. The strength of the relationships between the selected soil properties and the selected characteristics of *Prosopis* species ranged from no to moderate associations.

In the investigation of the relationship between soil characteristics and the growth stage of *Prosopis* species in the area, it was observed that soil pH and EC under class 3 *Prosopis* tree canopies were statistically significantly different from soil under class 1 and class 2 *Prosopis* tree canopies. Other selected soil attributes did not show significant differences in the soils.

A range of 47 to 1159 *Prosopis* seeds m^{-2} was observed in the study area. All sampling points were statistically significantly different in terms of soil seed bank ($P < 0.001$). The general distribution pattern of *Prosopis* seeds indicated that more seeds existed in the soil under *Prosopis* tree canopies in the 0-5 cm soil depth.

Anthropogenic activities contributed significantly in the spread of *Prosopis* species in the study area. Due to lack of resources, management of *Prosopis* species by the local communities was not systematic and effective. Therefore, an integrated management system in which exploitation or promotion of *Prosopis* products, biological, mechanical and chemical control options are applied on a case based approach was recommended for *Prosopis* control in the study area. The study concluded that the distribution of the investigated soil attributes did not influence *Prospopis* species distribution in the study area. On the contrary, the pattern of *Prospopis* species distribution affected the distribution of the soil properties. There were no associations between the growth stage of *Prosopis* trees, particularly tree height and capony size, and the investigated soil properties in the study area. Athropogenic activities, accumulation of *Prosopis* seeds under *Prosopis* tree canopies, rapid and prolific seeding appeared to be the main factors that facilitated the invasion of *Prosopis* species and influenced its distribution pattern in the study area.

CHAPTER ONE: This chapter provides an introduction to this study. It outlines the statement of the research problem, research aim, specific research objectives, research questions and the description of the study area. In addition, various legal frameworks that regulate the management of natural resources are briefly discussed in relation to *Prosopis* management.

CHAPTER TWO: An in depth literature review on *Prosopis* species is covered in this chapter. The general description of *Prosopis* genus and its taxonomy is provided. The general distribution and patterns of the introduction of the species into different regions of the world including Botswana are outlined. The significance of *Prosopis* species as both a natural resource and an environmental nuisance is also reviewed. The general perceptions of communities about *Prosopis* invasion, and the previous research work on *Prosopis* with regard to the study area are considered in this chapter. The chapter closes with a review of the environmental aspects and research techniques upon which research methods used in this project were premised.

CHAPTER THREE: This chapter outlines details on the methods, strategies and procedures used in data collection, sample collection, sample and data analyses in this study. The methods, strategies and procedures outlined are related to soils, vegetation, soil seed bank and the perceptions of the communities about *Prosopis* in the study area.

CHAPTER FOUR: The results of the study are outlined in this chapter. Graphs, charts, pictures, Tables, Figures and maps are used as illustrations that summarize data. Results from the study of soils, vegetation, seed bank and the perceptions of the communities are presented in this chapter. Detailed analyses of the results covering

various phenomena, multiple comparisons and correlations are presented in this chapter.

CHAPTER FIVE: This chapter provides a synthesis of the results presented in chapter four. There is a discussion on the invasion of *Prosopis* in relation to edaphic factors and anthropogenic activities. The spatial aspects of *Prosopis* invasion and management options are covered in this chapter. Finally, the chapter proposes a management system that is considered applicable for the control of *Prosopis* in the study area.

CHAPTER SIX: This chapter presents conclusions and recommendations drawn from this study.

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LIST OF ACRONYMNS

AAS	Atomic Absorption Spetrophotometer
BORAVAST	Bokspits, Rappelspan, Vaalhoek, and Struizendan
CBNRM	Community Based Natural Resources Management
CBO	Community Based Organization
CSO	Central Statistics Office
CAR	Centre for Applied Research
DEA	Department of Environmental Affairs
DFRR	Department of Forestry and Range Resources
DMM	Department of Ministry Management
DMS	Department of Meteorological Services
DNMM	Department of National Museum and Monuments
DSM	Department of Surveys and Mapping
DWMPC	Department of Waste Management and Pollution Control
DWNP	Department of Wildlife and National Parks
DOT	Department of Tourism
EIA	Environmental Impact Assessment
IVPBOT	Indigenous Vegetation Project of the Ministry of Agriculture and United Nations Development Program - Botswana
VDC	Village Development Committee
MIST	Ministry of Infrastructure, Science and Technology
MLG	Ministry of Local Government
MMEWR	Ministry of Mineral, Energy and Water Resources
MOA	Ministry of Agriculture
MTI	Ministry of Trade and Industry
MEWT	Ministry of Environment, Wildlife and Tourism
NGO	Non Governmental Organization
PHC	Population and Housing Census

Chapter 1

INTRODUCTION

1.0 Introduction

The invasion of *Prosopis* Linnaeus emend. Burkart (common name, Mesquite) continues to affect millions of hectares of rangelands in Africa, Australia and coastal Asia (Pasiecznik, 1999). The Nossob-Molopo River banks and the surrounding rangelands in Botswana, Namibia and South Africa are among the most affected areas in southern Africa. Communities living along the Nossob-Molopo River banks are negatively affected by the environmental impacts of *Prosopis* species invasion. Bokspits, Rappelspan, Vaalhoek, and Struizendan (BORAVAST) are amongst the villages that experience hostile environmental impacts associated with the invasion of *Prosopis* species in Botswana.

Data collected from the BORAVAST communities indicated that the then Department of Land Use which was under the Ministry of Agriculture introduced *Prosopis* species in the area between 1987 and 1989 (Centre for Applied Research (CAR), 2004; Timberlake, 1980). As it is the case with most areas where *Prosopis* species have been introduced, here too the objective was to stabilize sand dunes and to provide shade in homes (CAR, 2004). In spite of the availability of data indicating that *Prosopis* species were already a cause for concern in South Africa and Namibia (Van Wyk & Van Wyk, 1997), government officials recommended the utilization of the species for purposes of mitigating problems associated with soil erosion and supplementing fodder reserve (Timberlake, 1980). Furthermore, it is suspected that *Prosopis* species were introduced into the area from Namibia through the Nossob-Molopo River back in the years when it used to flow (CAR, 2004).

Over the past two to three decades, communities living in the

BORAVAST villages have observed a significant change in vegetation from the open arid savanna to bush thickening deciduous vegetation which is dominated by *Prosopis* species. The negative environmental impacts emanating from the invasion of *Prosopis* species in the BORAVAST villages have compelled the communities and the Community Resources Management Trust of the villages to recognize the need to establish a sustainable management strategy for the control of the species in their area.

1.1 Statement of the Research Problem

Over the years, *Prosopis* has continued to invade millions of hectares of rangelands in Africa, Australia and coastal Asia (Pasiecznik, 1999). In Botswana and South Africa, the Nossob-Molopo River banks and the surrounding rangelands constitute a hotspot of the invasion of *Prosopis*. The species have successfully colonised these areas forming dense thorn bushes. The invasion of *Prosopis* species has been associated with both negative and positive environmental impacts in the BORAVAST area. The negative impacts included depletion of underground water resources, clogging of boreholes, serious degradation of rangelands, while the positive impacts included improvement in the availability of fodder resources, fencing material, and fire wood. The scale of *Prosopis* invasion in the BORAVAST area has reached a level that warrants concern from the local communities and researchers.

1.2 Research Hypothesis

The research hypothesis was:

The invasion by *Prosopis* species occurs in the BORAVAST area irrespective of edaphic factors.

1.3 Research Aim

The aim of the research was to investigate the scale or spatial extent of the invasion of *Prosopis,* and environmental factors associated with the distribution of the species; and propose sustainable management options that could be implemented to control its spread.

1.4 Specific Objectives

I. To investigate the scale or spatial extent of the invasion of *Prosopis* species in the BORAVAST area.

II. To investigate the association between selected soil factors and the distribution of *Prosopis* species in the BORAVAST villages.

III. To assess the relationship between growth stage of *Prosopis* trees and selected soil properties.

IV. To investigate *Prosopis* soil seed bank in the study area and establish its relationship with the distribution of the species.

V. To examine the perceptions of the BORAVAST communities about *Prosopis* and assess the significance of the perceptions on the invasion and management of *Prosopis*.

VI. To propose sustainable management options that should be implemented in the control of *Prosopis* species.

1.5 Research Questions

1 What is the scale or spatial extent of the invasion of *Prosopis* species in the BORAVAST area?

2 What are the associations between soil factors and the distribution of *Prosopis*?

3 What are the relationships between the soil factors and the growth stages of *Prosopis* trees?

4 What is the pattern of *Prosopis* soil seed bank, and how does it relate to the distribution of *Prosopis* trees?

5 What are the perceptions of the BORAVAST communities about *Prosopis*?

6 What are the possible sustainable *Prosopis* management options that can be implemented to control *Prosopis* species?

1.6 Description of the Study Area

1.6.1 Climate

The study area is located in the driest part of Botswana (Figure 1.1). The mean annual rainfall in the Kgalagadi south is 300 mm (**Figure 1.2**) and the rainy season is characterized by erratic rainfall pattern (Bhalotra, 1985). The period starting from November to April marks the season during which the area experiences about 80 per cent of the precipitation. The study area experiences very high temperatures in summer which may reach up to over 40 ^{0}C, while the winter temperatures are normally between 2 to 4 ^{0}C (Timberlake, 1980). Daily temperatures that are below freezing point are commonly recorded in the area during winter seasons. Generally, the area experiences high mean annual temperatures (**Figure 1.3**).

1.6.2 Geology

The study area is situated on the Kgalagadi sand formation which is constituted by approximately 2.5 million km^2 of land surface area that stretches from the Orange River in South Africa to approximately one degree north of the Equator in the Democratic Republic of the Congo

(DRC) (Cooke, *et al.*, 1993). Parts of the Kgalagadi sand formation cover Botswana, South Africa, Zimbabwe, Angola, Namibia and DRC (Cooke, *et al.*, 1993). Mabbut (1977) indicated that the sand that has formed from the underlying calcareous sandstones ranges in thickness from 2 m to 100 m and it can be dated back to the late Cretaceous and the early Tertiary geological periods.

1.6.3 Topography

The study site is located in the southern Kgalagadi District in Botswana (Figure 1.4) which lies within the Kgalagadi Desert: a vast area covered of sand stretching from the western to the central part of Botswana. The Kgalagadi is mainly undulating plains with interspersed pans, rocky outcrops, dry river valleys and dune fields (Cooke, *et al.*, 1993). The study area is dominated by longitudinal dunes and some Barchan dunes (Lancaster, 1978a & 1978b; Cook, *et al.*, 1993). The former are long sand ridges which were formed parallel to the prevailing direction of wind at the time of their morphology, while the later are half-moon dunes with open ends on the windward faces (Lancaster, 1978a & 1978b). The inter-dune areas are predominantly sandy with underlying calcrete which is exposed in some areas leading to some patches of calcareous regosols (Lancaster, 1978a & 1978b; Cooke, *et al.*, 1993).

The Nossob-Molopo River valley that is found in the area is believed to have been part of the Orange River system (Cooke, *et al.*, 1993). The sand stone and quartz comprise the rocky outcrops in the Kgalagadi with calcrete dominating the riparian zones along the Nossob-Molopo River. Additionally, Lancaster (1978a, 1978b) noted that the Kgalagadi basin presents an area with highest pan density of one pan per 22 km^2 and some of these pans are located in the study area.

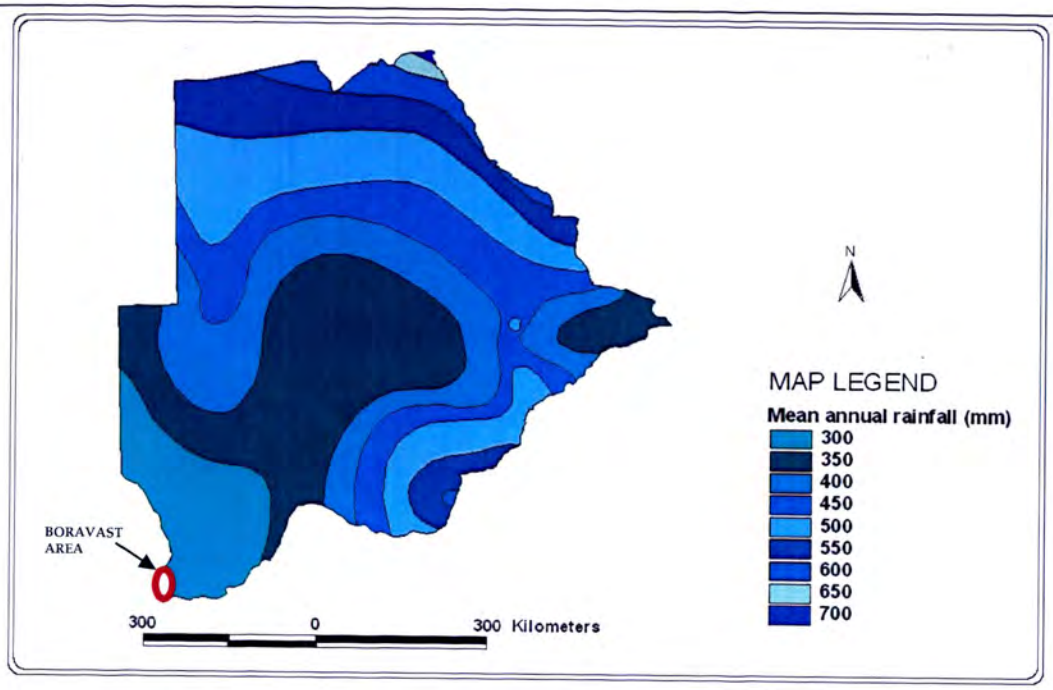


Figure 1.1 Mean Annual rainfall in Botswana showing that the BORAVAST area is in the driest region of the country (*Source: Department of Meteorological Services*).

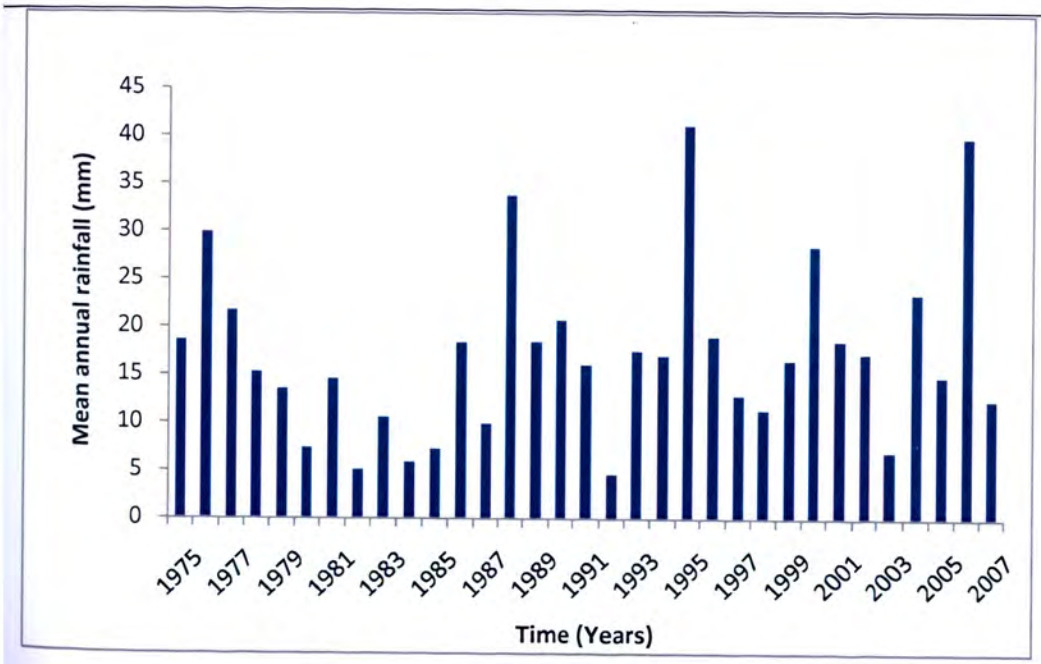


Figure 1.2 Mean annual rainfall in the study area (*Source: Department of Meteorological Services).*

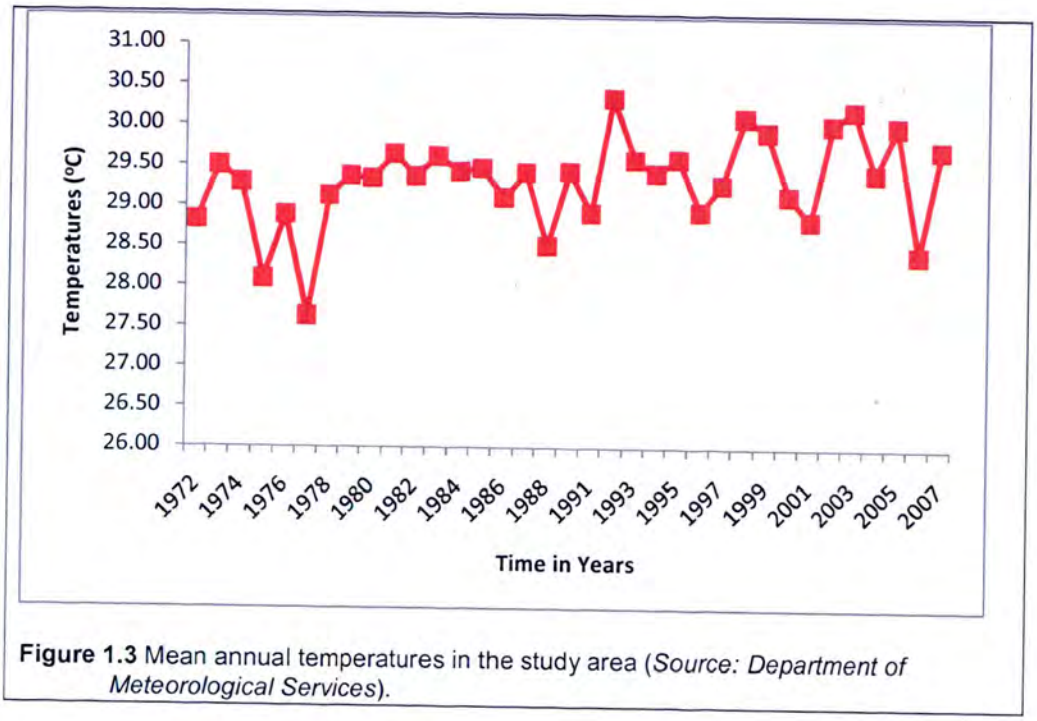


Figure 1.3 Mean annual temperatures in the study area (*Source: Department of Meteorological Services*).

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1.6.4 Soils

The Kgalagadi soils that characterize the study site are mainly aridisols according to the Soil Survey Staff of USDA (1999). Like other dry zones of the world, aridisols in the study area are associated with areas of shifting sand dunes. Soil formation in such active dune sand is minimal until the dune is colonized by vegetation. In places where the sand is stable, some humus accumulates in the surface soil and shallow, ochric surface horizon develops. Red, pink and white sand exists in the Kgalagadi area (Leistner, 1967). The process of ferrugination through which quartz or quartzite grains are coated by goethite causes the reddish colour of the soil (USDA, 1975). Mechanical abrasion and changes in the soil moisture content causes the coating to fade away resulting into pink and then white or light gray colour (Timberlake, 1980). White sand is commonly found in pans and river valleys (Lancaster, 1978a & 1978b).

1.6.5 Vegetation

The general vegetation cover of the Kgalagadi area shows a gradual change from open tree savanna to shrub savanna in the south west to the dense woodland or forest in the north (Cooke, *et al.*, 1993). Plant distribution patterns follow a gradient of precipitation. Generally, open tree and grass savanna with sparse cover of tussock grasses characterizes the study site. *Acacia erioloba, Acacia haematoxylon, Rhigozum trichotomum, Lycium namaquense, Monechma incanum, Prosopis chilensis, Prosopis velutina, Prosopis juliflora, Prosopis glandulosa,* hybrids of *P. juliflora* and *P. glandulosa, P. Juliflora* and *P. pallida, P. chilensis* and *P. glandulosa, P. glandulosa* and *P. pallida,* and *P. juliflora* and *Acacia karroo* comprise the main trees and shrubs found in the Molopo and Nosob River valley, the pans, surrounding rangelands and settlements (Leistner, 1967; Muzila *et al.*, 2011). *Schmidtia pappophoroides* and *Eragrostis* species are the main grass species found in the study site (Leistner, 1967). The interdune areas in the study site are normally characterized by *Acacia erioloba* and some perennial grass species which include *Stipagrostis ciliate, Stipagrostis obtuse, Stipagrostis uniplumis, Schmidtia pappophoroides* and *Asthenantherum glaucum.* Other grass species that grow in the interdune areas during rainy seasons include *Aristida congesta, Schmidtia Kgalagadiensis* and *Tribulus zeyheri* (Leistner, 1967). The dunes have a very sparse distribution of shrubs of *Acacia haematoxylon, Boscia albitrunca,* and *Acacia mellifera* with *Stipagrostis amabilis* which is a sand binding grass species (Leistner, 1967).

1.6.6 Land Use

The Kgalagadi area is well known as a desert that presents drastic challenges to both human and wild life, particularly due to lack of potable water resources. However, some animals which have adapted to the Kgalagadi environmental conditions inhabit the study area. These include gemsbok, wildebeest, eland, steenbok, kudu and others. The San are the people who are known as the first inhabitants of the Kgalagadi area in

Botswana (Lee & De Vore, 1976). The Kgalagadi people were mostly nomadic hunters and gatherers and depended on sip holes for water (Devitt, 1971) until they ceased their nomadic life by the end of the first quarter of the 20th century after the advent of pit wells and advanced underground water extraction technologies. The main land use types in the BORAVAST area include farming at commercial and subsistence levels, residential and commercial plots. Governmental institutions and non-governmental institutions have also been allocated some land in the area.

1.6.7 Demography

Population and Housing Census (PHC) Report of Botswana (2001) projections indicated that the projected changes in the population of the Kgalagadi South area under which the BORAVAST villages fall are small. The populations of villages close to the BORAVAST area like Gachibana and Bray were projected to change from 501 and 899 in 2001 to 539 and 968 respectively in 2011 (Central Statistics Office (CSO), 2005). Projections for the villages that are considered in this study are not covered in the PHC report. However, the 2001 census data for the villages is shown in Table 1.1.

Table 1.1 Population Census of the villages for 2001.

Village	Population	Male	Female
Bokspits	576	293	282
Rappelspan	458	230	228
Vaalhoek	346	167	179
Struizendam	313	147	166

(Source: Central Statistics Office (CSO), 2001)

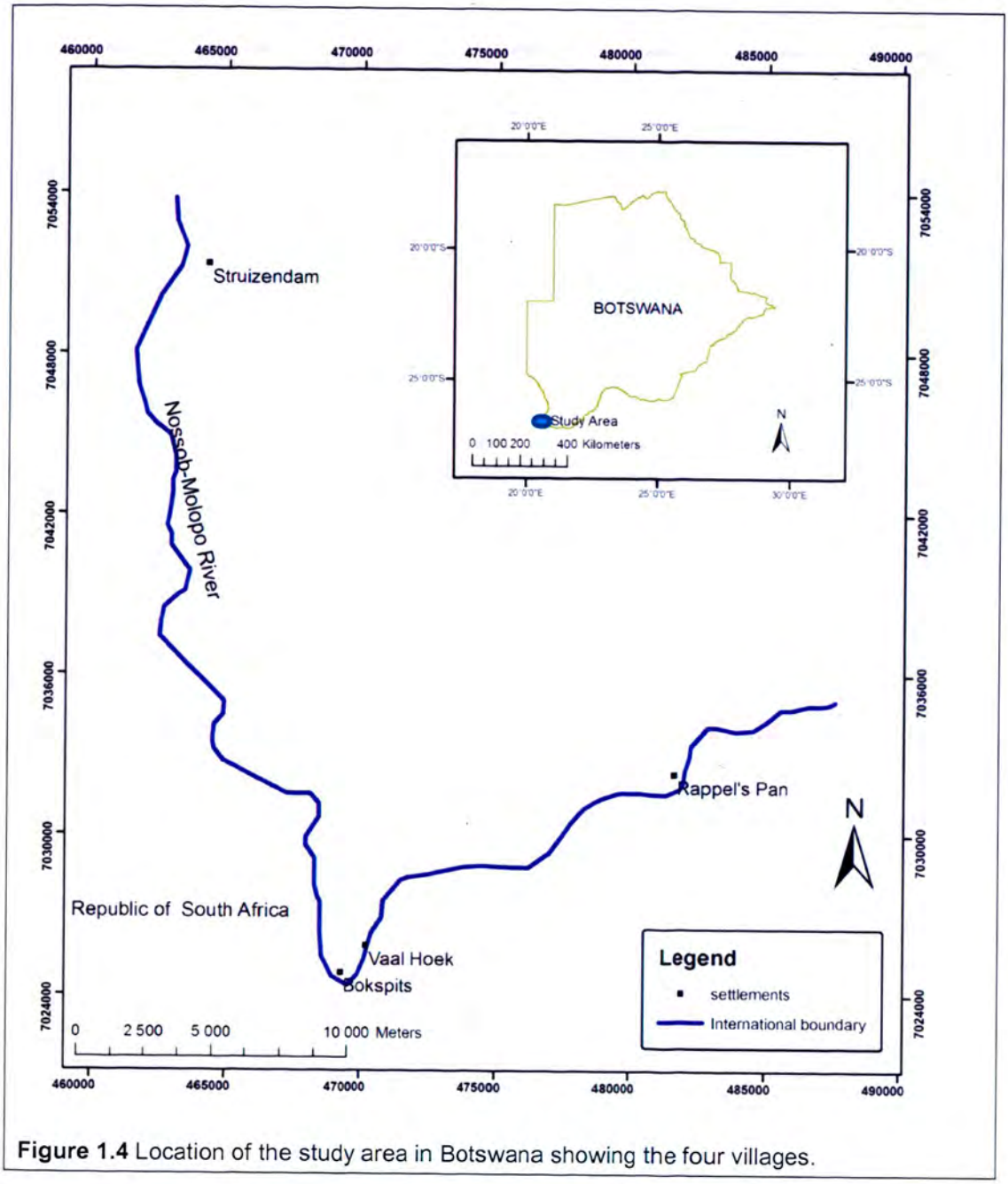


Figure 1.4 Location of the study area in Botswana showing the four villages.

1.7 Relevant Regulatory and Administrative Frameworks and Policies

Various legal frameworks that regulate the management of natural resources at the national and international levels have a direct bearing on the management of *Prosopis* species in the study area. The relevance of the main policies, Acts and regulations to the management of *Prosopis* species is briefly discussed below-:

Agrochemicals Act (CAP 35:09 of 2000): The Act provides for the matters relating and incidental to the registration and licensing of agrochemicals, control or regulation of their importation, manufacture, distribution, use and disposal in order to prevent pollution to the environment or harm to human, plant or animal life. This Act is very important as it needs to be considered in the assessment and selection of the potential agrochemicals that can be used in controlling the invasion of *Prosopis* in the study area.

Agricultural Resources Conservation Act (CAP 35:06 of 1974): The Act provides for the conservation and improvement of agricultural resources in the country and also provides for matters incidental to the foregoing. *Prosopis* plant species constitute important source of fodder in the study area. Consequently, implementation of the management strategies proposed in this study should not violate the guidelines stipulated in the Act.

Forestry Act (CAP 38:05 of 1976): The Act gazetted forest reserves, protected trees and the control of forest products. The use of timber products from *Prosopis* trees is subject to this Act. Therefore, the guidelines in the Act should be considered are to be considered in the production of fire wood from *Prosopis* trees.

Noxious Weeds Act (CAP 35:04 of 1916): This Act guides the eradication

and destruction of noxious weeds in Botswana. It is therefore important to observe this Act in cases or areas where eradication is considered a better option in controlling *Prosopis* species.

National Conservation Strategy (1990): The Act provides for the conservation of natural resources including soils, vegetation, water, and wildlife and includes guidelines for their sustainable use. It is essential that this Act is taken on board in considering management options for *Prosopis* species.

Herbage Preservation Act (CAP 38:02 of 1978): This Act requires all persons to obtain permission from the Herbage Preservation Committee to set fire to any vegetation on land of which one is not the owner or lawful occupier. The Act is very important in this study especially in cases where fire use is considered the best alternative in controlling *Prosopis* species.

Tribal Land Act (Amended 1993): This study involves investigation of *Prosopis* plant invasion in the tribal land. Therefore, it is one of the Acts that should be considered in this study as it provides for the regulation of all tribal land areas in Botswana.

National Policy on Natural Resource Conservation and Development (1990): This policy is intended to ensure conservation and sustainable use of natural resources. The current study deals with *Prosopis* species which form part of natural resources existing in the study area. It is therefore imperative to note guidelines in this policy that may relate to the implementation of management methods selected to control *Prosopis* species in the study area.

Botswana National Policy on HIV/AIDS (1993): This national policy on HIV/AIDS prevention and care outlines the national response to the epidemic in Botswana. It describes the role of national leaders, various

government ministries, the private sector, non-governmental and community-based organizations, persons living with HIV/AIDS, and individual community members, in the national response. The policy forms the basis on which a national strategic plan is premised. Within the national strategic plan, different ministries and organizations are required to formulate their sectoral plans and projects for implementation. The policy is used to guide all actors in HIV/AIDS prevention and care, including government ministries at policy-making and operational levels, non-governmental and community organizations, parastatals and private sector organizations and enterprises, and members of the community. HIV/AIDS epidemic is a crosscutting issue that particularly affects the livelihoods of poor rural communities. Therefore, it is very important to consider this policy in the implementation of methods recommended for the control of *Prosopis* species in the study area.

Convention on Biological Diversity (1992): This is an international convention that promotes conservation and sustainable use of biological diversity. Botswana subscribes to the values of this convention, and the Department of Environmental Affairs is the body that is entrusted with the responsibility of implementing the objectives of this convention in the country. Conservation and sustainable use of biological diversity is the core of this study. Thus, matters associated with this international convention warrant consideration in the implementation of the recommendation emanating from this research work.

Chapter 2

LITERATURE REVIEW

2.0 Introduction

This chapter presents a review of existing information related to this study. The review covers the characteristics, spatial distribution, usages, environmental impacts and control of *Prosopis* species. Previous studies on *Prosopis* species conducted in Botswana prior to the current one were also reviwed. The chapter ends with a literature review on the research methods that were used as the basis for designing methods used in this study.

2.1 General Characteristics of *Prosopis*

Prosopis Linnaeus emend. Burkart genus belongs to the family Leguminosae (Fabaceae), sub-family Mimosoideae (Pasiecznik, 2001). General features of *Prosopis* species, according to Burkart (1976) are outlined in Table 2.1. The best known and most widely spread *Prosopis* species is *Prosopis juliflora* (Pasiecznik, 1999; Pasiecznik, 2001). Burkart (1976) described *Prosopis* species as trees or shrubs of various sizes which are primarily xerophilous, aculeate, and spiny. Burkart (1976) compiled taxonomy of the *Prosopis* genus (Table 2.2) which included 44 *Prosopis* species and a number of varieties.

Most species of *Prosopis* originate from South America, Central America and the Caribbean where they serve as major plant resources that provide raw materials for shelter as well as fodder and fuel wood in arid and semi-arid environments (Mwangi & Swallow, 2005; Laxén, 2005). The species are famous for their rapid growth and their resilience under harsh arid and semi-arid environments (Harsh, *et al.*, 1996; Pasiecznik, 2001).

They have the capacity to assimilate and store nutrients and moisture in their root systems and as a result, they usually have relatively large root mass (Felker & Clark, 1981; Pasiecznik, 1999). *Prosopis* species are aggressive pioneers which predominate over indigenous flora wherever they are introduced and they are considered weeds in many areas (Pasiecznik, 2001; Diagne, 1996).

Table 2.1 General characteristics of *Prosopis* species (adapted from Burkart, 1976).

Attribute	Description
Leaves	Bipinnate with few pairs of opposite pinnae
Leaflets	Numerous, small, mostly opposite, linear, oblong, fusiform, entire , same colour on both sides
Venation	Pinnate, not very prominent
Petioles	Circular, sessile, apical glands
Flowers	Small, actinomorphic, pentamerous and Hermaphroditic
Aestivation	Valvate and the calyx iscampanulate
corolla	Fused or more or less free linear petals, glabrous or pubescent, frequently villous or pilose inside the tip
androecium	5+5 free stamens
Anthers	Elliptic, dorsifixed, introrse, with an apical, pedicellate, globose or ovoid connectival gland
Pollen grains	simple, isopolar, tricolporate, sub-spheroidal to prolate
ovary	Stipitate, villous or sometimes glabrous. Racemes are spike-like, amentiform, axillary, mostly densiflorous
Shoots	Dimorphic, long megablasts, flexuous
Fruit	Indehiscent, fleshy legume linear, straight, falcate, annular to spirally coiled with a fleshy sugary or fibrous mesocarp containing endocarps, divided into one-seeded, coriaceous to bony segments.
Seeds	Ovoid, hard, brown, with a mucilaginous endosperm, with a fissural line on the faces (pleurogram).

2.2 The General Spatial Distribution of *Prosopis* Species

The range of *Prosopis* species covers arid and semi-arid regions in Africa, Asia, Central, Northern and Southern regions of America (Pasiecznik, 2001). The world distribution map of *Prosopis* species (Figure 2.1) presented by Burkart and Simpson (1977) indicates that a larger proportion of *Prosopis* species are intrinsic to the continent of America.

Table 2.2 Taxonomy of the genus *Prosopis* Linnaeus emend. Burkart (adapted from Burkart, 1976).

I. Section *PROSOPIS*
- (1) *P.Cineraria* (L.) Druce
- (2) *P. farcta* (Solander ex Russell) MacBride
  - var. *farcta*
  - var. *glabra* Burkart
- (3) *P. Koelziana* Burkart

II. Section ANONYCHIUM
- (4) *P. Africana* (Guill., Perr. & Rich.) Taubert

III. Section STROMBOCARPA

Series Strombocarpae
- (5) *P. strombulifera* (Lam.) Bentham
  - var. *strombulifera*
  - var. *ruiziana* Burkart
- (6) *P. reptans* Bentham
  - var. *reptans*
  - var. *cinerascens* (A. Gray) Bentham
- (7) *P. abbreviate* Bentham
- (8) *P. torquata* (Cavanilles ex Lagasca) DC.
- (9) *P. pubescens* Bentham
- (10) *P. palmeri* S. Watson
- (11) *P. burkatii* Muñoz

Series Cavenicarpae
- (12) *P. ferox* Grisebach
- (13) *P. tamarugo* F. Philippi

IV. Section MONILICARPA
- (14) *P. argentina* Burkart

V. Section ALGAROBIA
- (15) *P. sericantha* Gillies ex Hooker & Arnott
- (16) *P. kuntzei* Harms

Series Ruscifoliae
- (17) *P. ruscifolia* Grisebach
- (18) *P. fiebrigii* Harms
- (19) *P. vinalillo* Stuckert
- (20) *P. Hassleri* Harms
  - Var. *hassleri*
  - Var. *nigroides* Burkart

Series Denudantes
- (21) *P. denudans* Bentham
  - Var. *denudans*
  - Var. *patagonica* (Spegazzini) Burkart
  - Var. *stenocarpa* Burkart
- (22) *P. ruizleali* Burkart
- (23) *P. castellanosii* Burkart
- (24) *P. calingastana* Burkart

Series Humiles
- (25) *P. Humilis* Gillies ex Hooker & Arnott
- (26) *P. rojasiana* Burkart

Series Pallidae
- (27) *P. rubriflora* E. Hassler
- (28) *P. campestris* Grisebach
- (29) *P. pallid* (Humbaldt & Bonpland ex Willd.) H.B.K
- (30) *P. affinis* Sprengel
- (31) *P.articulata* S. Watson
- (32) *P. elata* (Burkart) Burkart
- (33) *P. tamaulipana*

Series Chilenses
- (34) *P. chelensis* (Molina) Stuntz emend. Burkart
  - Var. *chilensis*
  - Var. *riojana* Burkart
  - Var. *catamarcana* Burkart
- (35) *P. juliflora* Swartz DC.
  - Var. *juliflora*
  - Var. *inermis* (H.B.K.) Burkart
  - Var. *horrid* (Kunth) Barkart
- (36) *P. nigra* (Grisebach) Hieronymus
  - Var. *nigra*
  - Var. *ragonesei* Burkart
  - Var. *longispina* Burkart
- (37) *P. caldenia* Burkart
- (38) *P. laevigata* (Humbodt & Bonpland ex Willd.)
- (39) *P. flexuosa* DC.
  - Forma *subinermis* (Burkart)
- (40) *P. glandulosa* Torrey
  - Var. *glandulosa*
  - Var. *torreyana* (Benson) Johnson
  - Var. *prostrate* Burkart
- (41) *P. alpataco* R.A. Philippi
- (42) *P. alba* Grisebach
  - Var. *alba*
  - Var. *panta* Grisebach
- (43) *P. velutina* Wooton
- (44) *P. pugionata* Burkart

NWU

Prosopis species found in Asia are native to the Middle East and they cover an area extending from east to India, west to Algeria and north to Georgia and Turkmenistan (Figure 2.1). *Prosopis africana* is indigenous to the Sudano-Guinean zone and neighbouring areas of Africa, stretching from Senegal in the west to Sudan and Kenya in the east. Pasiecznik (2001) pointed out that deliberate introduction and other human influences have extensively altered the distribution of *Prosopis* species over the last 500 years.

2.3 *Prosopis* Species as a Natural Resource

Introduction of different species of *Prosopis* has been undertaken in various countries with the primary aim of combating desertification and to improve fodder resource quality and quantity in arid and semi-arid regions (Timberlake, 1980; Diagne, 1996; Pasiecznik, 2001; El Fadl & Luukkanen, 2003). Most communities in the villages and settlements of various countries where *Prosopis* has been introduced initially welcomed



Figure 2.1 Approximate spread of introduced *Prosopis* species by the year 2000 (*grey*), and approximate natural distribution at 1500 (*black*) (Source: Pasiecznik, *et al.*, 2003).

the species until the invasion of the species and its negative environmental impacts became noticeable in their areas (Mwangi & Swallow, 2005); *P. juliflora* was appreciated as valuable fuel wood resource and marker of field boundaries (Binggeli, 2001) during its early years of introduction into the province of Rajasthan in India. Community members later rejected the species after experiencing undesirable environmental impacts caused by the invasion of the species. Although *Prosopis* species are frequently associated with the term 'invasive alien species' which most often than not is perceived to imply negativity, the species have been useful in diverse ways in many areas. Researchers like Varshney (1996) have concluded that, in spite of the perception that *Prosopis* is an alien invasive species in the arid and semi-arid regions of India, the benefits derived by the local communities from its presence by far outweigh the benefits that can be drawn from its absence. The significance of *Prosopis* species as a natural resource includes the following-:

a) ***Stabilization of sand dunes*** (illustrated in Plate 1)**:** *Prosopis* species have played a critical role in fighting desertification by preventing sand dune encroachment in arid zones (Mutsambiwa, *et al.*, 1998; El Fadl & Luukkanen, 2003).

b) ***Fuel energy resources*****:** India is one of the countries that consider *Prosopis* species as one of the valuable tree species of the arid lands (Mwangi & Swallow, 2005; Varshney, 1996). Varshney (1996) mentioned that, approximately 25 to 30 tons of biomass per hectare per year of *Prosopis* species may be produced at a short rotation age of 4 to 5 years. Wood from the species produces high quality calorific value and it burns well even when it is not dry (Mwangi & Swallow, 2005). The species also produce high quality charcoal (Pasiecznik, 2001).

c) ***Improvement of soil fertility:*** A study conducted by El Fadl (1997) showed that a significant improvement in soil texture and soil organic matter occurred under the *Prosopis* tree canopy, and that total nitrogen and available phosphorus were also higher under the tree canopy as compared to the inter canopy spaces. Therefore, *Prosopis* plants are able to form pockets of fertile islands which ultimately benefit other plant species in some areas (Archer, 1995; El Fadl, 1997).

d) ***Conservation of soil moisture:*** *Prosopis* species often tend to grow in bushy form with branches going down to the ground (Laxén, 2005; Pasiecznik, 2001). This nature of growth enables the species to reduce the above-ground surface temperature and soil erosion, favouring plant growth (Muthaiya & Felker, 1997).

e) ***Construction timber, shade and furniture wood:*** Because of the strong heartwood and its durability as a construction material, *Prosopis* timber is widely used for furniture manufacturing and as fencing post (Pasiecznik, 2001). Various *Prosopis* species provide good shade for both people and animals particularly in arid and semi-arid regions where big trees are scarce.

f) ***Feed and forage for grazing animals*:** Mexico, Brazil and Argentina are some of the countries where *Prosopis* pods are used as vital sources of livestock feed (Felker & Moss, 1996). Feeding trial results showed that rations of 60% ground *Prosopis* pods produced very good mass gain and milk production in dairy cattle, beef cattle, sheep, and goats (Abdel Gaabar, 1986). Consequently, *Prosopis* is used in many countries to reduce the cost of animal feed and mitigate shortage of fodder (Pasiecznik, 2001).

g) ***Food resources for humans:*** There are some *Prosopis* varieties which produce sweet pods (Pasiecznik, 2001). Mwangi and Swallow (2005) indicated that in countries like Peru, the pods are used as supplementary feed for humans because they have high protein and sugar content.

h) ***Honey production:*** *Prosopis* species play an important role in promoting the production of honey. One mature tree is able to produce as many as 630 000 to 980 000 flowers annually, availing the main raw material in the form of nectar for honey production (Felker, 1984).

i) ***Creation of employment:*** Gathering of *Prosopis* pods, production of charcoal from the species, production of honey undertaken at commercial scale in various countries have contributed significantly in employment creation (Pasiecznik, 2001). Mwangi and Swallow (2005) reported that in India, 200 metric tons of pods were collected and 300 000 bags of charcoal were manufactured by the Gujarat Agricultural University resulting in thousands of job opportunities being created for local communities.

j) ***Production of exude gums*:** A wounded *Prosopis* tree produces exude gums as a natural defence strategy. Under artificial utilization of exude gums, *Prosopis* trees may be stimulated to produce more exude gums by artificial wounding. The exude gum is soluble in water, and it is in liquid form when fresh with yellowish colour which darkens as it gets dry (Pasiecznik, 2001). The gum has been used as food and raw materials for the production of confectioneries, paint for skin, pottery, leather and a dye for baskets in North America (Felger, 1977). In the modern

world, *Prosopis* exude gum is used principally as food additive, emulsifier and thickener in food and pharmaceutical preparations, and as a raw material for producing adhesives (Vimal & Tyagi, 1986).

k) ***Production of fibres, tannins and dyes***: The bark of *Prosopis* contains approximately 14-16% catechol tannins (Doat, 1978). The tannin is used in leather production for tanning animal skin. For example, strong ropes were manufactured from roots of *Prosopis* in North America (Felger, 1977). In addition, a brown-purple dye produced from root extract is used for colouring cotton and other materials like baskets (Diaz Celis, 1995)

l) ***Medicinal use***: Various products from *Prosopis* species are used to cure diseases including universal pains, parasites and urinary diseases, mouth and throat infections, ulcers and bronchitis, dermatitis (Neuwinger, 1996).

2.4 *Prosopis* Species as Environmental Nuisance

In spite of the good attributes about *Prosopis* species (section 2.3), a number of communities inhabiting areas where the species grow around the world still perceive them as alien, invasive, noxious and a weed (Laxén, 2005). Pasiecznik (2001) noted that *P. juliflora* had been declared weedy in Venezuela and Colombia until the year 2000 and an alien invasive species in Sudan, Iraq, Pakistan, India, Australia, Carribbean, South Africa, western Africa, Eritrea and other countries. *Prosopis* species are notorious for their rapid and prolific seeding even under hostile conditions (Zimmerman, 1991).

The aggressive, invasive and allelophathic attributes of *Prosopis* species suppress growth in native plants (Mwangi & Swallow, 2005; CAR, 2004).

Consequently, invasion of *Prosopis* species has threatened the biodiversity in areas where they have been introduced. Some farmers in the countries where *Prosopis* invasion has occurred have complained about loss of their productive lands to the species (Mwangi & Swallow, 2005; Pasiecznik, 2001). Furthermore, *Prosopis* tap roots are able to reach a depth of 20 to 25 meters, and some *Prosopis* trees whose roots reached beyond this depth have been reported (Pasiecznik, 2001). The nature of their tap roots allows them to tap water from deep underground causing shortage of underground water by lowering the water table (Pasiecznik, 2001). This has caused drastic environmental problems to communities living in arid to semi-arid environments because a lot of them are dependent on underground water resources. Most *Prosopis* species have large thorns (Burkart & Simpson, 1977) which are often detrimental to people and farm equipment. In addition, there are claims that the species may cause some allergies and diseases in both livestock and wildlife (Silva, 1990; Mwangi & Swallow, 2005; CAR, 2004).

2.5 Introduction of *Prosopis* Species in Africa

Colonial administrators and seamen are responsible for the introduction of *Prosopis* species into Africa (Pasiecznik, 2001). The introduction of most *Prosopis* species started in Senegal in the West African region around 1822, and then Southern African region in South Africa around 1880 and Northern Africa in Egypt around 1900 (Diagne, 1996; Pasiecznik, 2001). It is generally believed that the introduction of *Prosopis* species into other African nations occurred in diverse ways from their neighbours (Pasiecznik, 2001). The principal objectives of the introduction of *Prosopis* species in various areas around the world including Africa have fundamentally remained the same: to mitigate the environmental impacts of desertification and to harness a rapidly growing and robust fuel wood and fodder species that are capable of tolerating climatic adversities such

as drastic arid and semi-arid conditions. Consequent to the introduction of *Prosopis* species in Africa and other areas, the species have aggressively invaded and continue to invade millions of rangelands (Pasiecznik, 1999; Pasiecznik, 2001). Due to the invasive nature of the species, they are widely declared weeds (El Fadl, 1997; Pasiecznik, 1999; Pasiecznik, 2001; Bokrezion, 2008).

2.6 Introduction of *Prosopis* Species in Botswana

The introduction of *Prosopis* species into southern Africa was marked by 23 seed lots which were brought from the USA, Hawai and Mexico to South Africa around 1897 to 1916 (Poynton, 1990). At their time of introduction, they were all called *P. juliflora* although they included a mixture of *P. juliflora, P. velutina* and some varieties of *P. glandulosa* (Pasiecznik, 2001). It is believed that the introduction of *Prosopis* species into Botswana originated from the *Prosopis* species that were introduced into South Africa as well as the species that were introduced into Namibia (Timberlake, 1980; CAR, 2004). Timberlake (1980) recommended trial use of *Prosopis* species in arid parts of Botswana to combat soil erosion and improve fodder reserve. Timberlake (1980) also noted that, although the species were already considered weeds in South Africa and Namibia, there was no sign that they were developing into weeds in Botswana. As a result, *Prosopis* species were introduced into many areas in the desert regions of Botswana including the BORAVAST villages mainly through the trial use of the species in combating soil erosion and improving fodder resource. However, it is also believed that some *Prosopis* species were introduced into Botswana through the Nossob-Molopo River during the years when it used to flow (Timberlake, 1980; CAR, 2004). Since the introduction of *Prosopis* species into Botswana, the species have colonized large areas of land in the country (Figure 2.2).

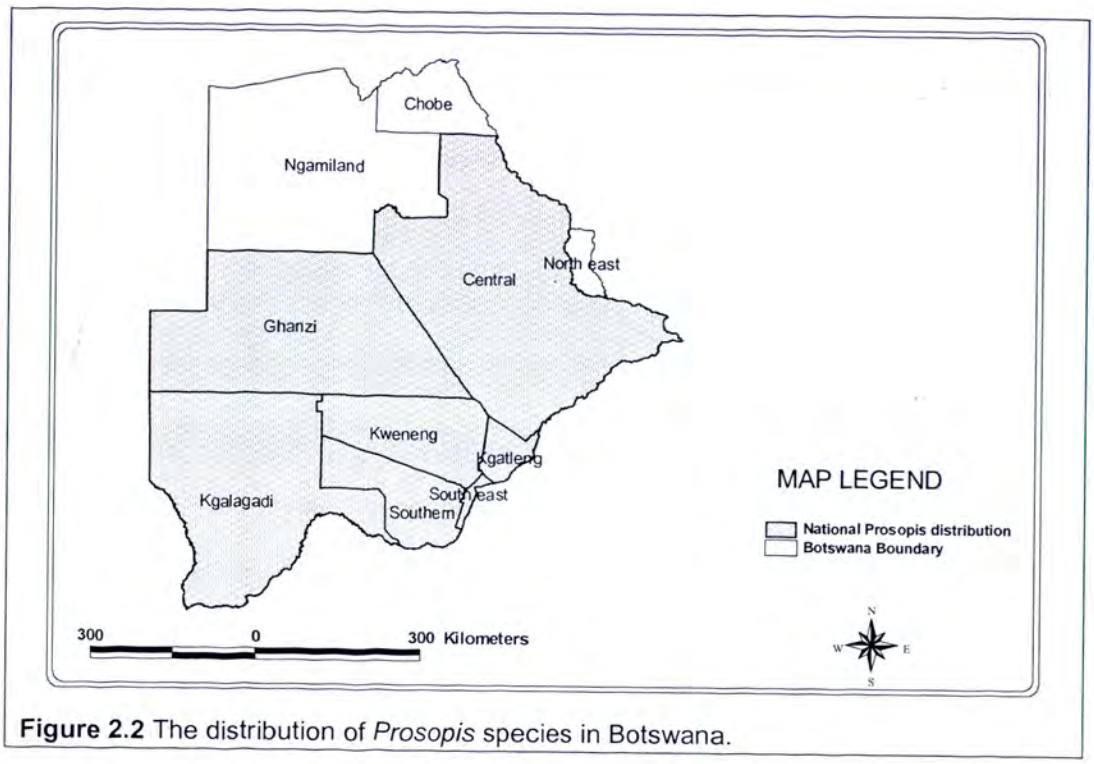


Figure 2.2 The distribution of *Prosopis* species in Botswana.

2.7 Previous Work Conducted in Botswana on *Prosopis* Species

There is paucity of work that has been conducted on *Prosospis* species in Botswana. However, Morapedi (2008) and Muzila, *et al.* (2011) conducted taxonomic studies on *Prosopis* species that grow in the Bokspits area in Botswana. The studies observed that four *Prosopis* species and five *Prosopis* hybrids existed in the area. The species identified in the area were *Prosopis chilensis, Prosopis velutina, Prosopis juliflora, and Prosopis glandulosa.* The identified hybrids were the products of *P. juliflora* and *P. glandulosa, P. Juliflora* and *P. pallida, P. chilensis* and *P. glandulosa, P. glandulosa* and *P. pallida,* and *P. juliflora* and *Acacia karroo.*

Another study worth mentioning is a study entitled "Management of *Prosopis* in Kgalagadi South" (BOT/SGPOP4/CORE/0701/02) which was funded by the United Nations Development Programme (UNDP) under the Global Environment Facility (GEF) Small Grants Programme (SGP). This study was planned to start in December 2007 and end in December 2010. However, the project lapsed before the end of its period due to

various challenges (see Setshogo, 2012).

The study had not produced or published any results or report during the period of the current study except the results presented in the afore-stated studies by Morapedi (2008) and Muzila, *et al.* (2011). When contacted about the project, the coordinator indicated that an official report on the project was due for submission before the end of February 2012. In a nutshell, the coordinator mentioned that the project met a few of its objectives due to various challenges as evident from his communication outline below.

> "The project fulfilled some of its research objectives. The main challenges had to do with the financial capability of the Trust, staff turnover and logistics. The time that was allotted for the project ran out (Dec 2007 to Dec 2010) because of poor accounting for project expenses. The project ran without a treasurer (who was BORAVAST treasurer) for about two thirds of the project life. The main problem was that the research team was far removed from access to the funds, e.g. not a signatory to research funds, and hence did not have a clue how the funds were being used other than making requests for field trip funds. There was also a persistent impatience by the communities to use the project money to create jobs which was not an objective of the project. The project could have been a means to poverty alleviation but there was an impatience with the research to get the project to that level where informed decisions could be made leading to sustainable livelihood projects for the communities. It is however not a lost course because other means

are being pursued to source funds to continue with the research." (Setshogo, 2012)

2.8 Characteristics of *Prosopis* Species Found in the Study Area

The morphology and anatomy of *Prosopis* species growing in the BORAVAST area are described below basing on Burkart and Simpson (1977).

Prosopis chilensis (Molina) Stuntz Emend, Burkart

***Stems and roots*:** Under undisturbed conditions the plant is characteristically a large, single-stemmed tree, 3 to 10 m tall with a well-developed crown, short trunk, knotty branches that are partly spiny, paired and axillary spines of 6 cm maximum length, but they are not present on all nodes.

Leaves: Leaves are equal in length or longer than the raceme. The petiole is 1.5 to 12 cm long with 1 to 3 pairs of pinnae 8 to 24.5 cm long, bearing 10 to 29 pairs of leaflets. Leaflets are pale green, with poorly visible veins, 10 to 63 mm long, linear and glabrous with entire margins, separated on the rachis by 4 to 12 mm, which is equal to or greater than their width of 1.1 to 3 mm.

Inflorescence: Racemes are spike-like, 7 to 12 cm long bearing about 250 flowers, flower petals are 3 mm long and hairy within, 5 to 6 mm long stamens and pubescent ovary.

Legume and seed: The legume is linear and flattened, about 12 to 18 cm long, 1 to 1.8 cm broad, and 0.6 cm thick with parallel margins, almost straight to sickle shape and contains 20 to 30 seeds, sugary mesocarp. Endocarp segments are rectangular in

cross section and broader than long. Seeds are rounded and flattened and are 6 to 7 mm long.

Prosopis glandulosa Torrey

Stems and roots: Maximum heights of 7 to 13 m may be reached by the largest individuals that grow in open stands. There is also a shrub type that commonly invades grasslands in dense stands and becomes a many-stemmed shrub on sandy areas, axillary spines, 1 to 4.5 cm long. They are sometimes paired but usually stay solitary. Some individuals have very few spines.

Leave: Glabrous with one or two pairs of pinnae 6 to 17 cm long that bears 6 to 17 pairs of leaflets each. Leaflets are 5 to 12 times as long as wide, mostly 1 to 4 cm long, spaced along the rachis at distances as great or greater than their width, and they are linear or oblong, obtuse in shape, and are prominently veined beneath.

Inflorescence: Spike-like raceme which is about 5 to 14 cm long. Flower petals are 2.5 to 3.5 mm long and the ovary is hairy.

Legume and seed: The pod is linear, flat, yellow, either straight or slightly curved and about 10 to 20 cm long, 1cm wide, and 0.5 cm thick. The exocarp is hard and underlaid by a pulpy, sweet mesocarp. Pods contain 5 to 18 oval, glossy brown seeds 5 mm wide, 7 mm long and 2 mm thick.

Prosopis glandulosa var. torreyana (Benson) Johnston

The variety is similar to those of *Prosopis glandulosa*. The differences between the varieties are mainly in leaf characteristics. The leaflets in *Prosopis glandulosa* var. torreyana are 15 to 25 mm long, 5 to 8 times as long as wide and 10 to 15 pairs per pinna. Leaflets of

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Prosopis glandulosa var. glandulosa are generally 30 to 45 mm long, 8 to 15 times as long as wide and 6 to 13 pairs per pinna.

Prosopis juliflora (Swartz) DC

It is difficult to distinguish *Prosopis juliflora* from a closely related species, *Prosopis pallida* (Pasiecznick *et al.* 2001). While both are distinctive from most other *Prosopis* species, they closely resemble each other in flower, pod and leaf morphology.

Stems and roots: Small spreading shrub or tree which is 3 to 8 m tall with a rounded or somewhat flattened crown, smooth or slightly fissured and brown bark, axillary and paired spines that are sometimes solitary and do not occur on all branches and vary in length from 0.5 to 5 cm; the longest occur on strong basil shoots.

Leaves: One to four pairs of pinnae with 10 to 16 pairs of leaflets, shorter or as long as the inflorescence, petiole and rachis (if present) are 0.5 to 7.5 cm long, elliptical-oblong leaflets, 6 to 23 mm long, 1.6 to 5.5 mm wide, and often glabrous.

Inflorescence: Almost cylindrical racemes, 7 to 15 cm long bearing greenish-white flowers that turn light yellow when mature. The calyx is 0.8 to 1 mm long with minute ciliolated teeth. Petals are 2.5 to 3 mm long and hairy within, but glabrous without, 4 to 5 mm long stamens.

Legume and seed: Flattened and straight pod that incurves at the apex, and sickle-shaped in some individuals. It is 8 to 29 cm long, 9 to 17 mm wide, and 4 to 8 mm thick. The seeds appear as low rounded prominences in the middle of the pod during the immaturity stage. With age, the pod becomes swollen and pulpy, and the outline of the seeds diminishes. The endocarp may have up to 25 rounded, rectangular segments. Seeds are oval and brown.

Prosopis juliflora var. horrida (Kunth) Burkart

Stems and roots: Generally a spiny tree or shrub, even though spines on some individuals may be rare, height range is 3 to 8 m. Branches are normally grayish to black with a zig-zag pattern.

Leaves: Leaves bear 2 to 4 pinnae 6 to 10 cm long with elliptical, ovate to oblong, pubescent, about 15 mm long, and 4 mm wide leaflets. Ten to 15 pairs of leaflets are broadly spaced along the rachis.

Inflorescence: Flowers are greenish/white. Racemes are 9 to 12 cm long.

Legume and seed: The legume is straight or arched, compressed, and including the stiple and terminal point, is 18 to 24 cm long and 1 to 1.2 cm broad. It is glabrous, with the exception of scattered hairs along the margins. It has up to 26 rectangular joints that are broader than they are long.

Prosopis juliflora var. inermis (H.B.K.) Bukart

This variety is distinguished from var. *juliflora* only by having finely pubescent leaflets and in its lack of spines. In spite of this, it is not always possible to distinguish from the typical variety.

Prosopis velutina Wooten

Stems and roots: Under undisturbed conditions, the plant is single-stemmed due to a strong predisposition for apical dominance with a height of up to 18 m. However, due to the vulnerability of the apical meristem to grazing animals, insects, or physical processes such as freezing, the plants are more commonly multi-stemmed and shrubby. Roots have been excavated at a depth of almost 50 m and over horizontal distances of more than 20 m. Consequently,

the plant is proficient in utilizing the available water in the upper soil layers, as well as that in the deeper layers often reaching the water table.

Leaves: similar to all species of the genus, leaves are doubly compound. Usually two pair of pinnae, but sometimes one or three pairs, may be present. The pinnae are 2 to 9 cm long and may support 12 to 30 pairs of leaflets. Leaflets are oblong and pubescent with entire margins, and almost or actually touch along the rachis. Stomata are found on the rachises and on both surfaces of the leaflets. They are neither sunken nor protected by trichomes, and, therefore, appear more like those of mesophytes. The leaf surfaces show single-celled glandular trichomes and wax crystals, which produce a velvety texture from which the species derives its common name, velvet mesquite.

Inflorescence: Racemes are spike-like 5 to 15 cm long with pale greenish-white florets. Florets have short pedicells and are to some extent pubescent on the outside, especially on the calyx. Petals are about 2.5 mm long with tips that are hairy on the inside. A small, multi-branched plant may produce about 6,000 inflorescences during a year.

Legume and seed: The legume is linear and quite straight, 8 to 16 cm long and 6 to 10 mm broad. Joints of the pod are approximately as long as broad or shorter. Fruit colour varies from pure yellow to mottled red or black. The outer surface is velvety on immature pods but becomes smooth at maturity.

2.9 Control of *Prosopis* Species as Invaders

A number of control approaches have been recommended as solutions to *Prosopis* invasion from a range of quarters around the world. The

approaches are basically dichotomous in nature. One category of the approaches focuses on eradication, while the other centres on management of the species. Eradication approaches entail systematic control of plant population that leads to its elimination from a particular area, region or country (Groves & Panetta, 2002). Bomford and O'Brien (1995) emphasized that eradication campaign should be time bound. Otherwise, eradication activities would fall under the management regime if eradication is conducted indefinitely. Management approaches involve systematic and sustainable containment of the plant population (Sharov & Liebhold, 1998; Bokrezion, 2008). Containment of plant population reduces the rate of spread of the plant species (Sharov & Liebhold, 1998).

Eradication approaches have been implemented in countries which experienced *Prosopis* invasion. In 1995, campaigns to implement the eradication methods on *Prosopis* trees started in Sudan following a declaration for eradication of the species by the Sudanese President (Laxén, 2005; Bokrezion, 2008). The eradication process was undertaken at the expense of millions of US Dollars (Laxén, 2005; Bokrezion, 2008). Notwithstanding the high costs of the eradication project, the rate of success was relatively insignificant even when *Prosopis* trees were uprooted (Laxén, 2005; Bokrezion, 2008). Furthermore, experiences from America, Asia, Australia and South Africa indicated that eradication of *Prosopis* is costly, difficult and often impracticable (Csurhes, 1996; Zimmerman & Pasiecznick, 2005). This is mostly attributed to the prolific seed production of the species and its capability to re-grow from vegetative buds (Pasiecznick, 2001). Eradication of *Prosopis* has also been complicated by the long dormancy period (up to 10 years) of its seeds in the soil seed bank which normally germinate immensely under environmental disturbance (Csurhes, 1996).

Various management approaches have been used with success to address

Prosopis invasion in countries like Argentina, Kenya, India, South Africa (Hoffmann, *et al.*, 1993a, 1993b; Coetzer & Hoffmann, 1997; Pasiecznik, 2001; Mwangi & Swallow, 2005; Zimmerman & Pasiecznik, 2005). Researchers have realized that the war against *Prosopis* would not be won by engaging a single method of control (Csurhes, 1996; Bokrezion, 2008). Consequently, integrated control approaches, implemented on a case based system have been adopted in many regions globally (Bokrezion, 2008; Csurhes, 1996; Pasiecznik & Choge, 2005). Some *Prosopis* control options that have been utilized around the globe are summarized in Table 2.3.

2.10 Relevant literature on Research Methods

This section presents the review of literature which was used as the basis for the design of methods that were used in gathering and analysing data in this study. Reference is later made to this literature in chapter three which entails details on the methods employed in this study.

2.10.1 Soil

Soil characteristics are highly heterogeneous both temporally and spatially (Farley & Fitter, 1999; Maestre, *et al.*, 2003; Austin, *et al.*, 2004) in arid environments. Temporal heterogeneity of soil properties emanates from high seasonal and annual variability in the climatic conditions (Xie & Steinberger, 2001; Austin, *et al.*, 2004; Huxman, *et al.*, 2004). Spatial heterogeneity of soil characteristics has been attributed to heterogeneous plant distribution in arid environments, which creates zones of enhanced nutrient accumulation and high deposition of organic materials in the soil (Prescott, 2002; Rietkerk, *et al.*, 2004; Rotundo & Aguiar, 2005). These plant-induced nutrient-rich zones, resulting from a range of interacting biotic and abiotic concentrating mechanisms, have been referred to as "fertile islands", "resource islands", or "islands of fertility" (Coppinger,

et al., 1991; Schlesinger, *et al.*, 1996; Reynolds, *et al.*, 1999; Stock, *et al.*, 1999; Camargo-Ricalde & Dhillion, 2003).

Spatial heterogeneity of soil properties in arid environments affects not only seedling establishment (Maestre, *et al.*, 2003) and plant–plant interactions (Aguiar & Sala, 1999), but also affects species distribution (Pan, *et al.*, 1998), diversity (Anderson, *et al.*, 2004) and productivity of plant communities (Mou, *et al.*, 1995). The conditions of soil under the canopy of an individual plant may be affected by its growth stage (Robinson, 1994; Maestre & Reynolds, 2006). At earlier stages when a plant is young and its canopy size is small, the fertile island may be very weak or non-existent, because organic matter may not be efficiently trapped under the small canopy within a relatively short period of time (Ludwig, *et al.*, 1975; Reynolds, *et al.*, 1999). With advancement in the growth stage of a plant, the canopy size and duration of nutrient accumulation may increase, leading to improvement in understory soil conditions (Charley & West, 1975; Ludwig, *et al.*, 1975; Reynolds, *et al.*, 1999). Many studies have investigated the phenomena of plant-induced fertile islands (Fransen, *et al.*, 1999; Wang, *et al.*, 2007), but more work needs to be conducted on the relationships between plant growth status and plant-induced fertile islands.

The intensity of resource islands may differ among habitats and micro-habitats (Derner, *et al.*, 1997; Su, *et al.*, 2004). The conditions of resource islands may also vary with soil depth (Charley & West, 1975; Soriano, *et al.*, 1987; Caldwell & Manwaring, 1994; Zaady, *et al.*, 1996; Derner, *et al.*, 1997). Therefore, soil heterogeneity and plant growth status are critical factors in studies that seek to investigate plant-soil relationships.

2.10.1.1 Soil Characteristics

Nutrient availability in the soil is one of the most important limiting factors affecting plant community structure (Grime, *et al.*, 1997).

Increasing soil nutrients availability often leads to a decrease in plant species diversity, which often favours competitive species that are capable of prolific moisture and nutrient resource extraction as well as rapid biomass production (Al-Mufti, *et al.*, 1977; Grime, 1979). Species composition in plant communities is influenced by differential limitation between plant species by different soil nutrients (Koerselman & Meuleman, 1996). Furthermore, land use practices affect various characteristics of plants including biomass production, species composition, species diversity, cover, height, distribution and density, which in turn affect soil moisture and nutrients availability (Bakker, 1994; Oomes, *et al.*, 1996; Smith, 2000; Critchley, *et al.*, 2002).

It is well established that Carbon, soil pH, total nitrogen (N), electrical conductivity (EC), Calcium (Ca), Sodium (Na), Potassium (K), and Magnesium (Mg) (e .g. Mountford, *et al.*, 1993; Willems, *et al.*, 1993; Smith, 1994; Oomes, *et al.*, 1996; Tallowin, *et al.*, 1997; Janssens, *et al.*, 1998; Zas & Alonso 2002; Monier & Amer, 2003; Wang, *et al.*, 2007) are among the soil characteristics that are commonly considered as limiting factors for plants across a range of soil types and environmental conditions.

2.10.1.2 Soil Sampling Methods

Different soil sampling techniques have been applied in various studies and their designs were dictated by the objectives of the studies undertaken, conditions of the study site and other factors. Li, *et al.* (2008) sampled soils at 0-10 cm and 10-20 cm depth at the stem of the plant, understory and canopy edge in their studies of fertile islands created by *Artemisia ordosica* in inland dunes of northern China. On the other hand, Zas and Alonso (2002) and Abril, *et al.* (2009) sampled at 0-20 cm soil depth in their investigations on the relationships between vegetation and soil characteristics, while Liu, *et al.* (2007) opted to sample at 0-10 cm and 10-20 cm depth under shrub crown, at the vertical projected limit of shrub

crown margin, and in the space between shrub crowns. In addition, the biochemistry of Kgalagadi soils was studied by Wang, *et al.* (2007) using 1 m deep soil pits, and collecting soil samples at 10 cm depth intervals.

2.10.2 Plant Communities

The nature of *Prosopis* species as a biotic component of the ecosystems in the BORAVAST area, the *Prosopis* species-biotic relationships and the *Prosopis* species-abiotic relationships form part of the main area of interest in this study. *Prosopis* species are not the only plant species that inhabit the study area, but the species exist within plant communities. Muller-Dombois and Ellenberg (1974) described a plant community as a combination of plants that are dependent on their environment, influence one another and modify their own environment. Floristic composition, plant species density, cover, distribution, and height are commonly included in studies that focus on plant communities and plant-environment relationships (e.g. Abbadi & El-Sheikh, 2002; Chanda, *et al.*, 2003; Monier & Amer, 2003; Mosweu, 2008)

2.10.2.1 Plant Community Characteristics

The floristic composition of a plant community includes all species occurring within a plant community (Bonham, 1989). However, most plant communities intrinsically comprise so many species that it is often not practically possible to discover and document all species within a community (Ter Braak, 1987; McDonald, *et al.*, 1996; Abbadi & El-Sheikh, 2002). Therefore, it is common in ecological studies to use dominant species in studying the floristic composition of plant communities in a given area (e.g. Ter Braak, 1987; McDonald, *et al.*, 1996; Abbadi & El-Sheikh, 2002; Monier & Amer, 2003; Mosweu, 2008).

Plant species density refers to a count of individual plants within a defined area (Kershaw, 1973). Plant species composition refers to a list of

plant species that exist in a particular plant community, while species distribution refers to the spatial range of a species or probability of finding it within a quadrat when the quadrat is laid on the ground (Bonham, 1989).

Table 2.3 *Prosopis* control options used around the world

Control Option	Description
Biological	Seed feeding and flower feeding bio-control agents (e.g. *Algarobius prosopis* (Le Conte) and *Asphondylia prosopidis*).
Fire	Application of controlled fire to thickets of *Prosopis* trees
Mechanical	Physical removal of *Prosopis* trees from the soil using machinery (e.g. chaining and blade-ploughing).
Chemical	Basal bark technique: application of herbicide (usually 'Garlon 600' mixed in diesel) onto the bark from ground level to knee height all the way around the stem.
	Cut stump technique: application of herbicide to a freshly cut stump.
	Foliar sprays (e.g. Garlon 600, Grazon DS): applied on dense bush of seedlings less than 1.5 m tall.
	Aerial Spray Treatment: Aerial application of herbicides (e.g. Grazon DS usually using helicopter) to stands of *Prosopis*.
Grazing Management System	Regulation of grazing pressure (e.g. reduction in grazing pressure may cause a reduction in the rate of *Prosopis* invasion).
Exploitation or promotion	Facilitation of utilization of the by-products of *Prosopis* trees such as seed pods, timber and firewood at commercial and subsistence scales.
Eradication	Complete removal of *Prosopis* trees. When eradication is not time-bound, it is viewed as one of the ways of managing species invasion.

(Sources: Moran, *et al.*, 1993; Csurhes, 1996; Coetzer & Hoffmann, 1997; Pasiecznik, 2001; Mwangi & Swallow, 2005; Zimmerman & Pasiecznik, 2005).

Plant cover is the vertical projection of the crown or shoots area of a plant to the ground surface expressed as a fraction or percentage of a reference area (Muller-Dombois & Ellenberg, 1974). The plant Crown-Diameter method proposed by Muller-Dombois & Ellenberg (1974) remains the commonly used method of determining plant crown cover (CC). The method employs the following formula:

$$cc = \pi\left(\frac{D1+D2}{4}\right)^2$$

Where;

D_1 = First Crown Diameter *(measured from the tree/bush perimeter across the centre to the other side of the perimeter.)*

D_2 = Second Crown Diameter *(measured perpendicular to D_1)*

CC = Crown cover

2.10.2.2. Sampling Methods for Plants

Sampling theory emphasizes randomization in order to provide a probability structure for statistical analysis or to give reliability to statistical models (Gillison & Brewer, 1985). However, randomization procedures may be counterproductive to the intent of ecological surveys, especially where the occurrence of natural pattern is known to be non-random (Gillison & Brewer, 1985). Consequently, environmental gradients are commonly used in plant ecological research to elucidate plant species and plant community characteristics (e.g. Skarpe, 1986; Chanda, *et al.*, 2003; Mosweu, 2008; Mosweu, *et al.*, 2010).

Gradient analysis techniques are classified into direct and indirect methods (Austin, *et al.*, 1984). Indirect gradient methods consider the major patterns of variation in the plant species and community characteristics and subsequently premise their explanation on environmental gradients (Gauch, 1982). Ecological data generated through indirect gradient methods are associated with serious challenges in relation to analysis and interpretation (Gauch, 1982; Ter Braak, 1995). Thus, direct gradient methods are normally considered as the best option in studies where essential environmental variables are distinct (Palmer, 1993). Direct gradient methods directly interrelates plant species and community characteristics to environmental variables using data on the

plant species and environmental variables that has been collected from the same sample areas (Ter Braak, 1995).

The Gradsect sampling technique is a direct gradients approach that was first defined by Gillison and Brewer (1985). The technique (Gillison & Brewer, 1985; Austin & Heyligers, 1989) aims to provide a description of a full range of biotic variability in a region by sampling along the full range of environmental variability. Transects that contain the strongest environmental gradients in a study area are selected in order to optimize the amount of data obtained in relation to the time and effort spent during the survey (Austin & Heyligers, 1989). The gradsect method facilitates positioning of sampling points in logistically more accessible areas than traditional methods such as systematic or random sampling, thus improving efficiency (Gillison & Anderson, 1981; Gillison & Brewer, 1985; Austin & Adomeit, 1991). Costs can also be reduced and efficiency maximized when stratifying variables are carefully chosen using existing information (Austin & Adomeit, 1991).

The relative efficiency of the gradsect sampling technique has been analyzed (Gillison & Anderson, 1981; Gillison & Brewer, 1985; Austin & Adomeit, 1991). Austin and Adomeit (1991) conducted a simulation study to assess several traditional statistical sampling techniques against the gradsect sampling technique. The simulated data set utilized for the tests was based on real natural landscape (Belbin & Austin, 1991). Among the three statistical sampling techniques compared, random sampling had more species recovery rate followed by transect sampling and then systematic sampling (Belbin & Austin, 1991). Transect sampling had the highest costs and detected the fewest species (Belbin & Austin, 1991). Gradsect sampling methods were compared to random sampling and detected more species at lower cost than random sampling (Belbin & Austin, 1991).

Sampling with quadrats is commonly practiced for most plant communities (Gross, *et al.*, 2000). Various researchers have recommended different quadrat sizes and shapes for plant sampling. Quadrat sizes and shapes were recommended based mainly on the objectives of the research, physiognomy of the plant community, accessibility, feasibility, efficiency, availability of resources and time. Sutherland (1996) recommended quadrat sizes of 0.01 - 0.25 m^2 for communities of bryophyte, lichen and algae; 0.25 - 16 m^2 for grassland, tall herb, short shrub communitis; 25 - 100 m^2 for tall shrub communities; and 400 - 2500 m^2 for trees in woods and forests.

2.10.3 Soil Seed Bank

Soil seed banks of most habitats contain both transient and persistent components (Walck, *et al.*, 2005; Baskin & Baskin, 1998). The transient component is composed of short-lived, non-dormant seeds that may not be viable at the onset of the second growing season (Baskin & Baskin, 1998; Wang, *et al.*, 2005). Current year seeds that remain viable at the onset of second growing season and viable seeds dispersed in the preceding years constitute the persistent component of the soil seed bank (Baskin & Baskin, 1998). Seeds enter the soil seed bank through seed dispersal processes, while germination, predation, senescence and pathogens remove the seeds from the soil seed bank (Walck, *et al.*, 2005). It is the balance between the processes responsible for the introduction of seeds into the soil seed bank and their removal from the soil seed bank that determines the turnover rate of the soil seed bank in a particular location (Bekker, *et al.*, 1997; Laura & Brenda, 2000; Snyman, 2004).

Soil seed banks have been investigated in various ecosystems including forests (Leckie, *et al.*, 2000), grasslands (Meerts & Grommesch, 2001), marshes (Leck & Simpson, 1995), abandoned fields (Batanouny, *et al.*, 1991; Khrikki, 1993; Leck & Leck, 1998) for purposes of environmental

monitoring and management as well as ecosystem conservation. To this end, understanding the seed bank ecology of plant species is considered important in elucidating the species recruitment, development and its distribution dynamics (Leck & Leck, 1998). It is also useful in practical aspects of environmental management, monitoring as well as ecosystem conservation.

2.10.3.1 Soil Seed Bank Sampling

Various soil sampling techniques have been employed in soil seed bank investigations. Many factors have been considered in the design of soil seed bank sampling techniques and they included the aim of the research, characteristics of plant species, field conditions, time, resource availability and others. For example, Liu, *et al.* (2011) sampled soil at 0-5 and 5-10 cm, Liu, *et al.* (2006) sampled at 0-10 cm, Ma and Liu (2008) sampled using 20 x 20 cm quadrat, Clemente, *et al.* (2007) sampled at 0–2.5 and 2.5–5 cm, Leck and Leck (1998) used a 10 x 10 cm quadrat and sampled at 0-3, 3-6, and 6-9 cm, and Shen, *et al.* (2006) used a 10 x 10 cm quadrat and sampled at 0–2, 2–5 and 5–10 cm in the studies of soil seed bank.

2.10.4 Social Factors

Questionnaire surveys have been used successfully to assess human perceptions about invasive species, the risks the species pose and the options for their control around the world (e.g. Perrins, *et al.*, 1992; Kowarik & Schepker, 1998; Williamson, 1998; Bardsley & Edwards-Jones, 2007; Daehler, 2008; Garcı´a-Llorente, *et al.*, 2008). Samples of people are normally selected from a larger population and asked the same set of questions. A number of informants are selected to account for variation in responses. This approach has been used at practically all levels, from the large-scale census to small-scale studies, and village-level research by governments and NGOs for planning, and research purposes (Pretty, 1993 & 1995; Garcı´a-Llorente, *et al.*, 2008).

Chapter 3

RESEARCH METHODS

3.0 Introduction

This chapter presents different research techniques that were used in this study. Details of methods used for soil and vegetation survey and analysis, soil seed bank investigation, and assessment of the perceptions of the BORAVAST communities about *Prosopis* species are covered in this chapter. The chapter also outlines methods and tools of data analysis and presentation that were employed in processing research data.

3.1 Soil-*Prosopis* Interrelationships

The gradsect sampling technique (section 2.10.2.2) formed the basis of investigations on soil-*Prosopis* interrelationships in this study. The method was considered appropriate as it directly relates plant characteristics with environmental attributes using information on plants and environmental variables that have been obtained from the same sample areas (Ter Braak, 1995). Previous studies conducted in the Kgalagadi area used various environmental gradients including moisture, topographic and land use gradients (e.g. Skarpe, 1986; Chanda, *et al.*, 2003; Mosweu, 2008; Mosweu, *et al.*, 2010). The most dominant and noticeable environmental gradients in the BORAVAST area were topography and land use. Therefore, the study area was stratified into riparian invaded sites being the area covering the Nossob-Molopo River and its flood plains, invaded settlement sites being the build-up areas of the four villages and non-invaded sites being the sites that had not been invaded by the species outside the built-up areas of the settlements.

3.1.1 Sampling of Vegetation

Sampling of vegetation was conducted in the riparian invaded sites, invaded settlement sites and non-invaded areas. Sampling of vegetation was not undertaken in the invaded settlement sites due to continuous uncoordinated cutting and uprooting of *Prosopis* trees that were taking place in the settlement areas (Plate 8). Vegetation characterization included the most commonly used factors in studies of this nature (section 2.10.2) which were species density, cover, distribution, height, and composition of woody vegetation. Various sampling quadrat sizes have been recommended for sampling different plant communities (section 2.10.2.2). On the basis of experiences from other studies and the field conditions that prevailed at the time of sampling, 42 quadrats of 25 m x 25 m (625 m^2) were used for sampling trees and 5 m x 5 m (25 m^2) sub-quadrats were used for sampling small shrubs. Sampling quadrats were laid along the Nossob-Molopo River riparian zone from Struizendam to Rapelspan (Figure 3.1). Identification of plant species in the field was conducted with the assistance of two plant taxonomists from the Department of Biological Sciences at the University of Botswana.

3.1.2 Sampling of Soil

Different researchers have sampled soils in the Kgalagadi region using different approaches (e.g. Skarpe, 1986; Chanda, *et al.*, 2003; Mosweu, 2008; Mosweu, *et al.*, 2010) to meet various objectives (section 2.10.1.1-2). The soil sampling strategy that was employed in this study considered the heterogeneity of soils and the soil-*Prosopis* relationships in the study area. Soil samples were collected along three small transects radiating from the main stem of randomly selected mature *Prosopis* trees located approximately at the centre of the 625 m^2 quadrat used for sampling vegetation (section 3.1.1). The transects were separated by approximately 120° angle (Figure 3.2). Using an auger, soil core of 5 cm in diameter and

20 cm in length was obtained; (1) under plant canopy or crown at about 0.5 m of the radius of the plant canopy and (2) in the space between plant canopy (inter-space/inter-canopy) at a distance of at least 100 m from the nearest *Prosopis* trees to minimize the effects of the trees on the characteristics of soil samples. Samples were collected at the depth of 0-20 cm and 60-80 cm resulting in a total of 504 samples. Soil samples were pooled by depth and location to reduce variability, increase efficiency and enhance the representativeness of the samples. Sample pooling resulted in a total of 168 soil samples.

3.2 Relationship between *Prosopis* Growth Stage and Soil Properties

The underlying assumption in the assessment of the relationships between the growth stage of *Prosopis* trees and soil properties was that *Prosopis* trees of different heights and canopy sizes were at different stages of growth. Therefore, *Prosopis* trees were categorized into three classes representing various growth stages using tree height and canopy cover as follows:-

- Class 1: 0.3-1.5 m height and 1-9 m^2 canopy cover.
- Class 2: 1.6-2.5 m height and 10-19 m^2 canopy cover.
- Class 3: 2.5+ m height and 20+ m^2 canopy cover.

The villages of Bokspits and Vaalhoek in the study area (Figure 3.3) were initially 5 km apart but are now joined to each other due to expansion of the settlements. Therefore, they were identified as Bokspits-Vaalhoek area for the purposes of this investigation. In the Rappelspan area, the riparian zone was dominated by *Acacia erioloba* and there were virtually no *Prosopis* species in the Nossob-Molopo River riparian zone. *Prosopis* species invasion had only affected the settlement area in Rappelspan.

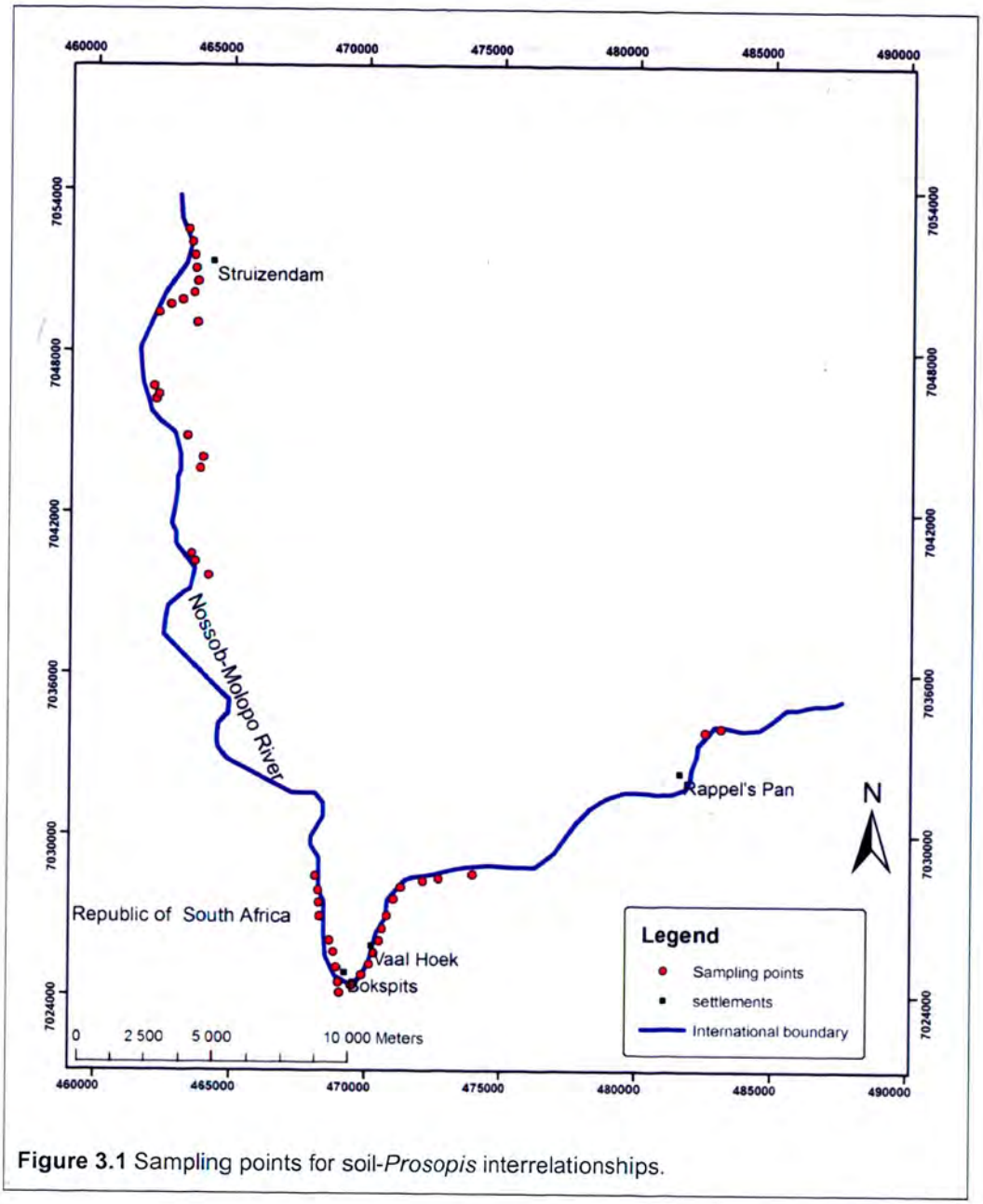


Figure 3.1 Sampling points for soil-*Prosopis* interrelationships.

Therefore, to maintain consistency in terms of sampling site conditions, sampling of soil for the purpose of assessing the interrelationships between the stage of growth of *Prosopis* trees and the selected soil characteristics excluded Rappelspan. Soil samples were collected from Struizendam and Bokspits-Vaalhoek area (Figure 3.3).

A total of 45 soil samples were collected per growth stage from each

village. Soil samples were collected along three small transects radiating from the main stem of randomly selected *Prosopis* trees at 0.20 m from the stem of a plant, while ensuring that the point falls under the canopy of the selected *Prosopis* tree. The depth of sampling was 0-10 cm and sampling was conducted by the use of a hand trowel. Soil samples were pooled according to sampling point to make a composite sample for analysis. The total number of soil samples that were collected was 270 (Table 3.1).

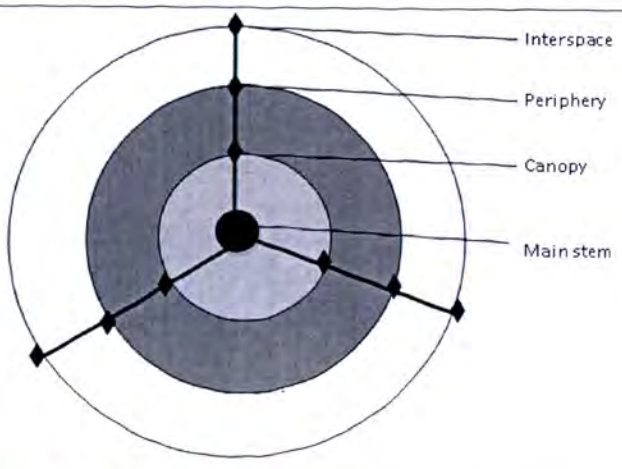


Figure 3.2 Illustration of soil sampling strategy.

3.3 Soil Analysis

Soil samples were prepared by air-drying and sieving through a sieve of 2 mm mesh to remove plant material. Previous research has indicated that organic carbon, pH, total nitrogen (N), electrical conductivity (EC), calcium (Ca), sodium (Na), potassium (K), and magnesium (Mg) are among the limiting factors in plants across various soil types (section 2.10.1.1). Therefore, they were considered relevant to this research. All soil samples collected according to sections 3.1 and 3.2 were analysed for the afore-mentioned soil properties as follows.

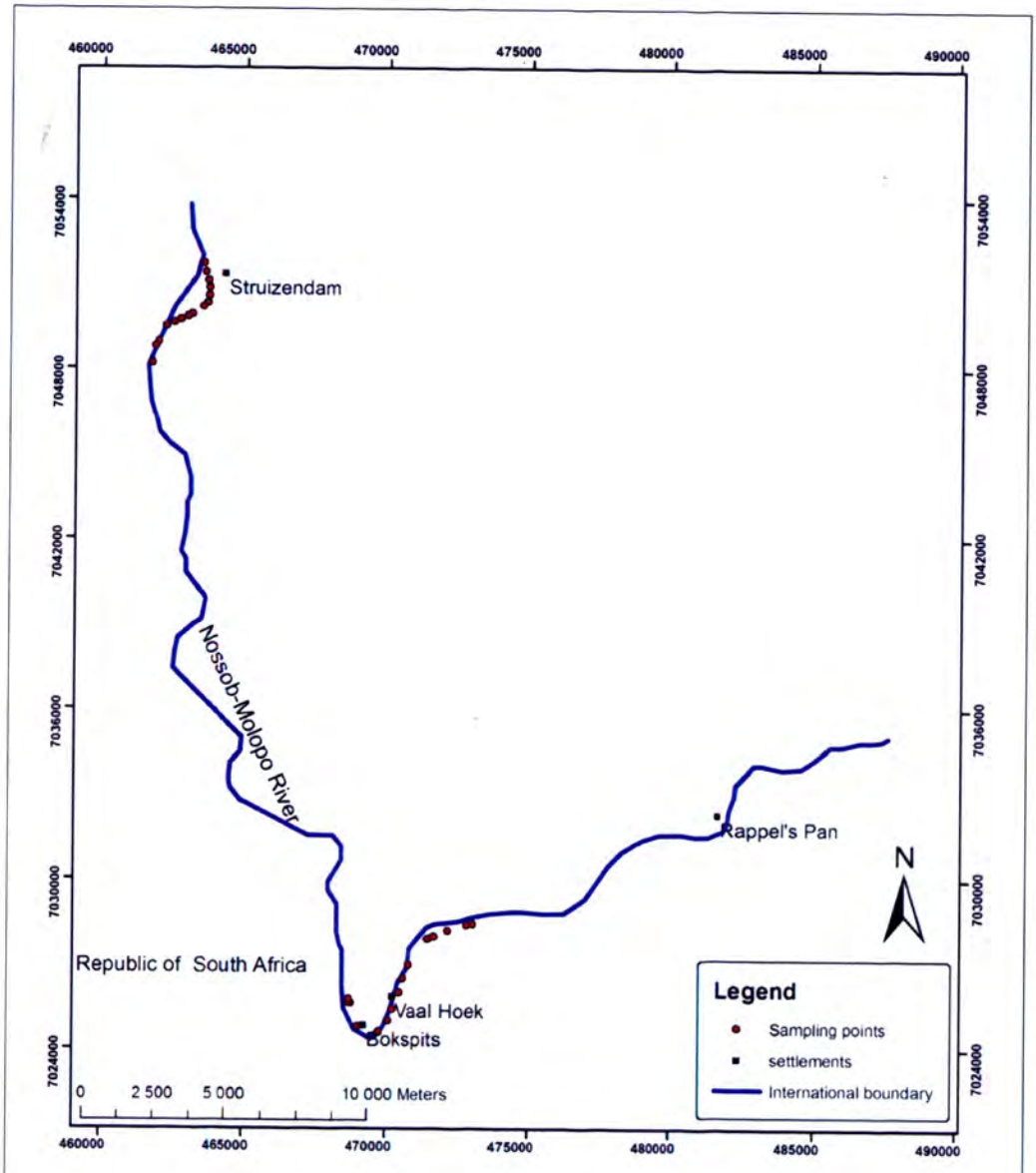


Figure 3.3 Sampling points for investigation of the relationships between *Prosopis* growth stage and soil.

➢ *Total Nitrogen and Soil Organic Carbon*

Total nitrogen and organic carbon were determined using the TRUSPEC CN. Pre-treatment of soil samples with 0.1M Hydrochloric Acid (HCl) to remove inorganic carbon was undertaken before analysis of soil for carbon. Hence, the soil carbon measurement indicated by the instrument was treated as soil organic carbon (SOC). The instrument analyses the sample in three phases referred to as the purge, combust and analyze. In the purge phase, the encapsulated soil sample is placed in the loading head, sealed and purged of any atmospheric gases that may have entered the system during sample loading. The system is also purged. The sample is then dropped into the hot furnace set at 950°C and flushed with oxygen (O_2) for very rapid and complete combustion. The products of combustion are passed through a secondary furnace set at 850°C for further oxidation and particulate removal. This is followed by removal of moisture in an additional furnace filter, a two staged thermoelectric cooler, and a collection of combustion gases in a collection vessel.

Oxygen is then injected into the collection vessel and mixed with the combustion gases in the analyze phase. The homogeneous combustion gases in the collection vessel are subsequently purged through the carbon dioxide (CO_2) gas infrared detector where carbon is measured as carbon dioxide. The combustion gases are then swept through hot copper to reduce nitrogen oxides (NO_X) to nitrogen gas (N_2) and through anhydrone to remove CO_2 and water and finally through a thermal conductivity cell which determines the amount of nitrogen in the sample.

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- ***Electrical Conductivity and pH***

  Electrical conductivity is a measure of total soluble salts in a soil sample. It is determined using an electrical conductivity meter on a soil extract. The 1:5 (soil : water) ratio extract is recommended because it is easier to work with and gives a larger yield of extract as compared to the saturation extract (International Soil Reference and Information Centre (ISRIC), 1993). On the other hand, the saturation extract has an advantage of representing the actual soil field condition with regard to the vegetation environment (Janzen, 1993), though not as much as direct extraction of the soil solution does (Soon & Warren, 1993). For the purpose of this study, a compromise between a soil extract and direct extract using the 1:2 (soil : water) ratio (Sonnevelt & van den Ende, 1971) was adopted.

- ***Exchangeable Cations*** (Ca, Na, K and Mg)

  The Silver thiourea method described by Chhabra, *et al.* (1975) was utilized in this study as it provides a more efficient way of determining exchangeable cations. The method is premised upon the strong affinity of the monovalent silver thiourea complex cation (AgTU) for negatively charged colloid surfaces, mineral and organic alike.

3.4 Soil Seed Bank and *Prosopis* Species Distribution

Studies on soil seed bank have been conducted in a range of environmental conditions through different methods of sampling (section 2.10.3). In this study, quadrats of 25 cm X 25 cm (625 cm^2) (Plate 2) were established along three transects separated by approximately 120° angle

and radiating from the main stem of randomly selected mature *Prosopis* trees (Figure 3.2 & Figure 3.4). Sampling points were located under randomly selected tree canopies at about 0.5 of tree canopy radius and in the inter-canopy areas at invaded sites. Sampling in non-invaded sites was conducted using the same quadrat size located randomly with deliberate efforts made to ensure spatial representativeness of samples. Within the quadrats, soil samples were collected at 0–5 cm and 5–10 cm depths.

Table 3.1 Number of soil samples for the assessment of plant growth stage-soils relationships.

Category	Struizendam		Bokspits-Vaalhoek	
	Plant No.	Soil samples	Plant No.	Soil samples
Class 1	15	45	15	45
Class 2	15	45	15	45
Class 3	15	45	15	45
TOTAL	**45**	**135**	**45**	**135**

The number of individual trees selected for sampling per site was 10 at invaded sites, while the number of sampling points at non-invaded sites was 30 (Table 3.2). Consequently, a total of 1 200 soil samples were collected. Soil samples collected around the same tree at similar points were pooled and sieved to extract *Prosopis* seeds for identification using master sample seeds. Seeds were counted and expressed as the number of *Prosopis* seeds per square meter (No. of seeds m^{-2}).

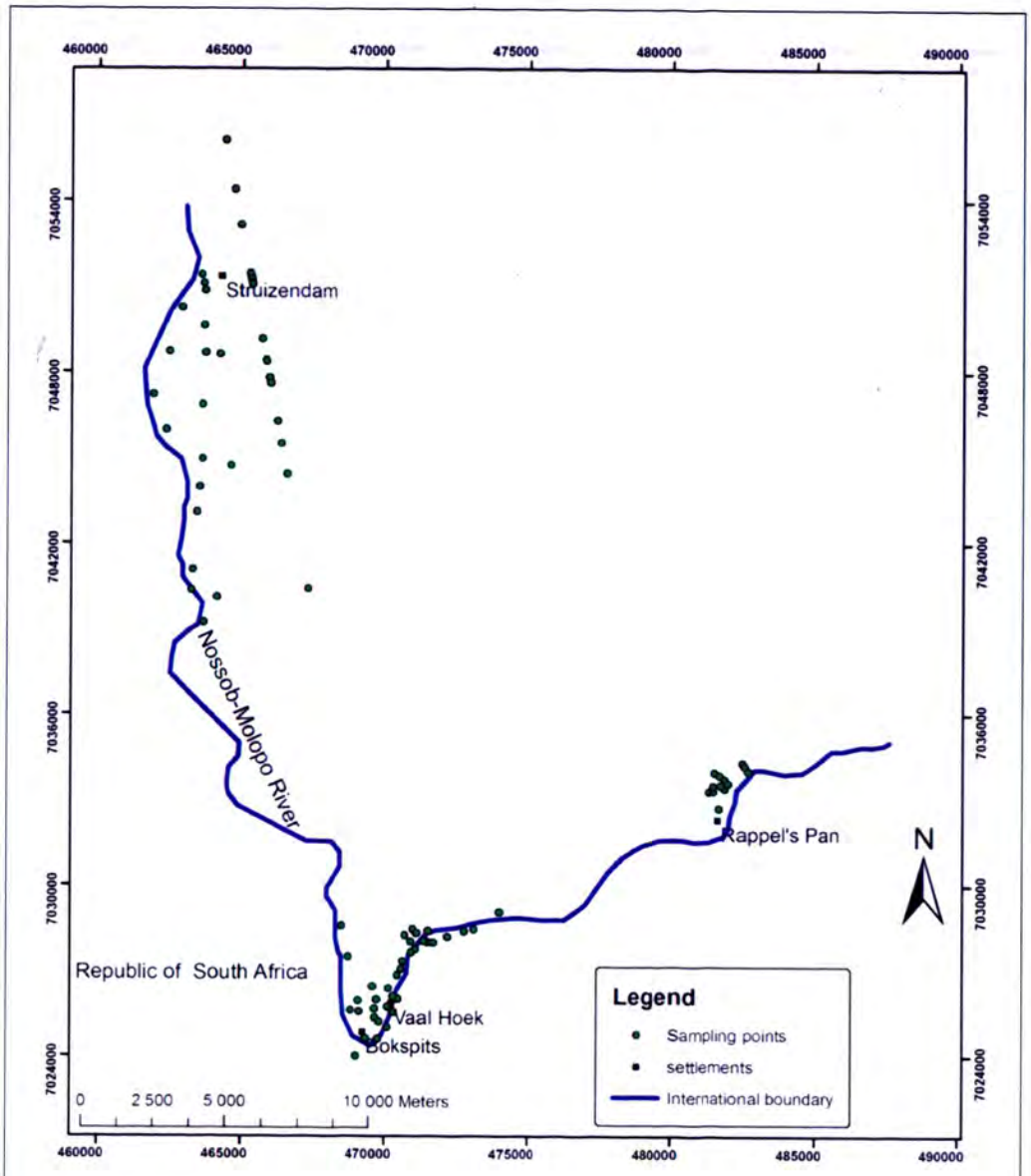


Figure 3.4 Sampling points for soil seed bank assessment.

3.5 Perceptions of the Communities about *Prosopis* Species

Questionnaire surveys have long been used as vital tools in numerous research works that focused on human perceptions in relation to environmental phenomena (section 2.10.4). Therefore, questionnaire surveys and focused group discussions were used in this research to

assess human perceptions about *Prosopis* species, the risks the species pose and the options for the species management. Questionnaire surveys and focused group discussions were conducted in the four villages after the chiefs, headmen and local authorities granted their consent for this research. Due to the problems that are usually associated with the predetermination of questions to be included in the questionnaire, a pilot questionnaire was designed and administered in two villages (Struizendam and Bokspits) in the research area in July 2009. On the basis of sample survey using the pilot questionaire, the questionnaire was fine-tuned to produce the final questionnaire (APPENDIX 1) that was administered in the four villages in the months of July and August 2010. The period of interview was selected to maximize the number of participants by planning it such that it coincided with the winter period during which farming activities are normally minimal.

A non-probability sampling procedure known as purposive sampling was employed in gathering data on the perceptions of the communities about *Prosopis* species. The method was found to be appropriate because it allows the researcher to use his or her professional assessment, instead of randomness, in choosing the respondents (Rea & Parker, 2005). For the purpose of this research, it was assumed that only adults who were twenty years and over were aware of the environmental changes that had taken place in their environments. Hence they were selected as the key respondents.

Prior to the conduction of interviews, efforts were made to search for secondary data that could indicate the number of households that existed in the four villages to maximise coverage of households for interviews. The efforts did not bear fruits in spite of contacts made with the CSO. Deliberate effort was then made to ensure that the spatial coverage of the interviews were 100% of the household in each village. In each household where there were potential respondents, at least one individual was

interviewed. In cases where more than one willing potential respondent were found in a given household, they were interviewed separately. Before the commencement of an interview process, the objectives of the study were explained to potential respondents and their consent to participate was also formally solicited. It was explained to the participants that they had the right to reserve their responses to some questions and even withdraw their participation at any stage of the interview process. Furthermore, potential respondents were assured of confidentiality and protection at all stages of the research. Multiple-answer and open-ended questions were posed to respondents as they presented respondents the opportunity to express themselves. In the questionnaire, the most predictable answers had been pre-stated for convenience, but were not read out to respondents to avoid influence on the respondent's choice or opinion. Recording of the responses was conducted during the interview process. In addition, notes were made on important information that had not been covered in the questionnaire.

Four focused group discussions were conducted in the villages. In Bokspits, the focused group discussion was attended by the BORAVAST Community Based Natural Resource Management Committee, the Chiefs and their assistants, headmen, Village Development Committee members (VDCs) and some elders of the communities. The Chiefs, VDC members accompanied by some elders of the communities were engaged in the focused group discussions separately held in Struizendam and Vaalshoek. In Rappelspan, the focused group discussion was conducted through a *kgotla* meeting attended by the Chief and his assistant, VDC and other members of the community. The questions that were addressed during the focused group discussions are outlined in APPENDIX 2.

The total number of respondents was 342 which comprised 139 male and 203 females (Table 3.3 and Figure 3.3). The majority of respondents were females with a ratio of approximately 2:3 (males: females). This is

Table 3.2 Number of soil samples for seed bank analysis.

Sampling Area	Bokspits			Rappelspan			Vaalshoek			Struizendam		
	Number of trees	Canopy	Inter-canopy	Number of trees	Canopy	Inter-canopy	Number of trees	Canopy	Inter-canopy	Number of trees	Canopy	Inter-canopy
Riparian invaded sites	10	60	60	10	60	60	10	60	60	10	60	60
Settlement invaded sites	10	60	60	10	60	60	10	60	60	10	60	60
Non-invaded sites	30	60		30	60		30	60		30	60	
TOTAL	**50**	**300**		**50**	**300**		**50**	**300**		**50**	**300**	

however not surprising because males are traditionally associated the responsibilities of caring for their families which often imply securing jobs in major villages, towns and cities, whereas women normally spend most of the time in their homes. Therefore, deliberate efforts were made to involve as many males as possible in the survey.

Table 3.3 Sample characteristics in the four villages.

VILLAGES		MALES	FEMALES	TOTAL
Bokspits	No. of individuals	42	60	102
	Per cent	12.3%	17.5%	29.8%
Rappelspan	No. of individuals	24	41	65
	Per cent	7.0%	12.0%	19.0%
Vaalhoek	No. of individuals	31	68	99
	Per cent	9.1%	19.9%	28.9%
Struizendam	No. of individuals	42	34	76
	Per cent	12.3%	9.9%	22.2%
TOTAL	**No. of individuals**	**139**	**203**	**342**
	Per cent	**40.6%**	**59.4%**	**100.0%**

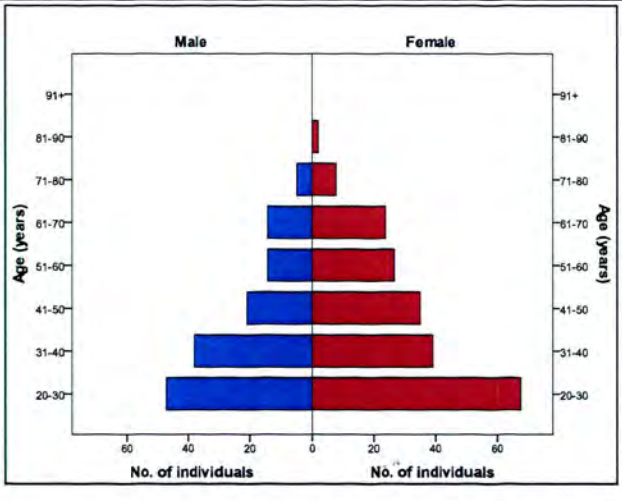


Figure 3.5 Age distribution of questionnaire respondents in the BORAVAST villages according to gender.

The lower ranges of the age groups (20-30 and 31-40 years) evidently dominated the number of respondents in both male and female categories, constituting 56.1% of the sample. This was attributed to the predominantly young population that existed in the area. However, considerable efforts were made to ensure that the elderly members of the communities in the four villages were actively involved during interviews. Consequently, a significant per cent (43.9%) of community members who were above 40 years were interviewed. This was considered important in the collection of vital data in relation to the chronology of *Prosopis* species invasion in the BORAVAST villages. On the other hand, involvement of a significant number of members of the community who constituted the lower age group ranges was a plus to this study as they normally comprise the active part of the community. Hence, community members who were in the 20-30 and 31-40 years age brackets were considered very important in relation to the aspects of *Prosopis* management.

3.6 Data Analysis

The main computer softwares that were used in data processing were Microsoft Excel 2010, Predictive Analytics SoftWare (PASW) Statistics 19.0 and ArcGIS 9.2. Tables, charts and maps were used to summarize the results.

3.6.1 Spatial Scale of *Prosopis* species

ArcGIS 9.2 software was used to analyse data on the spatial extent of the invasion of *Prosopis* species in the study area. The spatial extent of the distribution of *Prosopis* trees was illustrated using a map (Figure 4.2) which was produced through the process of interpolation using data on *Prosopis* tree density generated according to section 3.1.1.

3.6.2 Soil-*Prosopis* Interrelationships

Data generated from soil analyses (section 3.3) was used to assess the distribution patterns of selected soil properties in the study area. Analysis of Variance (ANOVA) and Student's t-Test statistic were used to compare soil samples collected from 0-20 cm canopy, 60-80 cm canopy, 0-20 cm inter-canopy and 60-80 cm inter-canopy. The mean values and the standard deviations of selected soil attributes were also determined.

The effects of *Prosopis* invasion on other woody plant species in the research area were investigated by subjecting data generated according to section 3.1.1 on vegetation to ANOVA and Student's t-Test. In addition, Spearman's rho correlation analysis was used to examine the strength and direction of the relationships between selected soil properties (sections 3.1.2 & 3.3) and selected characteristics of *Prosopis* species (section 3.1.1).

3.6.3 Relationships between *Prosopis* Growth Stage and Soil Properties

Student's t-Test statistic was used to compare the soil existing under the canopies of class 1, class 2, and class 3 *Prosopis* trees in relation to the selected soil properties using data generated according to sections 3.2 & 3.3. The mean values and the standard deviations of selected soil attributes were also calculated.

3.6.4 Soil Seed Bank

The mean number, standard deviation and coefficient of variation of *Prosopis* seeds in the riparian invaded canopy 0-5 cm, riparian invaded canopy 5-10 cm, riparian invaded inter-canopy 0-5 cm, settlement invaded canopy 0-5cm, settlement invaded canopy 5-10cm, and settlement invaded inter-canopy 0-5cm were computed to assess the distribution patterns of *Prosopis* seeds in the soil seed bank. In addition, the Chi Square test statistic was employed to assess the significance of the differences in the seed bank between riparian canopy 0-5 cm, riparian

canopy 5-10 cm, riparian inter-canopy 0-5 cm, invaded settlement canopy 0-5cm, invaded settlement canopy 5-10cm, and invaded settlement inter-canopy 0-5cm.

3.6.5 Questionnaire Survey and Focused Group Discussions

Information obtained from focused group discussions was recorded and qualitatively analysed. The results were presented as a summary of data obtained from the focused group discussions. Data obtained through the use of a questionnaire (APPENDIX 1), was captured and analysed quantitatively using Predictive Analytics Soft Ware (PASW) version 19.0 to assess the perceptions of the communities of the BORAVAST villages about *Prosopis* species. The results of the assessment were presented in the form of bar charts, pie charts and tables.

Chapter 4

RESULTS

4.0 Introduction

This chapter covers the results of the study. The results are presented in the form of statistical figures, tables, graphs, figures and maps. Supplementary materials on the results are provided as appendices to the thesis.

4.1 Soil-*Prosopis* Interrelationships

4.1.1 Soil Properties in the Study Area

Data generated from soil analyses (sections 3.1.2 and 3.3) was used to assess the distribution patterns of selected soil properties in the riparian sites. Comparisons of soil samples collected from 0-20 cm under canopy, 60-80 cm under canopy, 0-20 cm inter-canopy and 60-80 cm inter-canopy were conducted using Analysis of Variance (ANOVA) and Student's t-Test statistic (Table 4.1 & Figure 4.1).

Soil organic carbon at 0-20 cm under canopy (average = 3444.93 mg/kg), 60-80 cm under canopy (average = 5407.02 mg/kg), 0-20 cm inter-canopy (average = 3399.55 mg/kg) and 60-80 cm inter-canopy (average = 5003.90 mg/kg) depths were statistically significantly different ($F = 2.68$, $P = 0.05$, $\alpha = 0.05$) as determined from ANOVA. Student's t-Test showed that soil at 0-20 cm depth had significantly lower soil organic carbon content in comparison with soil at 60-80 cm depth under *Prosopis* tree canopies. In addition, soil at 0-20 cm depth in the inter-canopy had statistically significantly lower soil organic carbon compared to soil at 60-80 cm under canopy and 60-80 cm inter-canopy depth. Selected exchangeable cations

(Ca, Mg, K, and Na) as well as N did not show statistically significant differences in the soils.

ANOVA of soil pH indicated that soil differed significantly ($F = 44.81$, $P < 0.001$; $\alpha = 0.05$) at 0-20 cm under canopy (Average = pH 7.76), 60-80 cm under canopy (Average = pH 8.70), 0-20 cm inter-canopy (Average = pH 7.97) and 60-80 cm inter-canopy (Average = pH 8.97) depths. Student's t-Test showed that soil pH was significantly lower at 0-20 cm under canopy depth in comparison with 60-80 cm under canopy, 0-20 cm inter-canopy and 60-80 cm inter-canopy depths (Table 4.1). In addition, soil pH was significantly lower at 0-20 cm inter-canopy depth compared to 60-80 cm under canopy and 60-80 cm inter-canopy depths (Table 4.1). The general pattern in soil pH indicated significant lower pH levels at 0-20 cm soil depth as compared to 60-80 cm soil depth (Table 4.1). Normally soil pH is expected to be higher in the sub-soil than in the surface soil in sandy areas. However, it has been observed that *Prosopis* trees are associated with reduced soil pH due to tree litter accumulation, reduction in evaporation, and initiation of biological activities that take place where they grow (Bhojvaid *et al.*, 1996; Sigh, 1996). Therefore the observed pattern of soil pH in the study area could possibly be linked to *Prosopis* invasion. The soil pH values were all above pH 7, indicating that the soils were intrinsically basic (Figure 4.1).

Statistically significant difference ($F = 3.75$, $P = 0.01$, $\alpha = 0.05$) in the soil electrical conductivity (EC) at 0-20 cm under canopy (Average = 308.23 µS/cm), 60-80 cm under canopy (Average = 202.57 µS/cm), 0-20 cm inter-canopy (Average = 220.05 µS/cm) and 60-80 cm inter-canopy (Average = 226.45 µS/cm) depths was observed from ANOVA. The Student's t-Test indicated that soil EC was significantly higher at 0-20 cm under canopy depth compared to 60-80 cm under canopy, 0-20 cm inter-canopy and 60-80 cm inter-canopy depths (Table 4.1). Surface soil had significantly higher EC values ($P = <0.001$, $\alpha = 0.05$) under *Prosopis* tree canopies.

Table 4.1 Multiple Comparisons (Student's t *t* Test *P*-values) of soil properties in the study area.

		pH	EC	Ca	Mg	K	Na	N	C
0-20 cm canopy	60-80cm canopy	<0.001*	<0.001*	0.28	0.27	0.22	0.05*	0.11	0.05*
	0-20cm inter-canopy	<0.001*	0.02*	0.69	0.87	0.42	0.67	0.06	0.95
	60-80cm inter-canopy	<0.001*	0.02*	0.59	0.91	0.13	0.13	0.19	0.07
60-80 cm canopy	0-20cm inter-canopy	<0.001*	0.61	0.47	0.34	0.63	0.07	0.08	0.04*
	60-80cm inter-canopy	0.86	0.47	0.42	0.26	0.77	0.78	0.09	0.71
0-20 cm inter-canopy	60-80cm inter-canopy	<0.001*	0.87	0.92	0.80	0.13	0.20	0.60	0.05*

** The mean difference is significant at 0.05 level.*

4.1.2 The Distribution of Plant Species in the Study Area

Data on selected *Prosopis* characteristics in the riparian sites is summarized in Table 4.2. The distribution of *Prosopis* in the riparian sites showed high density and percentage cover close to the settlements (Figure 4.2). High density and canopy cover were found at livestock watering points (either boreholes or wells), particularly those that were located within the Nossob-Molopo riparian zone. Heavily invaded patches were found outside the villages between Struizendam and Bokspits villages in the farms that were not fenced (Figure 4.2).

Tree species that were found in the riparian sites apart from *Prosopis* were *Acacia erioloba, Acacia luederitzii, Acacia hebeclada* and *Acacia mellifera.* Shrubs were predominated by *Rhigozum trichotomum.* They included *Lycium* species, *Salsola* species, *Scrophularia* species, *Crotalaria spartioides* and *Gnidia polycephala.* Creepers that were found in the riparian sites were dominated by *Tribulus terrestris,* while grass species included *Aristida* species, *Stipagrostis* species, *Eragrostis* species, and *Schmidtia* species.

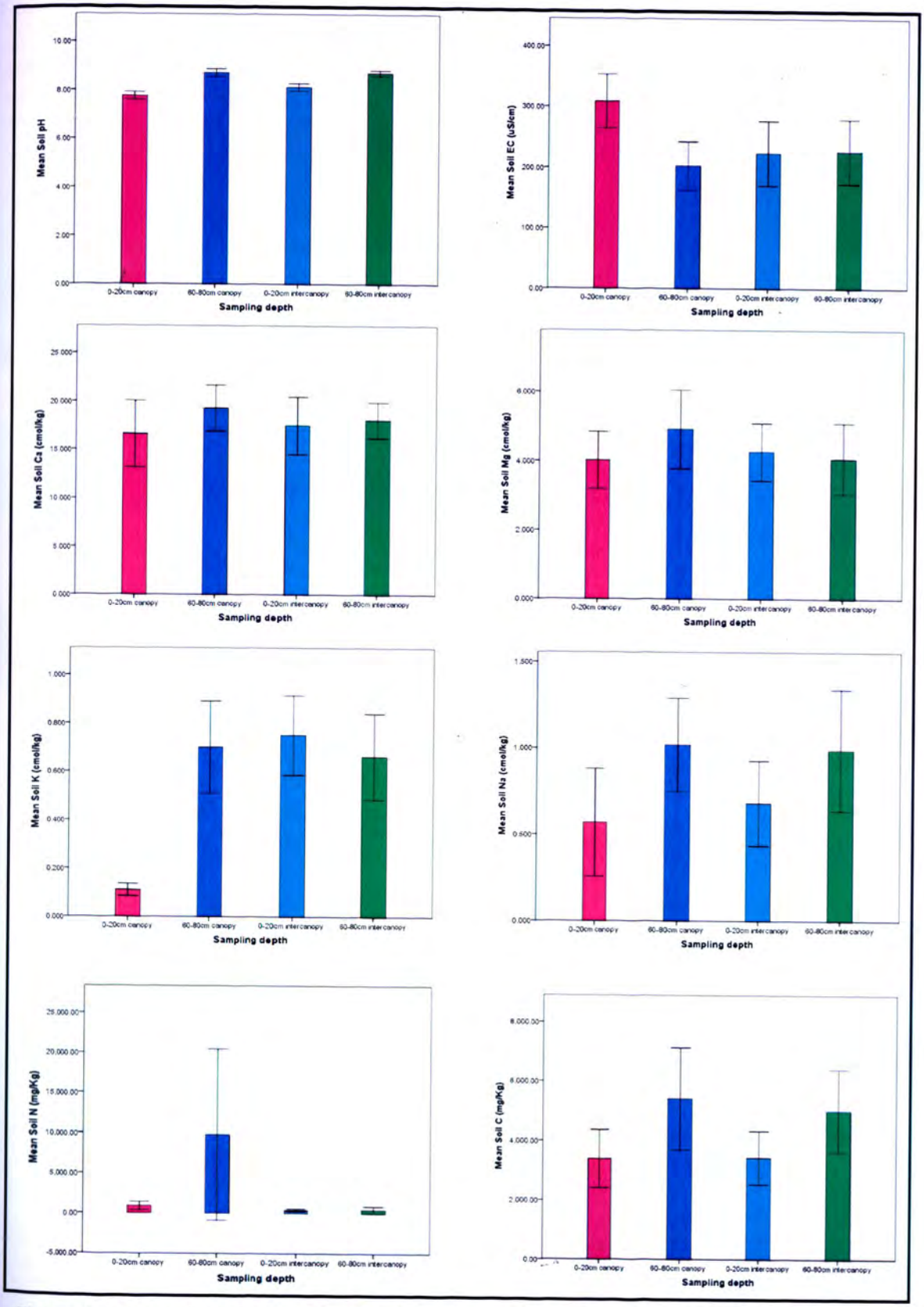


Figure 4.1 Mean values of selected soil attributes in the Riparian sites (*Error Bars: 95% CI*)

Table 4.2 Selected *Prosopis* properties in the BORAVAST area.

Quadrat No.	Sampling Position GPS Coordinates (UTM)		%Cover	Aver-Height (Meters)	Density (No. of plants/ha)
1	463346	7052503	3.18	0.66	160.00
2	463487	7052055	14.77	1.47	448.00
3	463582	7051543	0	0	0
4	463636	7051057	35.48	1.76	640.00
5	463702	7050587	78.55	2.37	848.00
6	463563	7050156	40.96	1.90	400.00
7	463123	7049907	41.21	2.70	672.00
8	463687	7049056	3.36	2.08	32.00
9	462698	7049718	27.57	2.20	256.00
10	462275	7049406	1.77	1.07	32.00
11	463333	7044818	0	0	0
12	464161	7039619	0	0	0
13	462199	7046118	49.82	1.89	896.00
14	462290	7046378	44.55	1.33	656.00
15	462112	7046681	45.36	1.35	864.00
16	463827	7043611	36.15	1.75	688.00
17	463926	7044011	28.23	1.47	496.00
18	463518	7040429	32.78	2.14	464.00
19	463653	7040130	26.10	1.44	368.00
20	468123	7028450	5.32	1.53	560.00
21	468252	7027903	7.54	1.45	256.00
22	468278	7027441	2.03	1.75	32.00
23	468296	7026948	8.48	2.17	720.00
24	468296	7026948	13.35	2.17	112.00
25	468702	7026037	19.00	2.58	304.00
26	468853	7025607	40.97	2.55	816.00
27	468963	7025029	42.54	2.11	448.00
28	469036	7024473	26.88	1.72	288.00
29	4699079	7024086	27.52	1.79	384.00
30	469504	7024357	38.12	1.75	464.00
31	469863	7024752	35.04	1.79	384.00
32	470151	7025136	19.82	1.10	304.00
33	470336	7025577	46.13	2.85	576.00
34	470553	70266024	31.24	1.83	304.00
35	470677	7026463	55.48	2.79	1952.00
36	470838	7026966	60.01	3.34	1088.00
37	471092	7027590	67.81	3.16	864.00
38	471336	7028019	39.80	2.69	624.00
39	472144	7028266	31.04	1.70	608.00
40	472732	7028350	27.79	1.28	592.00
41	473946	7028525	0	0	0
42	483102	7033984	0	0	0
43	482523	7033844	20.97	3.60	80.00

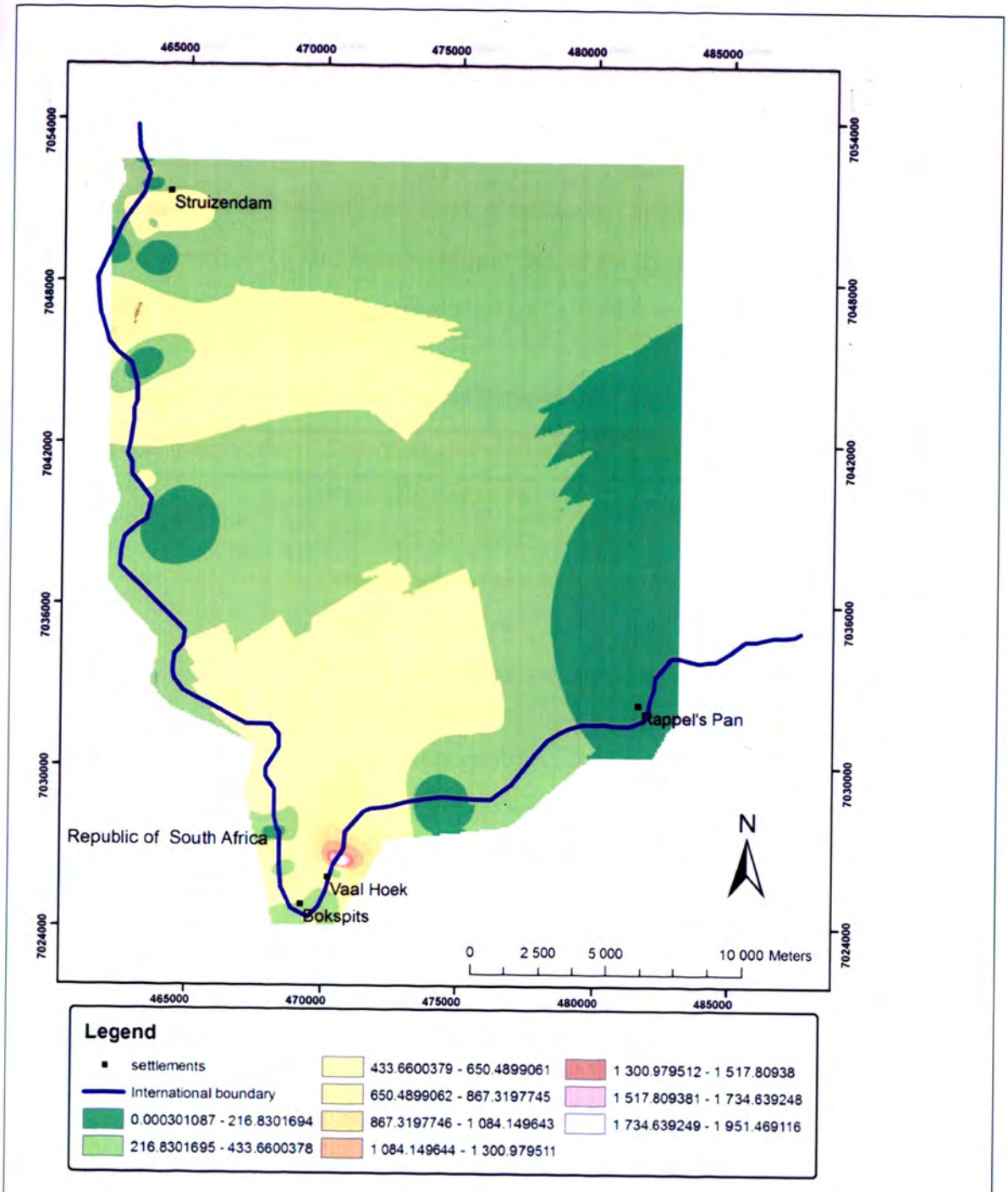


Figure 4.2 The spatial extent of *Prosopis* invasion (number of *Prosopis* trees/Ha) in the BORAVAST area, based on an interpolation of values derived at sampling points.

4.1.3 Correlation of Soil and *Prosopis* Properties

In the investigation of the relationships between selected soil properties (sections 3.2.2 & 3.4) and selected characteristics of *Prosopis* species (section 3.2.1) in the riparian sites, correlation analysis was considered appropriate as it evaluates the strength and direction of the relationships. Based on Table 4.3 (Zou, *et al.*, 2003), the results from correlation analysis presented in Table 4.4 were interpreted.

Table 4.3 Interpretation of correlation coefficient (Adapted from Zou , *et al.*, 2003).

Correlation coefficient value	Direction and strength of correlation
-1.0	**Perfectly negative**
-0.8	**Strongly negative**
-0.5	**Moderately negative**
-0.2	**Weakly negative**
0.0	**No association**
+0.2	**Weakly positive**
+0.5	**Moderately positive**
+0.8	**Strongly positive**
+1.0	**Perfectly positive**

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Selected *Prosopis* characteristics and soil pH at 0-20 cm depth in the inter-canopy had moderately negative relationships. However, the strength of the relationships between the selected soil properties and the selected characteristics of *Prosopis* species ranged from no to moderate associations (Table 4.4).

4.2 Relationships between Growth Stage of *Prosopis* Trees and Selected Soil Properties

The Student's t-Test statistic was used to assess if there were statistically significant differences in the soils existing under the canopies of class 1, class 2, and class 3 *Prosopis* trees for the selected soil properties. Therefore, data obtained from sections 3.2 & 3.3 was used to compare soil samples collected under the canopy of class 1,

Table 4.4 Correlation coefficient (*r*) between soil and *Prosopis* properties.

Soil Property	Sampling Depth	% Canopy Cover	Average Height	Density
pH	canopy 0-20cm	0.07	-0.09	-0.04
	canopy 60-80cm	0.03	0.05	-0.11
	Inter-canopy 0-20cm	-0.32	-0.53	-0.39
	Inter-canopy 60-80cm	0.15	-0.11	-0.05
EC	canopy 0-20cm	0.05	0.12	-0.03
	canopy 60-80cm	0.02	0.11	0.00
	Inter-canopy 0-20cm	0.19	0.28	0.15
	Inter-canopy 60-80cm	0.04	0.45	0.00
Ca	canopy 0-20cm	0.27	0.32	0.12
	canopy 60-80cm	-0.01	-0.05	0.04
	Inter-canopy 0-20cm	0.30	0.30	0.23
	Inter-canopy 60-80cm	-0.23	-0.05	-0.12
Mg	canopy 0-20cm	0.43	0.31	0.21
	canopy 60-80cm	-0.08	0.20	0.01
	Inter-canopy 0-20cm	0.21	0.12	0.16
	Inter-canopy 60-80cm	0.17	0.34	0.08
K	canopy 0-20cm	0.29	0.22	0.07
	canopy 60-80cm	0.03	0.26	0.02
	Inter-canopy 0-20cm	0.24	0.33	0.06
	Inter-canopy 60-80cm	0.04	0.41	0.00
Na	canopy 0-20cm	0.54	0.30	0.43
	canopy 60-80cm	0.09	0.18	-0.10
	Inter-canopy 0-20cm	0.14	0.07	0.21
	Inter-canopy 60-80cm	0.25	0.28	0.04
N	canopy 0-20cm	-0.01	-0.22	-0.02
	canopy 60-80cm	0.02	-0.07	-0.06
	Inter-canopy 0-20cm	0.31	0.32	0.10
	Inter-canopy 60-80cm	0.14	0.12	-0.05
C	canopy 0-20cm	0.13	0.34	0.05
	canopy 60-80cm	-0.11	0.16	0.12
	Inter-canopy 0-20cm	0.35	0.32	0.30
	Inter-canopy 60-80cm	-0.22	0.22	-0.03

class 2, and class 3 *Prosopis* trees in relation to the selected soil properties. It was observed that soil under class 3 *Prosopis* tree canopies were statistically significantly different from soil under class 1 and class 2 *Prosopis* tree canopies in terms of pH and EC (Figure 4.3 &Table 4.5). Other selected soil attributes did not show statistically significant differences in the soils existing under the canopies of class 1, class 2, and class 3 *Prosopis* trees. The observation was consistent with the results obtained in section 4.1.

4.3 Seed Bank Assessment

The soil seed bank was devoid of *Prosopis* seeds at 5-10 cm depth in the inter-canopy of *Prosopis* trees and 0-10 cm depth in the non-invaded sites and the riparian area in Rappelspan village. Few scattered small *Prosopis* trees were observed in the Rappelspan riparian area suggesting that the establishment of *Prosopis* in the site was in its early stages. A range of 47 to 1159 seeds m^{-2} was observed in the study area (Table 4.7). The standard deviation and coefficient of variation of the number of *Prosopis* seeds in the soil seed bank (Table 4.7) indicated that counts obtained for *Prosopis* seeds in the soil seed bank were widely dispersed around the mean values.

Table 4.5 Student's t comparison of the soils under the canopies of class 1, class 2 and class 3 *Prosopis* trees.

		pH	EC	Na	K	Ca	Mg	N	C
Class 1	Class 2	0.176	0.395	0.371	0.863	0.453	0.877	0.532	0.937
	Class 3	0.004*	0.004*	0.976	0.105	0.411	0.415	0.963	0.126
Class 2	Class 3	0.079	0.013*	0.397	0.134	0.112	0.311	0.423	0.121

**The mean difference is significant at the 0.05 level*

The Chi Square test statistic was utilized to assess the significance of the differences in the seed bank between riparian canopy 0-5 cm, riparian canopy 5-10 cm, riparian inter-canopy 0-5 cm, invaded settlement canopy 0-5cm, invaded settlement canopy 5-10cm, and invaded settlement inter-canopy 0-5cm (Table 4.6). All sampled depths (0-5 cm & 5-10 cm) and sites were statistically significantly different in terms of seed bank ($P < 0.001$). The general distribution pattern of *Prosopis* seeds indicated that more seeds existed in the soil under *Prosopis* tree canopies in the 0-5 cm soil depth.

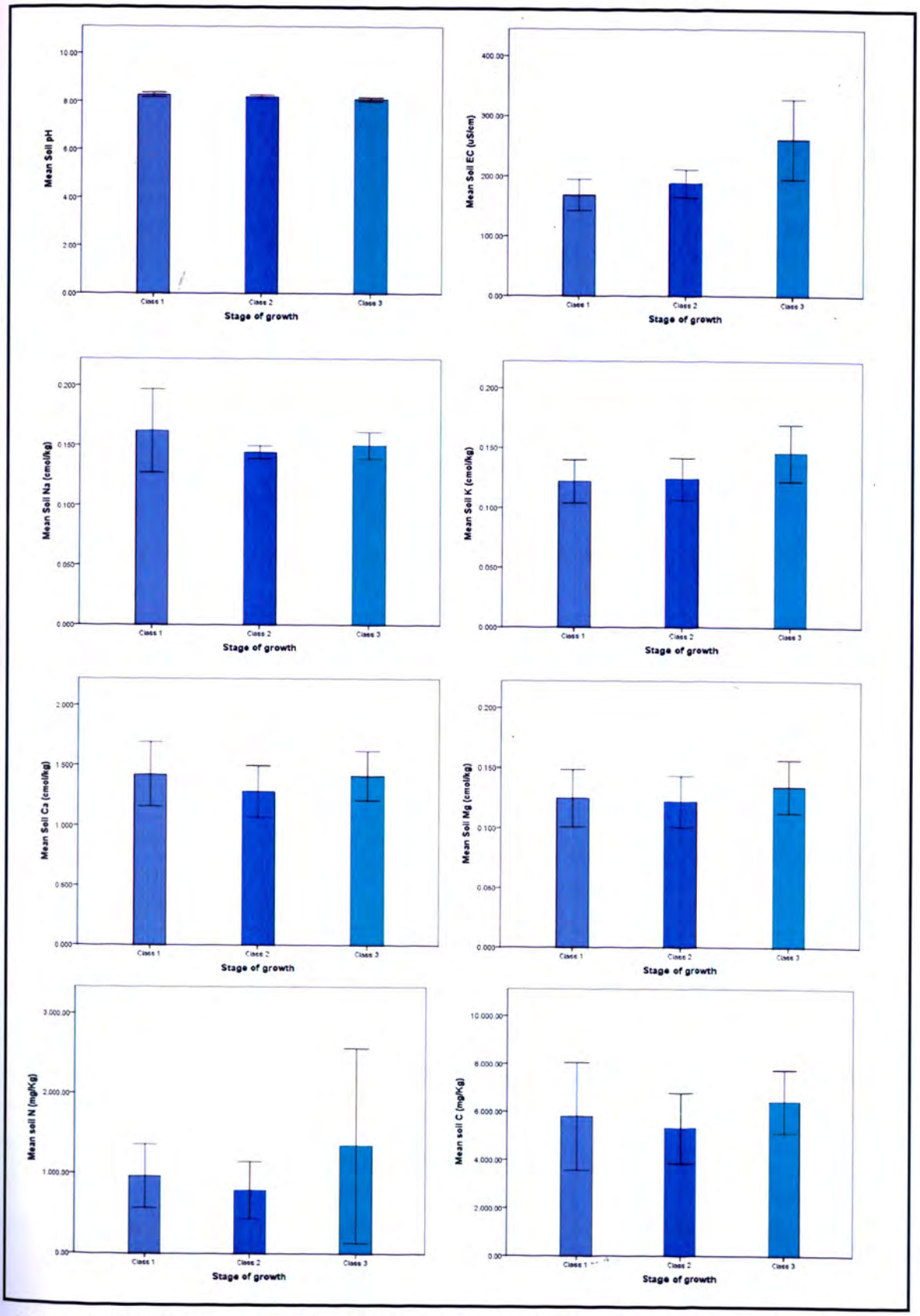


Figure 4.3 Mean values of selected soil properties for different *Prosopis* growth stages (*Error Bars: 95% CI*).

Table 4.6 Chi Square statistic (χ^2-values) for different sampling depths and sites.

	Riparian Canopy 5-10 cm	Riparian Inter-canopy 0-5 cm	Settlement invaded Canopy 0-5 cm	Settlement invaded Canopy 5-10 cm	Settlement invaded Inter-canopy 0-5 cm
Riparian Canopy 0-5cm	396.21	423.52	298.03	303.53	443.78
Riparian Canopy 5-10cm		195.15	250.17	199.83	190.55
Riparian Inter-canopy 0-5cm			288.79	142.89	209.16
Settlement invaded Canopy 0-5cm				98.94	158.43
Settlement invaded Canopy 5-10cm					136.46

Table 4.7 Number of *Prosopis* seeds in the seed bank at different sampling depth and sites.

Sampling site & depth	*Prosopis* seed number (No. of seeds m^{-2})		
	Mean	*Standard Deviation*	*Coefficient of Variation (%)*
Riparian Canopy 0-5cm	1159	3937	339.69
Riparian Canopy 5-10cm	107	223	208.41
Riparian Inter-canopy 0-5cm	277	1251	451.62
Settlement invaded Canopy 0-5cm	211	312	147.87
Settlement invaded Canopy 5-10cm	47	89	189.36
settlement invaded inter-canopy 0-5cm	144	192	133.33

4.4 Perceptions of the Communities about *Prosopis* Species

4.4.1 Focused Group Discussions

The following is a summary of information gathered through focused group discussions that were conducted in the BORAVAST villages. In addition, APPENDIX 2 shows separate views of the communities collected from the discussions.

- *Prosopis* species were mostly introduced in the BORAVAST area by the Ministry of Agriculture in the 1980s through the National Tree Planting Day programme. The main purpose of introducing the species by the Ministry of Agriculture was to stabilize sand dunes in the area. Some *Prosopis* trees were brought into the area from South Africa and Namibia much earlier than the 1980s by individuals who were employed in those countries. Individuals were motivated to plant *Prosopis* trees by the shade they provide during summer times.
- The species had increased in density over the years since its introduction.
- Since the introduction of *Prosopis* species in the area, its density did not cause concern until around the year 2000.
- The disadvantages of having the species in the environment by far outweighed the advantages. However, it was not desirable to eradicate the species without first identifying a replacement species with good qualities similar to those of *Prosopis* species, but lacking the bad properties associated with *Prosopis* species.
- The management strategy that was implemented to control the invasion of *Prosopis* species within the invaded settlement sites entailed pruning and uprooting of some trees through various Government assistance programmes like the *Ipelegeng* (drought relief) programme. The Department of Roads also assisted in clearing of *Prosopis* trees by uprooting them along roadsides. However, the focus of all government assistance programmes was not the management of *Prosopis* but poverty alleviation. Consequently, the programmes did not contribute in the effective management of *Prosopis* in the area.
- The problem of *Prosopis* invasion in the area had been a bone of contention in various meetings that were addressed by Government officials, but up to the date of the survey, nothing in

the form of assistance specifically targeting the species management had materialized.

- The seeds of the species were mainly dispersed by livestock particularly donkeys and horses which deposited intact seeds with their pellets. Ruminants like cattle and goats did not contribute significantly to the dispersal of the species seeds because their digestive systems effectively crush *Prosopis* seeds.
- Selective uprooting of *Prosopis* trees; where *Prosopis* trees are completely removed in areas where their presence is considered undesirable, was suggested as the most potentially effective management method.
- Generally, the communities did not generate funds from *Prosopis* species products. However, some farmers once in a while engaged some people to harvest pods for livestock feeding. The value of a bag full of *Prosopis* pods was five to ten Pula (value in Botswana Pula, BWP: P5.00 to P10.00).
- The communities had some revenue generation ideas that could be implemented to exploit *Prosopis* species. These included commercial production of treated poles for fencing and pods processing for fodder. Lack of market and expertise were cited as the main obstacles with regard to revenue generation from *Prosopis* by-products.
- The communities expressed interest in learning ways of exploiting *Prosopis* species to their own advantage if given an opportunity.
- The constraints in *Prosopis* management were mainly lack of relevant expertise and funds.
- The disadvantages of having *Prosopis* species in the area included the following;
    - Killing of other trees that grow within their environments.
    - Depletion of underground water resources.

- Possessing large thorns that cause tyre deflations and injure human.
- Killing of livestock particularly donkeys and horses through constipation caused by overfeeding on pods produced by *Prosopis* trees.
- Causing constipation in children who enjoy feeding on the sweet pods of some *Prosopis* species.

o The advantages of *Prosopis* species included the following;

- Provision of good shade.
- Stabilization of sand dunes.
- Serving as wind breakers.
- Provision of fodder resources (pods) for livestock.
- Provision of fire wood.
- Provision of timber for fencing. However, it was indicated that the timber does not last for more than two years when untreated.

4.4.2 Questionnaire Survey

At the completion of the social survey that was conducted through the use of a questionnaire (APPENDIX 1), data from the survey was compilled and analysed through the use of Predictive Analytics Soft Ware (PASW) version 19.0 to explore the perceptions of the communities of the BORAVAST villages about *Prosopis* species.

The survey indicated that 140 out of 339 respondents (41.3%) had reached up to primary education (Figure 4.4). On the other hand 145 (42.8%) respondents had gained secondary education, while 22 respondents (6.5%) had exposure to post-secondary education (Figure 4.4).

Most of the respondents (78.44%) indicated that *Prosopis* was brought into BORAVAST area in the early 1980s (Figure 4.5). In addition, the respondents pointed out that *Prosopis* was brought into the area by the

then Department of Forestry which was under the Ministry of Agriculture. Other respondents mentioned that before the Ministry of Agriculture brought the species into the area, some individuals in their community had already began as early as before and around the 1970s to bring the species into the area from Namibia and South Africa.

Concerning the allellopathic effects of *Prosopis* species on other plant species growing in the area, the data indicated that 94.20% of the respondents were on the affirmation side (Figure 4.6). A larger proportion of respondents (71.30%) asserted that the invasion of the species in the area had resulted in the deterioration of the livelihoods of the communities (Figure 4.7). On the other hand, 17.75% of the respondents considered *Prosopis* invasion as one of the factors that had contributed to the improvement of livelihoods in the area. The reasons that were advanced in favour or against *Prosopis* were similar to those that were gathered during focused group discussions (section 4.4.1). However, 80% of the respondents viewed the species as a nuisance (Figure 4.8). Similar to other communities elsewhere around the world where *Prosopis* species were introduced, the existence of the species in the BORAVAST villages was initially a well-accepted phenomenon. This was the *status quo* until around the early 1990s when some members of the communities became concerned about its spread in the area (Table 4.8). Around the year 2000, it became apparent to some of the respondents (59.9%) that the rate at which the species spread and their impacts on their livelihoods was becoming a cause for concern (Table 4.8). Consequently, 79.8% of the respondents indicated that they had endeavoured to control the spread of the species, while others had decided that the problem was beyond their control (Table 4.9)

The efforts that were undertaken to arrest the invasion of *Prosopis* in the BORAVAST villages mainly included clearing by cutting *Prosopis* trees through individual and community efforts (Figure 4.9). In most instances,

cutting was carried out by pruning of some *Prosopis* trees and uprooting some. According to the observations of the respondents, efforts that were undertaken to control the spread of *Prosopis* species did not bear fruit. The respondents indicated that the efforts produced insignificant changes in the rate at which the species continued to invade the area. Furthermore, some respondents observed that the methods that were used to control the invasion of the species resulted in an increase in the rate and scale of invasion of the species. Consequently, 72.30% of the respondents made efforts to report the species invasion (Figure 4.10) to Governmental institutions and NGOs. Many reports were presented at various fora like *Kgotla* meetings by the communities and their leaders.

The invasion of *Prosopis* was reported to the Department of Forestry and Range Resources (DFRR) in the Ministry of Agriculture, Kgalagadi District Council, community trust (BORAVAST Trust) and the VDCs (Table 4.10). The BORAVAST communities trusted that the afore-mentioned organisations would assist them in controlling *Prosopis*. However, Bokspits and Vaalhoek respondents indicated that no action was taken in response to their reports, while Rappelspan and Struizendam respondents mentioned that clearing of *Prosopis* trees was included in the drought relief programme as a reaction to their reports (Figure 4.11).

The respondents (76.83%) indicated that the main dispersal agent for *Prosopis* seeds was livestock (Figure 4.12). During the pilot social survey, the respondents mentioned that not all livestock but donkeys and horses promoted the dispersal of the seeds of the species as their digestive systems are unable to completely destroy the seeds. Therefore, the survey made an investigation regarding the claim and 22.87% of the respondents affirmed the claim with emphasis on donkeys. According to the respondents, human beings played insignificant role in the dispersal of the seeds of *Prosopis* species in their area.

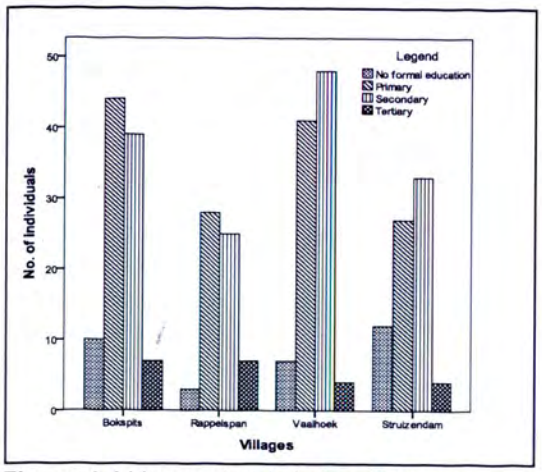


Figure 4.4 Literacy levels in the study area.

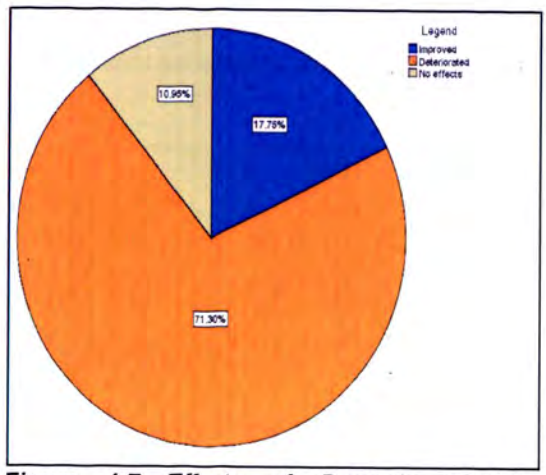


Figure 4.7 Effects of *Prosopis* species invasion on the livelihoods of the communities.

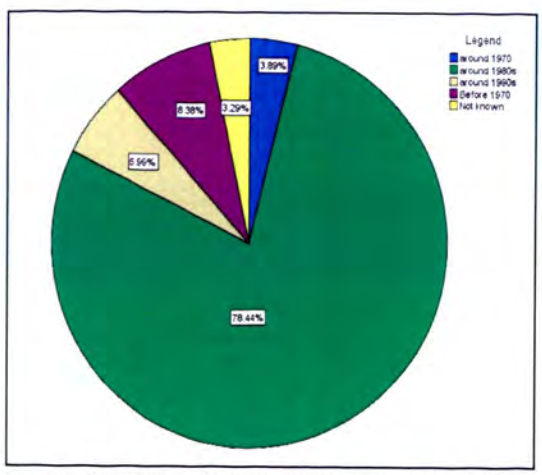


Figure 4.5 Year of *Prosopis* introduction in the BORAVAST area.

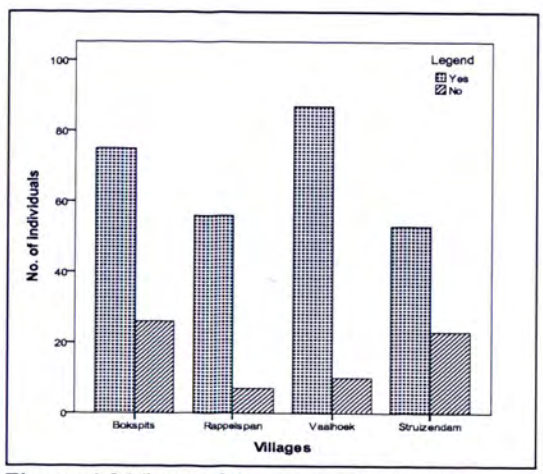


Figure 4.8 Views of the respondents on whether or not *Prosopis* species was a nuisance.

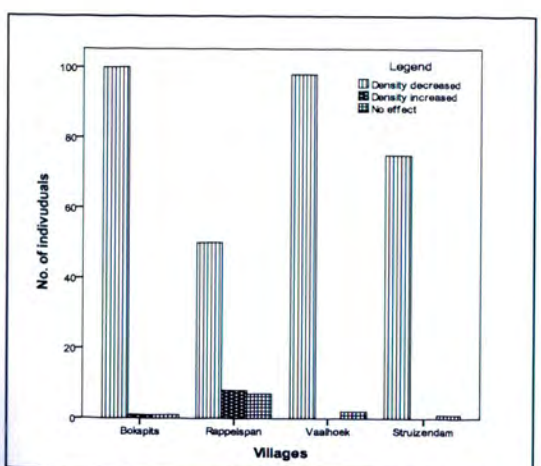


Figure 4.6 Effects of the invasion of *Prosopis* species on other plant species.

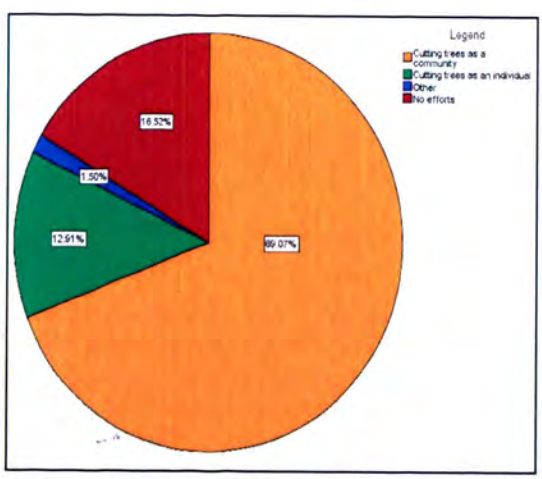


Figure 4.9 Methods of controlling the invasion of *Prosopis* species.

Table 4.8 The years when the spread of *Prosopis* species became a cause for concern to the communities.

	Villages	1970s	1980s	1990s	2000s	Other Years	TOTAL
Bokspits	No. of individuals	0	0	1	100	1	102
	% of Total	0%	0%	0.30%	29.20%	0.30%	29.80%
Rappelspan	No. of individuals	0	3	17	44	0	64
	% of Total	0%	0.90%	5.00%	12.90%	0%	18.70%
Vaalhoek	No. of individuals	7	10	65	16	2	100
	% of Total	2.00%	2.90%	19.00%	4.7%	0.60%	29.2%
Struizendam	No. of individuals	0	0	0	45	31	76
	% of Total	0%	0%	0%	13.20%	9.10%	22.20%
TOTAL	No. of individuals	7	13	83	205	34	342
	% of Total	2.00%	3.80%	24.30%	59.90%	9.90%	100%

Table 4.9 Efforts in *Prosopis* invasion control.

Villages		Made an effort	Made no effort	TOTAL
Bokspits	No. of individuals	63	39	102
	% of Total	18.40%	11.40%	29.80%
Rappelspan	No. of individuals	53	11	64
	% of Total	15.50%	3.20%	18.70%
Vaalhoek	No. of individuals	83	17	100
	% of Total	24.30%	5.00%	29.20%
Struizendam	No. of individuals	74	2	76
	% of Total	21.60%	0.60%	22.20%
TOTAL	No. of individuals	273	69	342
	% of Total	79.80%	20.20%	100%

The options of *Prosopis* management strategies that were suggested by the

respondents (Figure 4.13) included the following:-

1. Cutting or pruning of all mature *Prosopis* trees to prevent bush thickening.

2. Eradication of *Prosopis* trees by uprooting.

3. Selective uprooting of *Prosopis* trees in the area to control bush thickening. In this option, uprooting would only be applied to *Prosopis* trees which grow where they are not needed (e.g. along road side and inside the yards).

4. The use of a combination of uprooting process and chemical treatment to eliminate regeneration. This was considered as a long term solution that would lead to a reduction in the spread of the species in the area. This view was premised upon the belief that the species was able to regenerate even after total removal.

Respondents in Vaalhoek mainly advocated for the complete eradication of *Prosopis* species in their village, but respondents in other villages favoured management as opposed to eradication. Respondents who supported the idea of complete eradication of the species in the area indicated that the advantages of having the species in the area were outweighed by the disadvantages. However, the view of *Prosopis* management was sponsored on the basis that the species played a very critical role as a natural fodder resource in the harsh environment of the area. The respondents mentioned that the communities mainly harvested the pods of *Prosopis* species and used them as livestock fodder (Figure 4.14).

Harvesting of the pods was mainly undertaken during the summer period (Figure 4.15). The species was also significantly used as fire wood although it was indicated that it performed poorly in terms of energy output compared to other plants. It was used as the last resort for any

form of construction as the timber produced from the species was considered to be susceptible to attack by termites which shortened its life span. Susceptibility of timber produced from *Prosopis* to attack by termites was also expressed by other communities elsewhere where *Prosopis* grow (e.g. Bokrezion, 2008; Bloesch 2001)

Table 4.10 Institutions and departments to which *Prosopis* invasion was reported.

Villages		Agriculture	Council	Other	Missing	BORAVAS T TRUST & VDC	TOTAL
Bokspits	No. of	36	7	0	0	17	60
	% of	14.30%	2.80%	0%	0%	6.80%	23.90
Rappelspan	No. of	6	1	1	4	37	49
	% of	2.40%	0.40%	0.40%	1.60%	14.70%	19.50
Vaalhoek	No. of	5	0	2	1	69	77
	% of	2.00%	0%	0.80%	0.40%	27.50%	30.70
Struizendam	No. of	5	10	12	1	37	65
	% of	2.00%	4.00%	4.80%	0.40%	14.70%	25.90
TOTAL	**No. of**	**15**	**52**	**18**	**15**	**6**	**160**
	% of	**6.00%**	**20.7%**	**7.20%**	**6.00%**	**2.40%**	**63.70**

Harvesting of *Prosopis* species products presented various challenges to the communities (Figure 4.16). The main challenges mentioned by the respondents included the following:-

1. **Long distance to the locations where *Prosopis* resources were abundantly available**: Although the invasion of the species had affected the settlement sites, the respondents indicated that livestock normally loitered around the settlement areas during the fruiting period of the species. Consequently, *Prosopis* trees that were in the settlements sites lost their seed pods to livestock faster than those that were far afield. This reduced accessibility and availability of pods to people who preferred to harvest and use the

seed pods as livestock fodder.

2. **Lack of market for the resources or poor demand:** This was the main challenge that was identified concerning the harvesting of *Prosopis* products. The demand for *Prosopis* products was particularly low because the products were freely available to everybody. Therefore, there was nothing that motivated people to harvest *Prosopis* products especially those who did not have livestock.
3. **Low prices for the resources:** This was one of the challenges that were faced by those who sometimes attempted to generate some income from harvesting *Prosopis* pods. They indicated that low demand forced them to sell a bag of *Prosopis* pods at very low prices (P5.00-P10.00/bag) that were not commensurate with the efforts invested in the harvesting process.
4. **Physical injuries**: Other challenges included physical injuries that were associated with harvesting products of *Prosopis* species. Many *Prosopis* species that grow in the area have big thorns which may cause injuries.

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The respondents (48.98 %) identified some ways in which the communities could generate funds from some products of *Prosopis* species (Figure 4.17). Selling of timber for fire wood and pods for fodder were identified as the main potential ideas for generation of funds (Table 4.11).

There were some constraints that the respondents foresaw with respect to the ideas that they suggested as ways that could be implemented to generate revenue from *Prosopis* products (Figure 4.18). These included the following:-

1. **Low prices attached to the products:** The products harvested from *Prosopis* trees were of low price value in the BORAVAST villages. Consequently, the views of the respondents indicated that a

business undertaking associated with the species products was neither feasible nor viable particularly within the boundaries of the study area.

2. **Low demand or lack of market for the products:** The respondents attributed this to the fact that harvesting of *Prosopis* products was not regulated. However, those who held this view did not consider the possibility of exploring external market outlets for *Prosopis* products.

3. **Lack of resources:** Respondents who had ideas of revenue generation from *Prosopis* products mentioned this as the main obstacle. They mentioned that they lacked financial resources, equipment and relevant technical skills that could allow them to take advantage of the invasion of *Prosopis* in their area.

Table 4.11 Suggested ways of revenue generation from *Prosopis* products.

Villages		Suggested ideas of revenue generation				TOTAL
		Selling timber	Selling pods	Other	No idea or no response	
Bokspits	No. of individuals	34	39	3	26	102
	% of Total	9.90%	11.40%	0.90%	7.60%	29.70%
Rappelspan	No. of individuals	5	10	1	49	65
	% of Total	1.50%	2.90%	0.30%	14.30%	19.00%
Vaalhoek	No. of individuals	0	4	2	94	100
	% of Total	0%	1.20%	0.60%	27.40%	29.20%
Struizendam	No. of individuals	4	21	46	5	76
	% of Total	1.20%	6.10%	13.40%	1.50%	22.20%
TOTAL	No. of individuals	**43**	**74**	**52**	**174**	**343**
	% of Total	**12.50%**	**21.60%**	**15.20%**	**50.70%**	**100%**

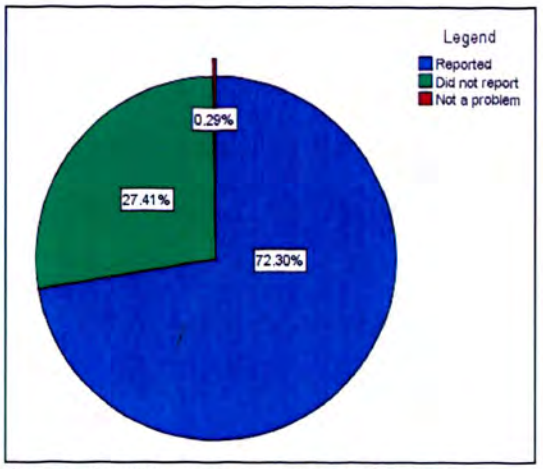


Figure 4.10 Reporting made on *Prosopis* invasion.

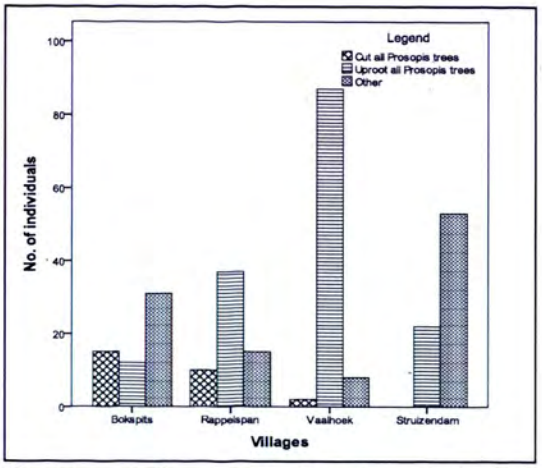


Figure 4.13 management strategies suggested by respondents.

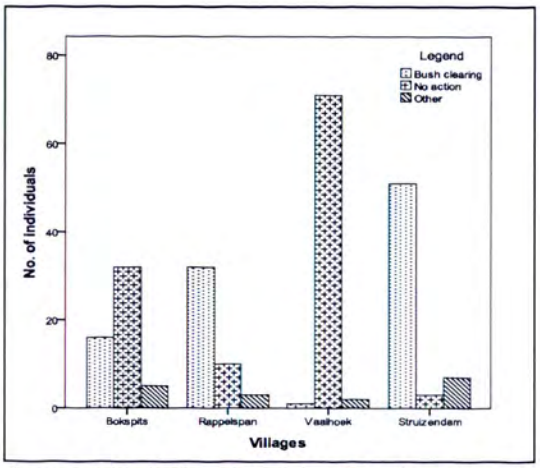


Figure 4.11 Actions taken by departments and institutions to which the *Prosopis* species invasion was reported.

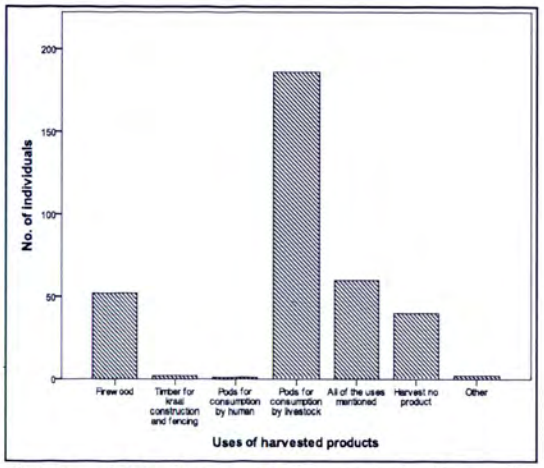


Figure 4.14 Uses of harvested *Prosopis* species products in the BORAVAST villages.

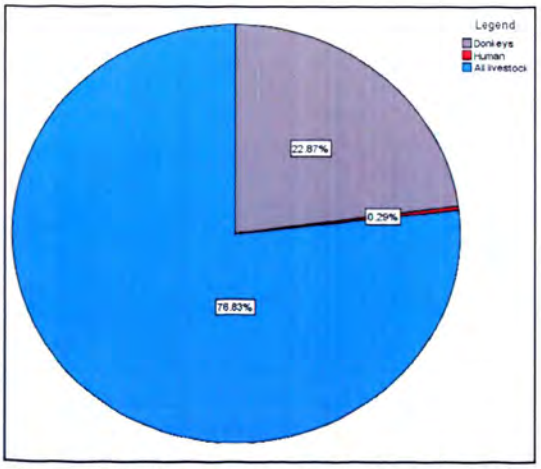


Figure 4.12 Dispersal agents for the seeds of *Prosopis* species.

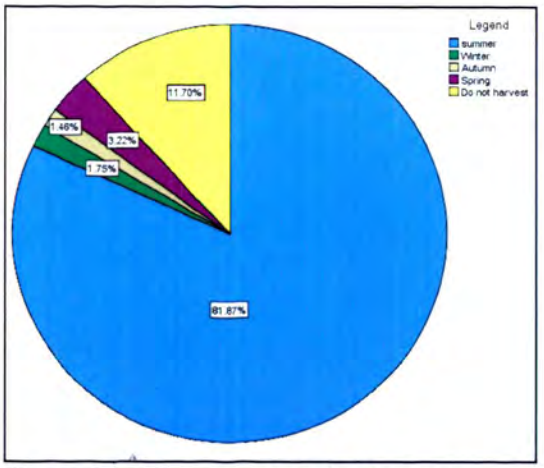


Figure 4.15 Harvest periods for *Prosopis* species pods.

The respondents were ready to accept new ideas concerning efficient exploitation of *Prosopis* species (Figure 4.19). With respect to the performance of the BORAVAST Trust and the VDCs in dealing with the invasion of the species in the area, the respondents were generally satisfied (Figure 4.20). Their satisfaction was based on the view that the CBOs were doing the best they could do with regard to the problem of *Prosopis* invasion under the conditions that existed, but support from the Government and NGOs was not sufficient.

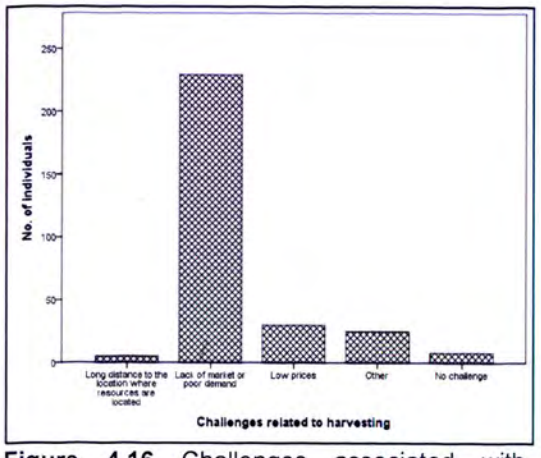


Figure 4.16 Challenges associated with harvesting of *Prosopis* products.

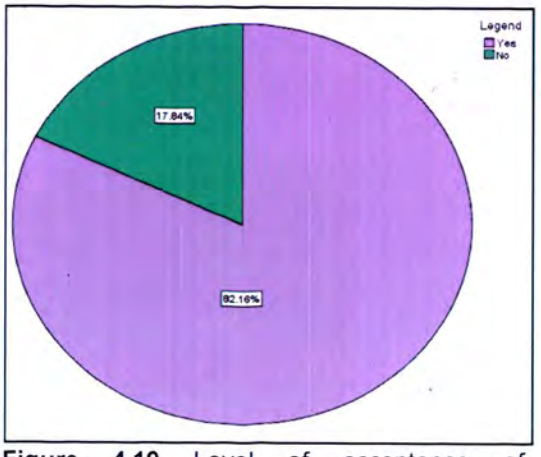


Figure 4.19 Level of acceptance of opportunites to learn ways of exploiting *Prosopis species.*

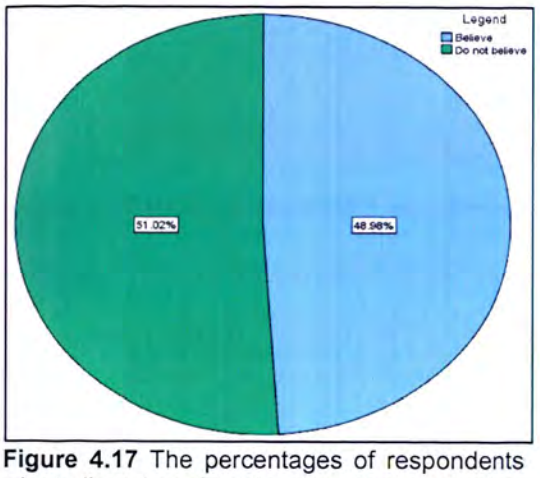


Figure 4.17 The percentages of respondents who believed or did not believe that generation of income from *Prosopis* products was possible.

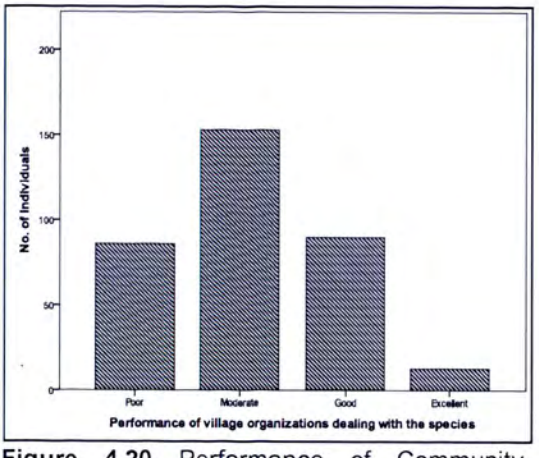


Figure 4.20 Performance of Community Based Organizations in controlling *Prosopis* invasion.

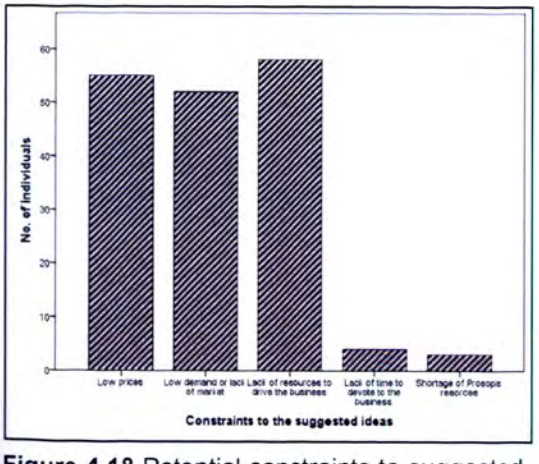


Figure 4.18 Potential constraints to suggested ideas of revenue generation.



Plate 1. *Prosopis* trees stabilizing a sand dune in Rappelspan village *(2008).*



Plate 2. A quadrat used for seed bank sampling.



Plate 3. *Prosopis* nursery established in the 1980s in Rappelspan (2010).

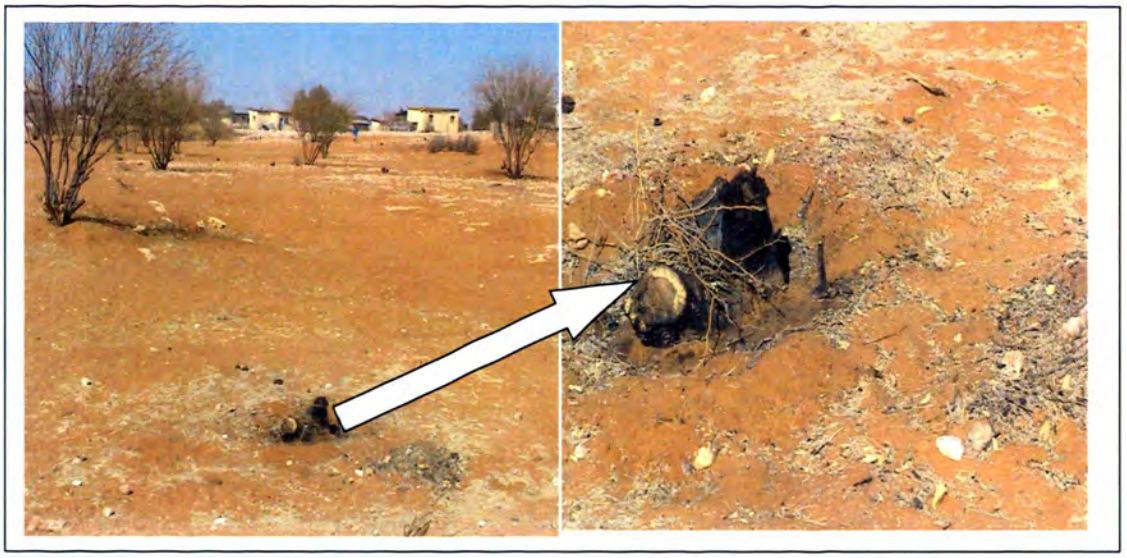


Plate 4. *Prosopis* management by cutting and fire application conducted in the study area (2010).



Plate 5. Abundant plant litter produced by *Prosopis* enriching soil with organic carbon.



Plate 6. Invasion of *Prosopis* in Struizendam village (2010).



Plate 7. Invasion of *Prosopis* around livestock watering points (2010).

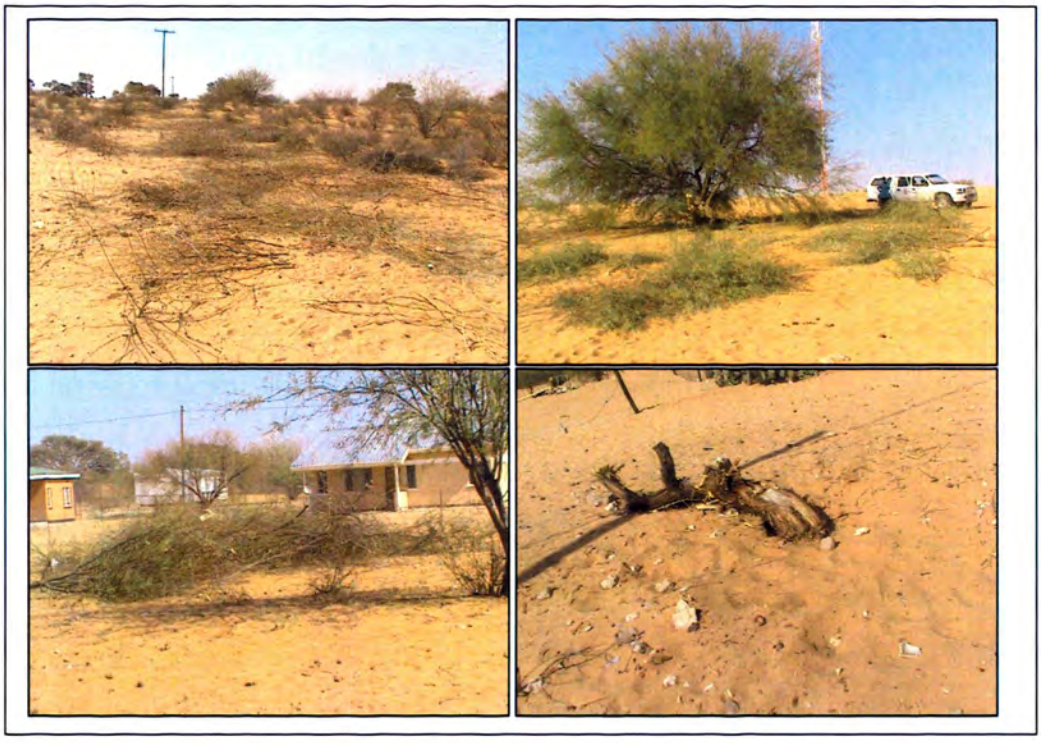


Plate 8. Indiscriminate cutting and dumping of *Prosopis* tree branches taking place in the study area.

Chapter 5

DISCUSSION

5.0 Introduction

This chapter synthesizes the results of the study. It discusses the relationships between *Prosopis* invasion and the distribution patterns of soil attributes, distribution patterns of *Prosopis* seeds in the soil seed bank and its implications on the invasion of the species, and the relationships between anthropogenic factors and the invasion of *Prosopis*. The spatial aspects of *Prosopis* species and *Prosopis* management approaches applicable to the study area are also considered. The chapter ends with an assessment of the research methods utilized in this study.

5.1 *Prosopis* Invasion in Relation to Edaphic Factors

5.1.1 Soil Fertility in Invaded Areas

The study established that soil nitrogen content in the study area was low (Figure 4.3), and that soils under *Prosopis* tree canopies and the inter-space were not significantly different in terms of soil nitrogen content (Table 4.1). This suggested that nitrogen fixing by *Prosopis* plant in the study area did not significantly modify the soil nitrogen content.

The observation made in this study on nitrogen was not in conformity with the results obtained from other parts of the world where *Prosopis* species grow. Other studies have indicated that *Prosopis* trees significantly modify the chemical and physical characteristics of soil on which they grow (e.g. Bhatia, *et al.*, 1998; Garg, 1998; Geesing, *et al.*, 2000; Rossi & Villagra, 2003). Such studies showed that increased soil nutrient content (e.g. soil organic matter, nitrogen (N), phosphorus (P), calcium (Ca), magnesium (Ca), potassium (K), sodium (Na)) and lower values of pH

levels are associated with soils found under the canopies of *Prosopis* trees compared to the inter-canopy areas in arid and semi-arid environments (Bhatia, *et al.*, 1998; Garg, 1998; Pasiecznik, 2001).

However, the results of this study were in harmony with the observations made in other previous research on the Kgalagadi soils. The studies on the Kgalagadi soils have indicated that high temperatures, low rainfall, low mineralization rates together with rapid uptake of plant nutrients which characterize arid and semi-arid plants, restrict the build-up of increased soil nitrogen content (McNaughton & Chapin, 1985; Doudill, *et al.*, 1998). Other studies have compared the Kgalagadi soils with other arid and semi-arid soils which are known for their very low nitrogen content and they observed that the Kgalagadi soils had even lower nitrogen content (Singh, *et al.*, 1991; Scholes & Walker, 1993; Doudill, *et al.*, 1998). Due to the constrained build-up of soil nitrogen in the study area, nitrogen was not able to accumulate to significant levels in the soils under *Prosopis* tree canopies than in the inter-canopy.

Soils in the study area had significantly lower soil organic carbon content at 0-20 cm soil depth in comparison with 60-80 cm soil depth under *Prosopis* tree canopies (Table 4.1 & Figure 4.1). The 0-20 cm soil depth in the inter-canopy area had significantly lower soil organic carbon compared to 60-80 cm under canopy depth and the 60-80 cm inter-canopy depth. Therefore, generally the soil in the study area had significantly higher soil organic carbon in the sub-surface soil as compared to the surface soil.

These results compare positively with previous studies which showed that *Prosopis* species produce abundant litter fall (Plate 5) (e.g. Singh, 1996; Garg, 1998). For instance, a 4 to 6 year old *Prosopis juliflora* stand produced 5 to 8 tonnes per hectare per year of dry leaf litter (Singh, 1996), while 8 year old *Prosopis juliflora* stand produced 7.4 tonnes per hectare per year

of dry leaf litter (Garg, 1998) in India. Fisher (1990) pointed out that carbon fixation through photosynthesis is the most important way in which plants enhance the soil organic carbon content and that the carbon fixed in the plant is transferred into the soil through litter fall. It is on these premises that the soil organic carbon content under the canopies of *Prosopis* trees in the study area was significantly higher than in the inter-canopy.

Due to the environmental conditions in the Kgalagadi Desert, the study area is dominated by aeolian processes (Leistener, 1967; Lancaster, 1978a & 1978b). Aeolian processes coupled with termite activity led to the removal of organic materials from the soil surface to the sub-surface soil (Leistener, 1967). As a result, the sub-surface soil had significantly higher soil organic carbon content than the surface soil.

The soils in the study area displayed low contents of potassium, sodium, calcium, and magnesium (Figure 4.1), and the contents of these soil nutrients under *Prosopis* tree canopies and the inter-canopies were not significantly different. This was not surprising because soils in the study area are sandy and they are known to be naturally poor in plant nutrients (Bergstrom & Skarpe, 1985; Perkins, 1991; Chanda, *et al.*, 2003; Vanderpost, *et al*, 2011).

The observation that no statistically significant differences in the soil existing under the canopies of class 1, 2 and 3 *Prosopis* trees in relation to the selected soil nutrients (soil organic carbon, Ca, Mg, K, Na and N) provided evidence that the influence of height and canopy size of *Prosopis* trees on the selected soil properties was not significant up to 0-10 cm soil depth. On the basis of previous studies that showed that the growth of a tree and the development of its canopy lead to an increase in the duration of nutrient accumulation and the improvement in understory soil conditions (Charley & West, 1975; Ludwig *et al.*, 1975; Reynolds *et al.*,

1999), statistically significant differences in the soil existing under the canopies of class 1, 2 and 3 *Prosopis* trees in relation to the selected soil nutrients was expected. However, this study has shown that soil organic carbon was statistically significantly different between the surface (0-20 cm soil depth) soil and the sub-surface (60-80 cm soil depth) under *Prosopis* tree canopies. This suggested that further investigation may have revealed that the height and canopy size of *Prosopis* trees have significant influence on the selected soil properties, particularly soil organic carbon.

In general, it was established that soils in the study area had low plant nutrient content. However, the soils displayed significantly higher soil organic carbon content under *Prosopis* tree canopies compared to the inter-space. Doudill, *et al.* (1998) rated soil organic carbon among the three most limiting factors in plant productivity in arid and semi-arid environments. Therefore, at least on the basis of the pattern of soil organic carbon distribution, evidence of the existence of "fertile islands", under *Prosopis* tree canopies was established in the study area.

5.1.2 *Prosopis* Seed Bank in the Soil

The study established that at the depths of 0-5 cm and 5-10 cm in the non-invaded areas, 5-10 cm in the inter-canopy sites and the Rappelspan riparian zone the soil did not contain *Prosopis* seeds. In addition, the number of *Prosopis* seeds was significantly higher under *Prosopis* tree canopies than in the inter-canopy sites. The observation did not imply that the soil seed banks at the depth of 0-5 cm and 5-10 cm in the non-invaded areas, 5-10 cm in the inter-canopy sites and the Rappelspan riparian zone were completely devoid of *Prosopis* seeds, but suggested that the probability of finding a *Prosopis* seed in the soil outside the canopy of *Prosopis* trees in the study area was significantly low.

Although the spatial distribution of *Prosopis* seeds appeared to be dependent on the external seed dispersal agents (e.g. wind, water, and

animals) during the early years of the introduction of the species in the study area, there was an indication that external seed dispersal agents did not play a significant role in the distribution of *Prosopis* seeds in the soil seed bank at the time of this study. However, research has shown that *Prosopis* species are notorious for rapid and prolific seeding even under hostile conditions (Zimmerman, 1991; Pasiecznik, 2001). The species are able to produce as many as 630 000 to 980 000 flowers per mature tree per year (Felker, 1984), which enhance the survival rate of flowers and their probability to develop into seed pods. Due to high number of *Prosopis* seeds which were deposited into the soil seed bank under *Prosopis* tree canopies, development of *Prosopis* thickets was common in the study area.

5.2 Perceptions of the Communities about *Prosopis* Species

5.2.1 Introduction of *Prosopis* Species in the BORAVAST Area

The questionnaire survey showed that 78.44% of the respondents mentioned that the introduction of *Prosopis* in the BORAVAST area was mainly done by the Ministry of Agriculture in the 1980s through the tree planting day programme which was still conducted annually in Botswana at the time of this research. As evidence to their claims, the communities identified one of the plots that served as a nursery for *Prosopis* species in the BORAVAST area established by the Ministry of Agriculture in Rappelspan village (Plate 3). The information gathered from the communities was found to be in line with the existing literature (section 2.6) on the introduction of the species in the area.

The perceptions about the introduction of *Prosopis* species in the BORAVAST area were influenced by the age, personal experiences and interests. This was evident in some instances where some respondents were unable to recall the year of introduction and instead mentioned the year in which they started to personally experience the negative impacts

of *Prosopis* invasion. Generational transfer of knowledge also dictated the responses from respondents who were considered to be too young to have witnessed and remembered the period of the introduction of the species in the area.

5.2.2 Impacts of *Prosopis* on Livestock

The respondents expressed the view that *Prosopis* was useful as part of fodder resources. They pointed out that livestock preferred *Prosopis* seed pods over the leaves and that livestock only browsed on leaves when they were presented with no alternatives particularly in winter. This was in conformity with empirical research works that investigated the feed potential of *Prosopis* (e.g. Abdel Gaabar, 1986; Felker & Moss, 1996; Pasiecznik, 2001). *Prosopis* pods were identified as a very nutritious forage and fodder resource which is high in soluble sugars, and contains low concentrations of tannins and other unpleasant chemicals, with moderate to high digestibility (Pasiecznik, 2001). On the other hand, *Prosopis* leaves are widely known to be relatively unpalatable to livestock due to the high content of condensed tannin (Abdel Gaabar, 1986; Felker & Moss, 1996; Pasiecznik, 2001).

Although the respondents acknowledged the importance of *Prosopis* as fodder resource, they indicated that they had experienced incidences of death of livestock which fed on *Prosopis* pods. This was common to donkeys and horses. It was believed that the cause of such deaths could be traced to the differences in the digestive systems of livestock. The respondents mentioned that the digestive systems of donkeys and horses do not effectively digest the pods as the systems for goats and cattle do. Similar accounts of incidences of death of livestock which fed on *Prosopis* pods elsewhere are available in the literature (e.g. Pasiecznik, 2001; Laxén, 2005; Bokrezion, 2008).

Abdel Gaabar (1986) observed that the cause of illness and death among livestock that were on an exclusively *Prosopis*-based diet was due to ruminal impaction caused by pods, which had been insufficiently digested. Contrary to what the respondents believed, the literature indicated that there is no correlation between the ability of an animal to digest *Prosopis* seeds and the animal's resilience towards ruminal impaction caused by *Prosopis* seeds ingestion (Abdel Gaabar, 1986; Tabosa, *et al.*, 2000; Mahgoub, *et al.*, 2005a & 2005b). The quantity of *Prosopis* seed pods consumed by an animal is a crucial factor that determines the effect of *Prosopis* ingestion on the animal's health (Abdel Gaabar, 1986; Tabosa, *et al.*, 2000; Mahgoub, *et al.*, 2005a & 2005b). Although no research has proven this in the study area, it is possible that livestock death in animals that fed on *Prosopis* could be related to the amount of *Prosopis* seed pods ingested by an animal.

The respondents also pointed out that amongst livestock, donkeys and horses contributed in *Prosopis* seed dispersal because seeds go through their digestive systems intact. Similar studies also indicated that sheep and goats are less effective in the dispersal of *Prosopis* seeds compared to donkeys, horses and cattle. Fisher, *et al.* (1959), found that 82% of *Prosopis* seed germinated after passing through horses, 69% through cattle and 25% through sheep, while Brown and Archer (1987) considered cattle as the most efficient dispersal agents for *Prosopis* seeds. However, due to restricted movement of livestock from water and fodder resources located within the riparian zone in the study area, most livestock waste was deposited within the riparian zone. As a result, *Prosopis* seed dispersal by donkeys and horses did not contribute significantly to the spatial extent of *Prosopis* seeds distribution in the soil seed bank.

5.2.3 The Impacts of *Prosopis* on Rangeland Resources

The respondents generally mentioned that the negative impacts of

Prosopis species on the rangelands, riparian vegetation and native plant species by far outweighed the benefits derived from its existence in the area. Binggeli (2001) and Pasiecznik (2001) pointed out that people's perceptions of invasive species are moulded by the economic impacts of the species in their livelihoods. Therefore, the observation suggested that the perceptions of the respondents were premised upon their general views that *Prosopis* species degraded their livelihoods (Figure 4.7). It was however interesting to note that during the focused group discussions that were held in the area, reference to economic significance of *Prosopis* realized in other countries generated some curiosity among attendants.

The respondents indicated that the invasion of *Prosopis* species had resulted in the decline in the plant diversity over time (Figure 4.6). This was consistent with empirical research that pointed out that the ability of *Prosopis* species to become established over a large area from a single introduction or a few scattered trees has been observed throughout semi-arid Africa and Asia (Pasiecznik, 2001). The robust adaptation characteristics that allow the species to establish itself, survive and out-compete other plants under harsh conditions have been covered in more detail in Chapter 2. The positive and negative impacts of *Prosopis* species on rangeland resources noted in the study area were found to be comparable to those observed in similar studies elsewhere (e.g. Pasiecznik, 2001; Binggeli, 2001; Mwangi & Swallow, 2005; Laxén, 2005; Bokrezion, 2008).

5.2.4 The Socio-economic Benefits of *Prosopis*

Various ecological research have been conducted on *Prosopis* but recently researchers' attention has shifted focus to considering possible socio-economic benefits that can be derived from the species (e.g. Mwangi & Swallow, 2005; Pasiecznik, 2001; Bokrezion, 2008). The exploitation of *Prosopis* species for rural livelihoods and communities is the

contemporary key issue in the international research arena over *Prosopis* and its management. The current view of most researchers is that, the potential of *Prosopis* has not been fully realised by rural communities (Bokrezion, 2008). Consequently, management of the species through exploitation is widely supported by researchers (Mwangi & Swallow, 2005; Bokrezion, 2008).

The respondents did not attach expected significant socio-economic value to *Prosopis* species. Their predisposition to *Prosopis* limited their innovation potential concerning utilization of the species. Additionally, it was clear that the respondents lacked the capacity for *Prosopis* exploitation. However, the fact that 82.16% of the respondents showed interest in learning ways of exploiting the species as a measure of managing it was a positive observation as far as the feasibility of the management of the species through exploitation is concerned.

5.2.5 The Impacts of *Prosopis* Invasion within Settlement Areas

Most of the concerns of the respondents about *Prosopis* invasion mirrored the concerns that have been encountered by other researchers in other countries where *Prosopis* invasion exists, for instance in Sudan, Kenya and Eritrea (Bokrezion, 2008; Laxén, 2005; Mwangi, 2005) (section 2.4). *Prosopis* bushes provided thieves with good hiding places. The species has also been associated with the depletion of underground water resources, injuries caused to people and livestock, damage to car, donkey cart and bicycle tyres.

5.3 Spatial Aspects of *Prosopis* Invasion

5.3.1 *Prosopis* Distribution in Relation to Soil Properties

The soil under the canopies of *Prosopis* trees had significantly higher soil organic carbon than soils in the inter-spaces, indicating the establishment

of "fertile islands" (Table 4.1, Figure 4.1 & Section 5.1.1-2). Therefore, the patterns of the distribution of selected soil attributes in the study area suggested that the soil attributes did not dictate the spatial extent of the distribution of *Prospopis* species. Instead, the distribution of *Prosopis* trees in the study area affected the distribution of soil attributes particularly soil organic carbon. Similar observations have been made in other studies which pointed out that the distribution of *Prosopis* species was not influenced by the establishment of "fertile islands", but the distribution of the species determined the establishment of "fertile islands" (Bhojvaid & Timmer, 1998; Geesing, *et al.*, 2000; Mishra & Sharma, 2003).

5.3.2 *Prosopis* Distribution in Relation to the Soil Seed Bank

The distribution of plant species is normally linked to the initial structure created by the patterns of seed dispersal (Warr, *et al.*, 1994; Li, 2008). This appeared to be the case with *Prosopis* species in the study area, particularly during the early years of the introduction of the species. When *Prosopis* species was introduced in the study area, the communities planted *Prosopis* plants in their homes to take advantage of their good shade (Section 4.4.1). The built-up areas in the settlements border the Nossob-Molopo riparian zone. Livestock water points in the study area are located in the riparian zone due to the availability of underground water in the site. Owing to the paucity of grazing and surface water resources in the study area, livestock movements are normally restricted to the Nossob-Molopo riparian zone and the settlements environments. In the light of the studies that indicated that some livestock like donkeys and horses are known for their efficiency in *Prosopis* seed dispersal (Brown & Archer, 1987; Pasiecznik, 2001), livestock probably initiated the spread of *Prosopis* into the Nossob-Molopo riparian zone as they moved between the settlements where *Prosopis* trees were planted and livestock water points located in the Nossob-Molopo riparian zone in search of fodder and water.

5.3.3 *Prosopis* Distribution in Relation to Anthropogenic Activities

Settlement areas and their environs had high density and percentage cover of *Prosopis* trees (Figure 4.2 & Plate 6). High density and canopy cover were found around livestock watering points that were located within the Nossob-Molopo riparian zone (Plate 7). Heavily invaded patches were also observed outside the villages between Struizendam and Bokspits villages in the unfenced farms located along the riparian zone. For these reasons, anthropogenic activities, particularly livestock keeping, appeared to be related to the distribution patterns of *Prosopis* trees in the study area.

The management methods of *Prosopis* that were used in the study area included cutting and uprooting of *Prosopis* trees within settlement areas (Sections 4.4.1-2) which were indirectly promoted by the government through the poverty alleviation programme referred to as *Ipelegeng*. The main aim of the *Ipelegeng* programme was not related to the management of *Prosopis* species, but the programme focused on poverty alleviation in the communities. Communities were compelled to undertake some communal activities to attract poverty alleviation funds from the programme. As a result, the BORAVAST communities identified cutting and uprooting of *Prosopis* trees as the activity that they could use to attract the funds. It was therefore clear that even though the communities were concerned about the invasion of *Prosopis* species in their area, they were more interested in the financial benefits of the *Ipelegeng* programme. The Department of Roads also periodically engaged some community members to clear *Prosopis* trees growing on the roadsides of the main roads in the study area. The main aim of the Department of Roads was not to contribute to *Prosopis* management but to maintain the roads. Consequently, the process of cutting and uprooting of *Prosopis* trees was not based on empirical research and it was not systematically coordinated. Instead of controlling the spread of *Prosopis*, cutting and

uprooting of *Prosopis* trees in the area promoted the invasion of *Prosopis* species within settlement areas. This was exacerbated by the fact that uprooted and cut *Prosopis* trees with aerial seed pods were dumped indiscriminately (Plate 8) leading to the propagation of *Prosopis* seeds in the environment.

5.3.4 Factors Influencing the Distribution of *Prosopis*

The following were considered as the major factors that influenced the distribution of *Prosopis* trees in the study area:-

- On the basis of the results of this study, it appears that during the early years of the introduction of *Prosopis* species, the initial framework created by the patterns of *Prosopis* seed dispersal determined the distribution *Prosopis* trees in the study area.
- The invasion of *Prosopis* in the Nossob-Molopo riparian zone was initiated through *Prosopis* seed dispersal by livestock as they moved between the settlements areas where *Prosopis* was initially planted and livestock water points that were located in the Nossob-Molopo riparian zone in search of fodder and water.
- Minimal disturbance to *Prosopis* trees in the form of cutting and uprooting in the Nossob-Molopo riparian zone and the accumulation of *Prosopis* seeds in the soil under *Prosopis* tree canopies facilitated the invasion of the species in the Nossob-Molopo riparian zone.
- Restricted livestock movements in the study area constrained the role of livestock in the spread of *Prosopis* to other sites located outside settlements and riparian areas.
- Lack of technical expertise and resources required to manage *Prosopis* in the communities of the study area facilitated the invasion of *Prosopis* species.

5.4 *Prosopis* Management Options

The applicability of *Prosopis* management approaches that have been utilized around the globe (Section 2.9 & Table 2.3) to the study area is evaluated in this section. Eradication of *Prosopis* trees in the study area was not considered a potential management option as it has already proved to be ecologically and economically unsustainable (Pasiecznik, 2001; Geesing, *et al.*, 2003; Bokrezion, 2008). The use of fire as *Prosopis* management tool requires sufficient fuel load in the form of dry grass material. The study area is characterized by predominance of bare land. Therefore, the use of fire as the only potential *Prosopis* management option was also ruled out. Eradication of *Prosopis* trees and fire as management methods of *Prosopis* species can best be applied with other methods on a case based approach.

5.4.1 Biological Control

The biological control method entails the use of insects as biological control agents. Zimmerman (1991) recommended that the selection of insects for biological control of *Prosopis* should be confined to those destroying seeds only, as the seed is considered a key attribute of *Prosopis* invasiveness. The focus on seed-feeding insects would also resolve issues related to the unplanned destruction of the useful non-seed *Prosopis* properties that would be lost when using other control methods. Biological control needs to be augmented by other control measures (Zimmerman, 1991), especially in areas where *Prosopis* seed banks exist, as the positive impact of seed-feeding may not be evident until the soil seed bank is exhausted.

Countries which have a long history of *Prosopis* invasion like the United States of America have comprehensively studied insects that are known to attack *Prosopis* seeds. The studies have established lists of insects that feed on *Prosopis* seeds. Biological methods in *Prosopis* management

require host specificity tests before implementation to alleviate undesirable environmental consequences (e.g. Zimmermann, 1991; Hoffmann, *et al.*, 1993a & 1993b; Coetzer & Hoffmann, 1997).

No study had been conducted in Botswana on the potential use of biological methods in *Prosopis* management at the time of this study. However, the neighbouring country, the Republic of South Africa (RSA), has made considerable progress concerning the use of *Prosopis* seed feeding insects in the management of the species invasion (e.g. Zimmermann, 1991; Hoffmann, *et al.*, 1993a & 1993b; Coetzer & Hoffmann, 1997). Therefore, due to the proximity of the RSA to Botswana and the similarities in the environmental conditions of the two countries in some *Prosopis* invaded areas, knowledge accumulated by the RSA in this field may serve as a reference point for the studies that aim at developing biological methods for *Prosopis* management in Botswana.

Studies relating to *Prosopis* biological control methods in South Africa started around the 1980s. On the basis of the initial studies, bruchid seed weevils *Algarobius prosopis* (Le Conte) and *Algarobius bottimeri* Kingsolver were selected as the most effective biological control agents due to their host-specificity and their capability of reducing the invasiveness of *Prosopis* without destroying its beneficial characteristics (Zimmermann, 1991). From 1987, *A. prosopis* was released in the Northern Cape Province and other *Prosopis* invaded parts of RSA until 1989, while *A. bottimeri* was released in 1990 (Zimmermann, 1991; Hoffmann, *et al.*, 1993a & 1993b). Due to its failure to establish on *Prosopis*, the use of *A. bottimeri* as biological control in RSA was discontinued (Hoffmann, *et al.*, 1993a & 1993b). *A. prosopis* showed 92% success rate in destroying *Prosopis* seed pods (Zimmermann, 1991; Coetzer & Hoffmann, 1997), and its use has continued in RSA up to date. Therefore, *A. prosopis* is recommended for experimental investigations and possible use depending on the results in the study area (BORAVAST villages).

Further studies conducted on the possible biological control of *Prosopis* species in RSA showed that two additional South Western United States seed bruchid weevils *Mimosestes protractus* (Horn) and *Neltumius arizonensis* (Schaeffer) met the host specificity criteria (Moran, *et al.*, 1993). In the comparison of the two bruchid seed weevils, *N. arizonensis* was selected as the best option as it was found that its larvae was capable of colonizing immature seed pods of *Prosopis* before they became available for dispersal by livestock (Moran , *et al.*, 1993). Therefore, *N. arizonensis* was released in 1993 and 1994 in the Western Cape Province and was found to be effective in controlling *Prosopis* invasion (Coetzer & Hoffmann, 1997). Consequently, the use of *N. arizonensis* has continued up to date.

On the basis of the research undertaken in RSA on biological control of *Prosopis* using bruchid seed weevils, *A. prosopis* and *N. arizonensis* were selected for use due to their efficiency in decreasing the rate of *Prosopis* invasion under environmental conditions existing in RSA. However, Moran, *et al.* (1993) pointed out that bud and flower feeders can be efficient biological control of *Prosopis* species, while Coetzer and Hoffmann (1997) mentioned that *Asphondylia prosopidis* (Cockerell Cecidomyiidae) was regarded as one of the promising bio-control agent among bud and flower feeders in RSA.

Basing on the experience from RSA, studies on the applicability of *A. prosopis* and *N. arizonensis* as biological controls of *Prosopis* in the study area are recommended. Studies on the efficiency of bud and flower feeders, *Asphondylia prosopidis* Cockerell Cecidomyiidae in controlling *Prosopis* invasion under the environmental conditions existing in Botswana may either be conducted concomitantly with studies on *A. prosopis* and *N. arizonensis* or at a later stage.

In addition to the similarities in environmental conditions between the

two countries, *Prosopis* species existing in RSA (*Prosopis chilensis, Prosopis juliflora, Prosopis velutina, Prosopis glandulosa*) have been identified in the study area. To this end, there is a significant potential for success in the application of *A. prosopis* and *N. arizonensis* as biological controls of *Prosopis* in the study area.

5.4.2 Mechanical Control

Mechanical methods of controlling *Prosopis* invasion involve physical removal of *Prosopis* trees which is usually conducted through the use of heavy machinery. This method has been tried in other countries, with reasonable success (e.g. Australia) (Csurhes, 1996). However, in the African countries with lower economic muscle compared to the first world countries, the viability of the methods has been found to be questionable (Bokrezion, 2008). When the mechanical methods are not applied correctly, regrowth is inevitable. To mitigate against the effects of regrowth, blade-ploughing is normally implemented subsequent to the removal of the tree. Blade ploughing was found to be effective when the blade passes under the root-crown of the plant or at least 30 cm below the soil surface (Csurhes, 1996).

The methods can be applied in the research area on a case based approach. The application of these methods can only be effective when resources are sufficient and a systematic coordination and monitoring system (elaborated upon in Section 5.5) is in place. At the time of this research, cutting and uprooting were used in the study area but they were not effective because of lack of technical expertise and resources in the communities. The communities also failed because the implementation of the methods was conducted through programmes that were only targeting poverty alleviation rather than the management of the species.

5.4.3 Chemical Control

The chemical control method requires application of herbicides to *Prosopis* trees. The effectiveness of chemical control usually varies with the size, age, density and habitat of the target plants (Csurhes, 1996). For instance, sparsely distributed multiple-stemmed *Prosopis* trees and hybrids observed in the Rappelspan riparian zone and outside the settlements may need foliar sprays, while dense infestations along the Nossob-Molopo riparian zone and within the settlement areas may require mechanical control, followed by fire applied to plant waste and foliar spraying of seedlings. Isolated, single-stemmed plants found outside the settlement may require basal bark or cut-stump techniques.

A number of herbicides have shown potential in controlling *Prosopis* species in some countries. Csurhes (1996) found that herbicide Grazon DS mixed with pulse wetting agent was aerially applied by helicopter to *Prosopis* stands in Australia, and it produced over 90% *Prosopis* mortality rate at the cost of about BWP 750-840 per hectare. Grazon DS currently costs about BWP 540.00/100 litre. Other herbicides that have proven to be effective in controlling *Prosopis* invasion include Access, which currently costs BWP 3990.00/100 litre and has a success rate of 97-100% in killing *Prosopis*, and Garlon 600 which currently costs about BWP 4590.00/100 litre and has a success rate of 97-100% in killing *Prosopis* (Csurhes, 1996). Problems with application in dense thickets, costs, soil pollution, possible poisoning of livestock and other undesirable consequences associated with their application are the main disadvantages of using herbicides (Csurhes, 1996) in controlling the spread of *Prosopis*. Therefore, implementation of chemical control in the management of *Prosopis* in the study area should be considered the last option and should also be implemented with caution.

5.4.4 Grazing Management System

Grazing facilitates the establishment and survival of woody plant species (i.e. bush encroachment) by reducing competition from grass and by reducing the incidence and intensity of fires (Moleele & Perkins, 1998). A number of researchers have indicated that an increase in the number of cattle causes an increase in the density of *Prosopis* trees in *Prosopis* invaded areas (e.g. Csurhes, 1992). However, other studies showed that protection from grazing alone does not prevent *Prosopis* invasion and that additional factors such as fire were required to control *Prosopis* (Smith & Schmutz, 1975). The study area is among the arid rangelands characterized by scanty to no grass cover, low rainfall, communal grazing system, as well as poor communities. Combinations of these factors negate the implementation of grazing management system as the main *Prosopis* management method for the area. It can, at best, be utilized with other management approaches.

5.4.5 Exploitation or Promotion of *Prosopis*

Prosopis invasion continues to pose challenges to the livelihoods of the communities in the study area. The concerns of the communities have been outlined in detail (Chapter 4) and it was made clear that the communities had not realized the socio-economic potential of the species. It was also highlighted that the communities were incapacitated by lack of expertise and essential resources required to manage *Prosopis* in their area. However, in the view of the huge costs and labour that are associated with alternative approaches, management of *Prosopis* species through exploitation of the species appears to be a better option for the BORAVAST communities. The sustainability of this approach highly depends on the implementation of a coordinated *Prosopis* management and monitoring systems (elaborated in Section 5.5).

Since the communities in the study area had not recognized the socio-

economic potential of *Prosopis* species, the applicability of experiences on management of *Prosopis* through exploitation from other countries that have a history of making use of the approach warrants consideration. Therefore, in the light of experiences from other countries, the following are proposed as possible activities worth considering in the implementation of a sustainable management approach (Section 5.5) that hinges on exploitation or promotion of *Prosopis* species in the study area.

a) ***Stabilization of sand dunes*:** On the basis of experience from other countries, Timberlake (1980) recommended the introduction of *Prosopis* in the study area with the main objective of stabilizing sand dunes. However, the distribution pattern of *Prosopis* trees did not indicate any form of coordination that suggested that the planting of *Prosopis* trees was in line with the objective of stabilizing sand dunes. The introduction of the species was initiated by providing *Prosopis* seedlings to community members during tree planting day to plant in their homes. *Prosopis* seedlings were not planted in areas dominated by sand dunes. As a result, sites dominated by sand dunes were not invaded by the species and the encroachment of sand dunes into built-up areas in settlements still presented major challenges to the communities. Therefore, a coordinated system (Section 5.5) of establishing *Prosopis* plants in areas that are prone to mobile sand dunes is essential. When the system is in place, *Prosopis* plants established in the areas that are susceptible to mobile dunes could be managed and monitored to eliminate potential uncontrollable spread of the species that could lead to problems associated with the invasion of the species.

b) ***Use as energy (fuel) resources*:** Experiences from countries like India, Sudan, and Kenya (Varshney, 1996; Pasiecznik, 2001;

Mwangi & Swallow, 2005) indicated that wood from *Prosopis* species produces high quality calorific value and high quality charcoal. However, the respondents pointed out that firewood from *Prosopis* trees was poor in quality. Their perceptions were influenced by the comparisons that they made between *Prosopis* firewood and firewood produced from other tree species that existed in their environment. Therefore, promotion related to the use of firewood from *Prosopis* requires the process of changing the perceptions of the communities regarding the quality aspects. The process of changing the perceptions of the communities is possible through efficient transfer of technical information to communities which can be facilitated by Governmental Organizations and NGOs (Section 5.5) through demonstrations and provision of support to the communities.

Commercialization of firewood and charcoal production were other options that were available to the communities. However, the local market appeared to be poor and the only alternative was to establish market outside the boundaries of the study area. This option requires financial and specialized expertise that the communities could not have without external support from the Government or Non-Governmental Organizations (NGOs). Therefore, the communities need external support to exploit the commercial value of *Prosopis* species (Figure 5.1). The implementation of this approach would assist in suppressing the regeneration rate of *Prosopis* species. To maintain the sustainability of the approach, monitoring of the balance between harvesting and regeneration is crucial in the *Prosopis* management and monitoring system for the study area.

c) ***Use as construction timber and furniture wood:*** Research undertaken in other countries indicated that *Prosopis* timber is widely used for furniture manufacturing and as fencing post due to its strong heartwood and its durability as a construction material (Pasiecznik, 2001). The communities in the study area mentioned that timber from *Prosopis* was not strong and was susceptible to termite attack compared to timber from other plant species. However, the lifespan of timber from *Prosopis* plants could be improved by treatment before use.

Due to lack of exposure, the communities were not aware that timber from *Prosopis* could be used for furniture production. This is one of the options that require support for the communities in the study area from Government or Non-Governmental Organizations (Section 5.5) due its considerable financial implications. Systematic implementation of this option would subdue the regeneration process of *Prosopis* in the area.

d) ***Use as feed and forage for grazing animals*:** *Prosopis* is used in many countries to reduce the cost of animal feed and mitigate shortage of fodder (Pasiecznik, 2001). For instance, the results of feeding trials from Sudan showed that rations of 60% ground *Prosopis* pods produced good weight gain and milk production in dairy cattle, beef cattle, sheep, and goats rations (Abdel Gaabar, 1986). However, due to predominance of subsistence pastoral farming and poverty in the research area, few people would afford to participate in the implementation of this method. A better alternative could be an establishment of a community based project by the Government or Non-Governmental Organizations (Section 5.5) focusing on producing livestock feed containing ground *Prosopis* pods which could be marketed beyond the borders of the

study area. Another alternative would be for the Government or Non-Governmental Organizations to encourage and support the local commercial farmers to establish facilities that would enable them to make livestock feed out of ground *Prosopis* pods. Coordinated implementation of this approach would reduce the rate of *Prosopis* invasion by decreasing the rate of seed deposition into the soil seed bank.

e) ***Use as food for humans:*** In countries like Peru, *Prosopis* pods are used as supplementary feed for humans because they have high protein and sugar content (Mwangi & Swallow, 2005). The implementation of this requires special expertise and significant financial injection that the communities could not afford without external support. Therefore, the communities in the study area would require support from Government or Non-Governmental Organizations (Section 5.5) to exploit the high protein and sugar content found in *Prosopis*. The approach has direct implications on human health. As a result, the involvement of organizations like the Botswana Bureau of Standards (BOBS) and National Food Technology Research Center (NFTRC) is critical. This is one of the approaches that would lead to a reduction in the rate of *Prosopis* invasion by decreasing the number of seeds deposited into the soil seed bank.

f) ***Honey production:*** It was observed that one mature *Prosopis* tree is capable of producing as many as 630 000 to 980 000 flowers annually (Felker, 1984), availing the nectar required for honey production. This approach could be implemented at a commercial level as a community based project. However, the communities would need to be empowered by Government or Non-Governmental Organizations in terms of expertise and funds

(Section 5.5).

g) ***Creation of employment opportunities***: Instead of allowing the communities to find projects that they can embark on in order to enjoy benefits from programmes like the *Ipelegeng* programme, communities should be assisted to identify ways in which available funds for poverty alleviation and rural community support may be sustainably utilized. A coordinated management system for *Prosopis* species described in Section 5.5 efficiently addresses this matter.

5.4.6 Implications of Regulatory and Administrative Frameworks and Policies on the Proposed *Prosopis* Management Options

Compliance with relevant regulatory and administrative frameworks and policies (outlined in section 1.7) should be integral to the implementation of the proposed control methods for *Prosopis* shown in Figure 5.1. In the application of chemical control methods, the guidelines provided in the Agrochemical Act (CAP 35:09 of 2000) in relation to the matters relating and incidental to the registration and licensing of agrochemicals, control or regulation of their importation, manufacture, distribution, use and disposal in order to prevent pollution to the environment or harm to human, plant or animal life should be observed. Other acts provided in section 1.7 cut across all proposed methods of control for *Prosopis* species. Therefore, applicable parts of the regulatory frame works should be followed in the implementation of the proposed methods of control of *Prosopis* in the study area.

5.5 A Proposed Integrated *Prosopis* Management System

Due to the individual inadequencies of each of the options for the management of *Prosopis* as pointed out in section 5.4, an integrated

management system is proposed for the study area (Figure 5.1). The proposed *Prosopis* integrated management approach is in line with the Integrated Pest Management paradigm (IPM), a contemporary approach that is recommended for pest management (Brader, 1988; Morse & Buhler, 1997; Ehler, 2006) and it is premised upon an Integrated Environmental Management (IEM) model. The IPM paradigm is generally described as a control strategy in which different biological, chemical and mechanical control methods are used in combination to provide socio-economically and ecologically sustainable pest control method (Thill, *et al.*, 1991). The IEM model is a coordinated control, direction or influence of all human activities in a defined environmental system to achieve and balance the broadest possible change of short and long-term objectives or coordinated proactive or preventative measures that maintain the environment in good condition for a variety of long-term or sustainable uses (Born & Sonzogni, 1995; Margerum & Born, 1995; Scrase & Sheate, 2002). The IEM model was considered the best foundation for the integrated *Prosopis* management and monitoring system proposed for the study area as it facilitates the reflection of the dynamics between the social welfare, economical welfare and environmental sustainability matters in the implementation of the potential *Prosopis* management options for the study area. The proposed approach incorporates the biological, chemical, mechanical control and control of *Prosopis* species through exploitation.

The integrated *Prosopis* management and monitoring system proposed and recommended for the study area is summarized in Figure 5.1. The system indicates that the Ministry of Environment, Wildlife and Tourism (MEWT) supported financially and technically by NGOs, should be responsible for the facilitation, initialization, implementation and monitoring of the management system. The BORAVAST Trust should be responsible for the implementation and monitoring of the management system with the support of MEWT and NGOs. The system also indicates

that exploitation or promotion of *Prosopis* should be given priority over other management options, followed by biological control, mechanical control and chemical control options. The proposed integrated *Prosopis* management and monitoring system (Figure 5.1) can only function efficiently when supported by the organizational and communication network for the *Prosopis* management and monitoring system discussed in section 5.5.1 and illustrated in Figure 5.2.

5.5.1 Organizational and Communication Structure

Aitken *et al.* (1995) pointed out that success in the long-term implementation of the IPM is usually related to the existence of an active and efficient network that provides different forms of support to local communities, assisting the communities to efficiently adopt management practises and to sustain acceptable levels of performance. Therefore, this study took into consideration the importance of the involvement of a broad range of relevant organizations and other stakeholders at national and international levels towards an effective and sustainable implementation of the *Prosopis* management and monitoring system (Figure 5.1) recommended for the study area. The main organizations and stakeholders which were considered important in the network included the following:-

- Ministry of Environment, Wildlife and Tourism through the Department of Environmental Affairs (DEA) (e.g. to be involved in matters related to the general coordination of *Prosopis* management activities and sustainable environmental management) and the Department of Forestry and Range Resources (DFRR) (e.g. to be involved in issues concerning forest resources management).
- Ministry of Lands and Housing and the Ministry of Trade and Industry (e.g. to contribute in aspects of investment and commercial trade on *Prosopis*-based products).

- Ministry of Minerals, Energy and Water Resources through the Department of Energy (e.g. to assist in matters associated with charcoal production and use of fire wood).
- NGOs and Community Based Organizations (CBOs) (e.g. UNDP, BORAVAST Trust, and VDCs to be involved in matters related to community mobilization and implementation of the *Prosopis* management and monitoring system).
- Merchants (e.g. to contribute in aspects of investing, exploiting, valuing, marketing, and selling of *Prosopis*-based products).

The organizational and communication network for the *Prosopis* management and monitoring system proposed and recommended for the study area is illustrated in Figure 5.2. The structure suggests that the main ministry that should be responsible for the coordination of activities involved in both the initialization, implementation and monitoring of the *Prosopis* management and monitoring system should be the Ministry of Environment, Wildlife and Tourism (MEWT) through the Department of Forestry and Range Resources (DFFR) and Department of Environmental Affairs (DEA) at a national level. Other departments within MEWT should also be involved by DFRR and DEA in their activities where necessary (e.g. in issues of permits and specialized expertise). MEWT should liaise with other ministries and NGOs (e.g. UNDP and Conservation International) to promote sustained and efficient support for the *Prosopis* management and monitoring system. Involvement and commitment of Governmental organizations at the top level of the structure should ensure availability of sufficient funds, availability of relevant expertise and efficient implementation and coordination of the *Prosopis* management and monitoring system. Therefore, MEWT (i.e. headquarters) should play facilitation role at the national level.

The liaison from the national level should cascade down to the District or regional level (i.e Governmental organizations in the Tsabong Village; the

administration centre for the District) where the actual initialization, implementation and monitoring activities of the *Prosopis* management and monitoring system should be planned and applied. At the local or village level, the Community Based Natural Resources Management (CBNRM) Trust (BORAVAST Trust) should be responsible for community mobilization, coordination, implementation and monitoring of the *Prosopis* management and monitoring system in liaison with VDCs, NGOs, CBOs and other relevant stakeholders. The MEWT from Tsabong village should play a major facilitation role at local level ensuring that the actual implementation and monitoring of the *Prosopis* management and monitoring system is undertaken by the local communities in the study area. In addition, MEWT should ensure that matters relating to funding, training, research, promotion of community awareness, community mobilisation, and implementation and monitoring of the *Prosopis* management and monitoring system are efficiently addressed.

The double pointed arrows between the levels (National, District and Local) in the organizational and communication structure (Figure 5.2) imply that a clear-cut top-down or bottom-up approach in the implementation of the organizational and communication structure for the *Prosopis* management and monitoring system should be avoided as the use of either one of them will negate the sustainability of the *Prosopis* management and monitoring system. Other double pointed arrows symbolize reciprocal consultation processes among all stakeholders involved in *Prosopis* management. In addition, all stakeholders involved in the initialization, implementation and monitoring of the *Prosopis* management and monitoring system should play facilitation role, while the participatory role as described by Chambers (1994) and Reij and Waters-Bayer (2001) should be promoted among the local communities.

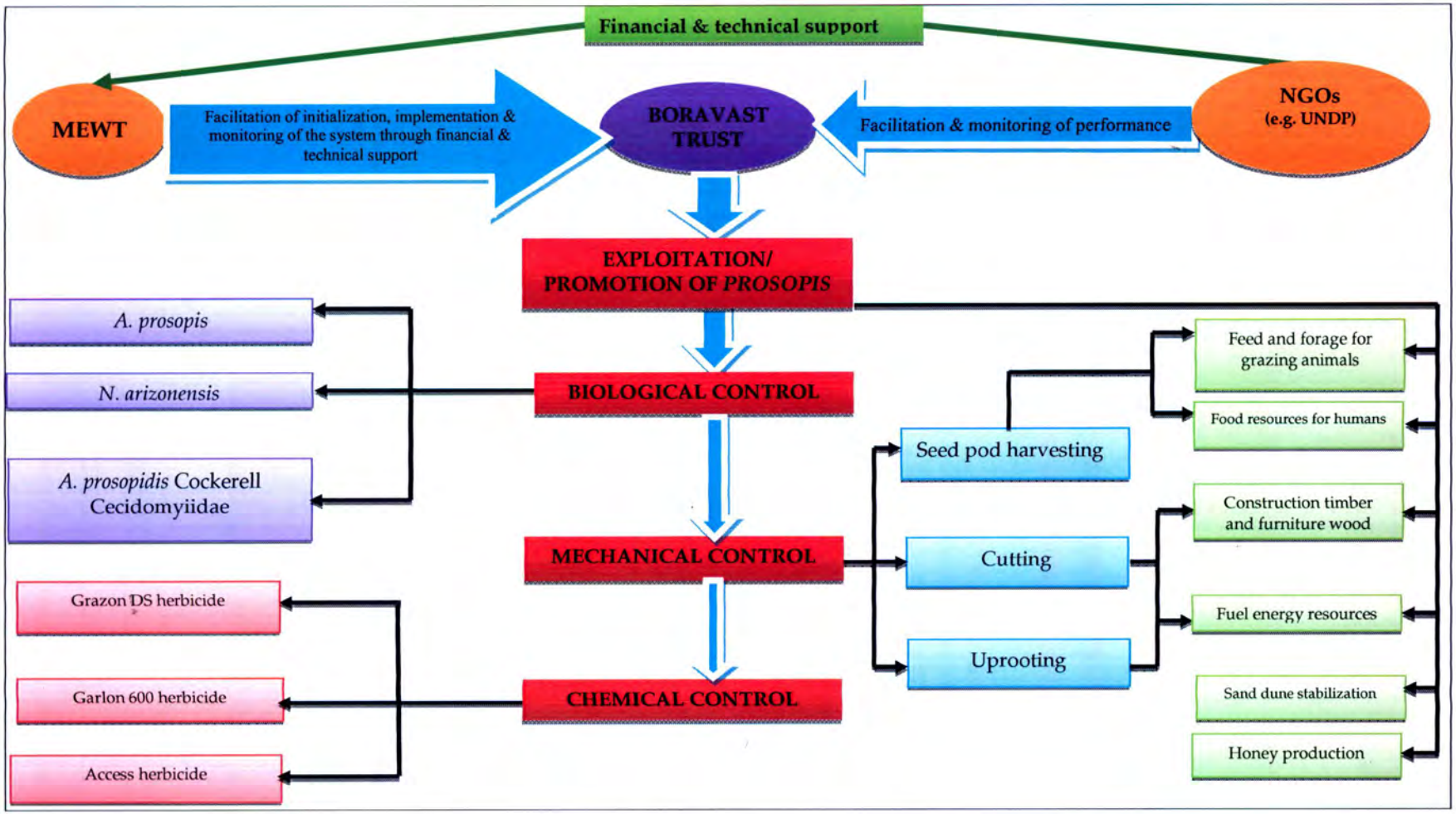
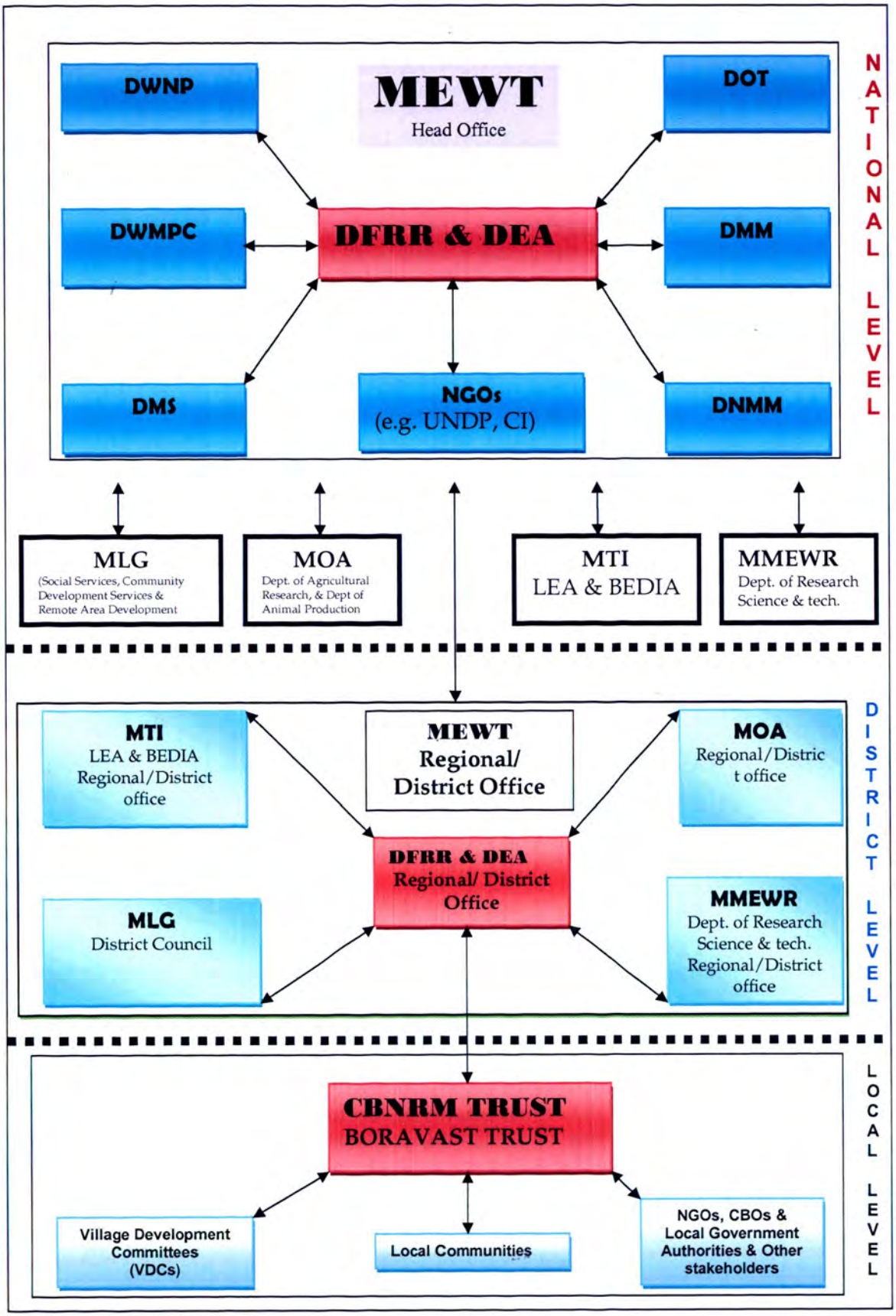


Figure 5.1 Framework for the Integrated Management and Monitoring System for *Prosopis* species in Botswana's Kgalagadi District, BORAVAST villages. (*The proposed Prosopis management options are arranged in a descending order of priority as indicated by the decrease in the thickness of the arrow. The methods indicated under the Prosopis management options also follow the same arrangement.)*



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Figure 5.2 The proposed organizational and communication structure for the *Prosopis* management and monitoring system.

Abbreviations Used in Figure 5.1

CBNRM	Community Based Natural Resource Management
CBOs	Community Based Organisations
CI	Conservation International
DEA	Department of Environmental Affairs
DFRR	Department of Forestry and Range Resources
DMM	Department of Ministry Management
DMS	Department of Meteorological Services
DNMM	Department of National Museum and Monuments
DOT	Department of Tourism
DWMPC	Department of Waste Management and Pollution Control
DWNP	Department of Wildlife and National Parks
MLG	Ministry of Local Government
MMEWR	Ministry of Minerals, Energy and Water Resources
MOA	Ministry of Agriculture
MTI	Ministry of Trade and Industry
MEWT	Ministry of Environment, Wildlife and Tourism
NGOs	Non Governmental Organizations
UNDP	United Nations Development Program
VDCs	Village Development Committees

It is essential to consider issues related to the adoption of the integrated *Prosopis* management and monitoring system recommended for the study area. Adoption and sustainable implementation of the integrated *Prosopis* management and monitoring system would not be possible without the participation of the local communities. Therefore, local communities in the study area are considered the most important potential adopters of the recommended management options. Critical issues that are expected to have a bearing on the adoption of the proposed options are discussed in section 5.5.3.

5.5.2 Information Dissemination and Community Mobilization for *Prosopis* Management

Information dissemination on the recommended management options and mobilization of local communities and other relevant stakeholders are pivotal in the adoption of the proposed integrated *Prosopis* management and monitoring system (Figure 5.1). The main objective of information dissemination is to make the intended potential adopters to effectively adopt the *Prosopis* management and monitoring system. The major anticipated challenge in the adoption of the system is related to the rate of adoption which, in the case of the recommended integrated *Prosopis* management and monitoring system, could be determined by the perceptions about the system's attributes by the potential adopters particularly the communities in the study area. Five characteristics of innovations proposed by Rogers (1995 & 2003) are used below to discuss issues associated with the rate of adoption of the integrated *Prosopis* management and monitoring system.

- ***Relative advantage:*** This is the degree to which the options presented in the integrated *Prosopis* management and monitoring system are perceived as better than existing ideas. The degree of relative advantage may be viewed on the basis of socio-economic

and ecological factors in this research. The rate of adoption of the proposed options will be directly proportional to the degree of the perceived relative advantage of the options over the existing ideas. The study has shown that the communities had lost hope on the existing ideas and they were ready to embrace ideas that could mitigate the impacts of *Prosopis* invasion. Therefore, the *status quo* confers a potentially high rate of adoption to the recommended integrated *Prosopis* management and monitoring system.

- ***Compatibility:*** This is the degree to which the options presented in the integrated *Prosopis* management and monitoring system are perceived as being consistent with the existing values, past experiences, beliefs, interests and needs of potential adopters. The results of this study indicated that the potential adopters (communities) were interested in finding better solutions to the impacts of *Prosopis* invasion. The options presented in this study are considered to be in line with the existing values, past experiences, beliefs, interests of potential adopters. Therefore, the rate of adoptability of the proposed management options is expected to be high.

- ***Complexity:*** This is the degree to which the options presented in the integrated *Prosopis* management and monitoring system are perceived as difficult to comprehend and utilize by the potential adopters. The rate of adoption of the options will be premise on their degree of simplicity as perceived by the potential adopters. More often than not, new ideas that are easily comprehended and used are adopted more swiftly than those that call for the development of new skills or radical lifestyle shift on the part of the adopter. The solution to the complexity of the integrated *Prosopis* management and monitoring system hinges on the

efficient implementation of the recommended communication and organizational structure for *Prosopis* management and monitoring system (Figure 5.2). Radical lifestyle changes will not be required, while development of new skills will be facilitated by Governmental Organizations and NGOs (Figure 5.1).

- ***Triability*:** This is the degree to which the approaches presented in the integrated *Prosopis* management and monitoring system can be experimented within a reasonable period of time. It is generally believed that an idea that can be tried on partial basis stands a better chance of rapid adoption as it presents less uncertainty to the individual who is considering it for adoption because of the opportunity to learn from practice. The options proposed are implementable on a partial basis. Therefore, triability is not expected to negate their adoption.

- ***Observability*:** This is the degree to which the results of the options presented in the integrated *Prosopis* management and monitoring system are perceived as visible by potential adopters. The easier the potential adopters see the results of the proposed *Prosopis* management options, the more likely they are expected to adopt them. Efficient implementation of the recommended communication and organizational structure for *Prosopis* management and monitoring system (Figure 5.2) is expected to promote information dissemination and transfer of technical skills which will in turn enhance the visibility of the positive outcomes of the recommended system.

5.6 Methodological Aspects

5.6.1 Soil Sampling and Analysis

One of the limitations of this study was the intensity of sampling. It is always desirable to collect as many samples as possible to increase the representativeness of the samples. The number of samples in this study was limited by the availability of time and other resources, but the quality of the details needed for sound conclusions and recommendations was considered to be sufficient.

5.6.2 Vegetation Sampling

Limitations in vegetation sampling emanated from qualitative judgement of the stage of growth of *Prosopis* trees (Class 1, Class 2, and Class 3). To avoid destructive methods of determining the stage of growth of *Prosopis* trees, the main characteristics that were used were the tree height and canopy cover. It is well known that trees of the same age and species normally grow at different rates depending on a number of environmental factors. Therefore, some trees may have been wrongly classified. However, other factors like stem diameter were qualitative considered to minimise the effects of erroneous classification of *Prosopis* trees. The choice of the method used in this study was made mainly to avoid using the destructive method of determining the growth stage of *Prosopis* trees which requires cutting of the stem of a tree.

5.6.3 Social Survey

Communication was one of the limitations during the conduction of interviews. The native language of the communities in the research area is Afrikaans. As a result, an interpreter had to be used to effectively communicate with some of the respondents who could speak neither Setswana nor English. Some meaning was inevitably lost under circumstances where communication was conducted through an

interpreter. The effects of this on the quality of the results was minimised by using interpreters who were fluent in Setswana, English and Afrikaans.

Chapter 6

Conclusion and Recommendations

6.0 Introduction

This chapter presents the summary of the findings of this study. The conclusions and recommendations emanating from the study are also outlined.

6.1 Summary

The aim of this study was to investigate the scale or spatial extent of the invasion of *Prosopis*, and environmental factors associated with the distribution of the species; and propose sustainable management options that could be implemented to control its spread. The hypothesis of the study was that, the invasion by *Prosopis* species occurs in the BORAVAST area irrespective of edaphic factors.

The results indicated that the soils in the study area were generally poor particularly in the selected soil nutrients. However, soil organic carbon content was significantly higher under *Prosopis* tree canopies as compared to the inter-canopy sites. This was attributed to the species ability to enhance soil organic carbon content by producing abundant litter fall. Other selected soil attributes did not show significant differences between soils existing under *Prosopis* tree canopies and the inter-spaces as well as soils under class 1, class 2 and class 3 *Prosopis* trees. This was linked with the intrinsically poor fertility status of the soils.

Soil organic carbon is rated among the most limiting factors in plant productivity in arid and semi-arid environments. Therefore, on the basis of the distribution of soil organic carbon, it was established that the distribution of *Prosopis* trees had caused the development of "islands of

fertility". It was also established that the distribution of selected soil attributes did not influence the distribution of *Prospopis* trees. Conversely, the distribution of *Prospopis* trees affected the distribution of selected soil properties.

The investigations on soil seed bank showed that significantly high *Prosopis* seed numbers existed in the soil seed bank under *Prosopis* tree canopies as compared to the inter-space sites. Deposition of high numbers of seeds into the soil under tree canopies, rapid and prolific seeding were considered to be important survival characteristics that facilitated the invasion of *Prosopis* species and influenced the distribution pattern of *Prosopis* trees in the study area.

The distribution of *Prosopis* showed high density and percentage cover of *Prosopis* trees close to the settlements and farms. This was mainly attributed to livestock keeping. Social survey results indicated that the communities generally believed that the disadvantages of having *Prosopis* in the study area outweighed the advantages. The communities showed interest in learning and embracing new and effective ideas of *Prosopis* management. They also lacked the expertise and necessary resources to effectively manage *Prosopis* in their area. As a result, attempts to control *Prosopis* were futile.

Management options that were considered applicable in the study area included exploitation, biological, mechanical, and chemical approaches. It was pointed out that a single management approach would not win a fight against *Prosopis* species. To this end, an integrated *Prosopis* management and monitoring system in which applicable control options are premised and implemented on a case based approach was recommended for the study area.

The hypothesis that the invasion by *Prosopis* species occurs in the BORAVAST area irrespective of edaphic factors was accepted.

6.2 Conclusion

On the basis of the objectives of this study, the conclusions are as outlined below.

Objective 1: To investigate the scale or spatial extent of the invasion of *Prosopis* species in the BORAVAST area. The conclusions made against this objective are outlined below.

- *Prosopis* trees grew in high densities around settlement areas and livestock watering points that were located within the Nossob-Molopo riparian zone.
- Heavily invaded patches existed outside settlements between Struizendam and Bokspits villages in the unfenced farms.
- There was a link between anthropogenic activities, particularly livestock keeping and the spatial distribution patterns of *Prosopis* trees.
- During the early years of the introduction of *Prosopis* species in the study area, the distribution of *Prosopis* trees appeared to have been determined by the framework created by the patterns of its seeds dispersal. After reaching the invasive levels, the distribution of *Prosopis* trees in the study area influenced the patterns of the distribution of *Prosopis* seeds in the soil seed bank.

Objective 2: To investigate the associations between selected soil factors and the distribution of *Prosopis* species in the BORAVAST villages. The conclusions emanating from this objective are as follows:

- Soils in the study area were poor in soil nutrients that are important for plant productivity.
- The distribution of soil nutrients did not influence the distribution of *Prosopis* trees. On the contrary, the pattern of the

distribution of *Prosopis* trees influenced the distribution of soil nutrients.

- *Prosopis* trees did not grow on "fertile islands", "resource islands", or "islands of fertility", but they led to their development.

Objective 3: To assess the relationship between growth stage of *Prosopis* trees and selected soil properties. The following conclusion arose from this objective:

- There were no associations between the growth stage of *Prosopis* trees and soil properties in the study area.

Objective 4: To investigate *Prosopis* seed bank in the study area and establish its relationships with the distribution of the species. Against this objective, the following conclusions were drawn:

- *Prosopis* seeds existed in high numbers in the soil seed bank under *Prosopis* tree canopies as compared to inter-canopy sites.
- Accumulation of seeds in the soil seed bank under *Prosopis* tree canopies, rapid and prolific seeding appeared to be the main survival characteristics that promoted the invasion of *Prosopis* species.

Objective 5: To examine the perceptions of the BORAVAST communities about *Prosopis* and assess the significance of the perceptions on the management of *Prosopis*. The conclusions arising from this objective are as follows:

- The communities lacked technical expertise and essential resources needed for the effective management of *Prosopis* in their area.
- Efforts made by the communities to control the spread of *Prosopis* failed due to the inappropriateness of the objectives

associated with the activities that the communities implemented in an attempt to control the *Prosopis*.

- The potential for adoption of the recommendations postulated in this study was considered to be high as the communities were ready to ambrace new ideas related to sustainable *Prosopis* management.

Objective 6: To propose sustainable management options that should be implemented in the management of *Prosopis* species. On the basis of this objective, the following conclusion is drawn:

- Management of *Prosopis* species through an integrated management system based on a frame work illustrated in Figure 5.1 is the most sustainable approach for the study area.

6.3 Recommendations

The following recommendations were made on the basis of this study:-

- Eradication of *Prosopis* species should not be considered as the main potential management option for the study area as it has proved to be unsustainable elsewhere. It should only be considered for use with other management options.
- An integrated *Prosopis* management and monitoring system discussed in section 5.5 is recommended for the management of *Prosopis* species in the study area.
- Management options (exploitation or promotion, biological, mechanical, and chemical approaches) included in the integrated *Prosopis* management and monitoring system should be applied on a case based approach. Requirements of relevent policies, Acts and regulations (section 1.7) should be considered in the implementation of the management options to promote compliance and sustainability.

- Monitoring of sites which have not experienced *Prosopis* invasion should be conducted to prevent further invasion in the sites. Establishment of *Prosopis* trees in such areas should be prevented by removal of *Prosopis* seedlings as and when they are spotted.

Future studies recommended to augment the findings of the current study should focus on the following:-

- Increasing the spatial scale of the study by conducting the same study in other regions of Botswana where *Prosopis* species grow.
- Investigation of the associations between soil attributes and *Prosopis* species using more characteristics of soil (e.g. Phosphorus, Iron, Zinc, Manganese, Boron) and *Prosopis* species (e.g. root distribution patterns, stem diameter, chemical composition of seed pods) and higher sampling intensities.
- Feasibility study of the production and commercialization of *Prosopis* products (e.g. fire wood, charcoal, livestock feed, honey, timber) in Botswana.

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APPENDIX 1. The Social Survey Questionnaire.

1. Date of interview_____
2. Gender (Interviewee)
   a. Female
   b. Male
3. Location/Village:
   a. Bokspits
   b. Rappelspan
   c. Vaalshoek
   d. Struizendam
4. Age Group:
   a. 20-30
   b. 31-40
   c. 41-50
   d. 51-60
   e. 61-70
   f. 71-80
   g. 81-90
   h. 91+
5. Education/literacy level
   a. No formal education
   b. Primary
   c. Secondary
   d. Tertiary
6. How was the species introduced in your village? By who? And when?
   a. Agriculture (1980s) _____
   b. Individual members of the community (1980s)_____
   c. Other (specify who and when)_____
7. How has the change (if any) in *Prosopis* species density affected indigenous plants in your village?

a. Indigenous plants have decreased in density over the years
b. Indigenous plants have increased in density over the years
c. Indigenous plants have not changed in density over the years

8. How has the change affected your life and the life of other members of your community?
   a. Improved livelihood of the community
   b. Deteriorated livelihood of the community
   c. Did not affect livelihood of the community
9. Do you regard *Prosopis* as a nuisance in your village?
   a. Yes
   b. No
10. When did you realize that the species has become a cause for concern (if you regard it so) in your village?
   a. 1960s
   b. 1970s
   c. 1980s
   d. 1990s
   e. 2000
   f. Other (specify year)_____
11. Have you made an effort to manage the species as an individual and/or as a community?
   a. Yes
   b. No
12. If yes, what are the efforts and what are the results produced from implementation of your management strategy(ies)?
   a. Clearing by cutting trees as a community

      Results: Increase in density; decrease in density; no change in density
   b. Clearing by cutting as an individual

      Results: Increase in density; decrease in density; no change in density

c. Other (Specify effort:)_____

Results: Increase in density; decrease in density; no change in density

13. Have you reported the problem (if you regard it so) to anyone or any organization?
    a. Yes
    b. No
    c. It is not a problem
14. If yes, what is/are the organization(s)/ individuals and what action did they take?
    a. Agriculture

       Action taken:
    b. Other

       (Specify)_____

       Action taken

       (Specify)_____
15. What promotes the dispersal of *Prosopis* seeds?
    a. Goats
    b. Donkeys
    c. Cattle
    d. Human
    e. Goats, Donkeys and Cattle (livestock)
16. What management strategies do you suggest that can assist in controlling the invasion of the species in your village?
    a. Cutting all *Prosopis* trees
    b. Uprooting all trees
    c. Other (Specify method (s))_____
17. What products do you harvest from the species? 18. What are the products mentioned above used for?
    a. Fire wood
    b. Timber for kraal construction and fencing

c. Pods for consumption by human

d. Pods for consumption livestock

e. All of the above

f. Harvest no product

g. Other (Specify)_____

19. When are the products normally harvested?

a. Summer (Specify months)_____

b. Winter (Specify months)_____

c. Aotum (Specify months)_____

d. Spring (Specify months)_____

20. What are the challenges that you normally face in relation to harvesting?

a. Long distance to the location where resources are available

b. Lack of market for the resources or poor demand

c. Poor prices for the resources

d. Other (specify challenge)_____

21. Do you think there are some ways in which the community can generate some revenues from the *Prosopis* species?

a. Yes

b. No

22. If yes, can you suggest some ways of revenue generation from the species?

a. Selling of timber for fuel wood

b. Selling of pods

c. Other (Specify)_____

23. What constraints can you foresee concerning your suggestion(s)?

a. Poor prices

b. Poor demand or lack of market

c. Lack of resources to drive the business

d. Lack of time to devote to the business

e. Shortage of *Prosopis* resources

24. If offered an opportunity to learn ways of exploiting the species for your own benefit and community benefit, would you be interested?
    a. Yes
    b. No
25. How is the performance of your village organizations (e.g. VDC, BORAVAST trust) in dealing with the species invasion?
    a. Poor
    b. Moderate
    c. Good
    d. Excellent

APPENDIX 2. Questions Addressed in the Focused Group Discussions.

1. How was the species introduced in your village? By whom? And when?
2. How has the change (if any) in *Prosopis* species density affected indigenous plants in your village?
3. How has the change affected the life of members of the community?
4. Do you regard *Prosopis* as a nuisance in your village?
5. When did you realize that the species has become a cause for concern (if you regard it so) in your village?
6. Have you made an effort to manage the species as an individual and as a community?
7. If yes, what are the efforts and what are the results produced from implementation of your management strategy(ies)?
8. Have you reported the problem (if you regard it so) to anyone or any organization?
9. If yes, what is/are the organization(s) and what action did they take?
10. What promotes the dispersal of *Prosopis* seeds?
11. What management strategies do you suggest that can assist in controlling the invasion of the species in your village?
12. What products do you harvest from the species?
13. What are the products mentioned above used for?
14. When are the product normally harvested?
15. What are the challenges that you normally face in relation to harvesting?
16. Do you think there are some ways in which the community can generate some revenues from the *Prosopis* species?
17. If yes, can you suggest some ways of revenue generation from the species?
18. What constraints can you foresee concerning your suggestion(s)?

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19. If offered an opportunity to learn ways of exploiting the species for your own benefit and community benefit, would you be interested?
20. How effective are your village organizations (e.g. VDC, BORAVAST trust) in dealing with the species invasion?

The following issues were noted during the group discussion participants in Struizendam village;

1. The *Prosopis* species were introduced in Struizendam in large numbers by the Ministry of Agriculture in 1989 through the tree planting day programme. The main purpose of introducing the species was to stabilize sand dunes in the area. It was also pointed out that some *Prosopis* trees were brought into the village from South Africa and Namibia in the early 1980s by individuals who were employed in those countries. Individuals who brought the species were intending to take advantage of its good shade during summer times.
2. The species have increased in density over the years since its introduction.
3. The disadvantages of having the species in the environment outweigh the advantages. However, it would not be desirable to eradicate the species without first identifying an indigenous species with similar good qualities to *Prosopis* species, but lacking the bad properties found in the *Prosopis* species.
4. Initially the density of *Prosopis* species did not cause concern, but it became a cause for concern around the year 2000.
5. Currently the only management strategy that is implemented to control the invasion of *Prosopis* species within the residential area of the village entails pruning and uprooting of some trees through the Government assistance programmes like the drought relief and Ipelegeng. However, it was mentioned that the efforts are bedeviled by the species quick rate of seed dispersal and growth. The Department of Roads also assists in clearing the *Prosopis* trees by uprooting them along roadsides.

6. The problem of *Prosopis* invasion in the area has been a subject in various meetings that were addressed by government officials but up to date nothing in the form of assistance specifically targeting the species invasion management has materialized.
7. The seeds of the species are mainly dispersed by livestock particularly donkeys and horses which deposit intact seed with their pellets. It was indicated that ruminants like cattle and goats do not contribute in the dispersal of the species seeds because they effectively crush and digest them.
8. It was suggested that the management method that can be implemented in controlling the invasion of the species is by uprooting some individual trees. If possible, the species should gradually be replaced with other indigenous species that possess good qualities that are similar to the qualities of *Prosopis* species, but void of the bad properties found in the *Prosopis* species.
9. There is no individual who is generating money from the species products, but treated poles for fencing and pods for fodder can be used for revenue generation provided the market for the products is available. It was also mentioned that even though there is no one who is currently involved in business that deals with products from *Prosopis* species, some farmers once in a while request some members of the community to harvest pods for them to be used for livestock feeding. In many instances, a bag full of pods will be sold for five Pula (P5.00).
10. The community if given an opportunity will be interested in learning ways of exploiting the *Prosopis* species to their own advantage.
11. The constraints in *Prosopis* management are mainly lack of relevant expertise and funds.
12. The disadvantages of the *Prosopis* species include the following;
    - Killing of other trees that grow within their environments

- Depletion of underground water resources
- Large thorns that cause tyre deflations and injure human
- Killing of livestock particularly donkeys and horses through constipation caused by overfeeding of pods produced by the *Prosopis* trees.
- Causing constipation in children who enjoy feeding on the sweet pods of some *Prosopis* species

13. The advantages of the *Prosopis* species include the following;

a) Provision of good shade
b) Stabilization of sand dunes
c) Serve as wing breakers
d) Provision of fodder resources (pods) for livestock
e) Provision of fire wood
f) Timber for fencing even though the timber does not last for two years when untreated.

Rapelspan group discussion yielded the following points;

1. The *Prosopis* species were introduced in Rapelspan mainly by the Ministry of Agriculture in the 1980s through the tree planting day programmes. The main purpose of introducing the species was to stabilize sand dunes in the area. It was also mentioned that some *Prosopis* trees were brought into the village from South Africa and Namibia also in the early 1980s by individuals.
2. The species have increased in density over the years since its introduction.
3. The disadvantages of having the species in the environment outweigh the advantages.
4. Initially the density of *Prosopis* species was not a cause for concern, but it became a cause for concern around the year 2000.
5. The management strategy that was implemented to control the invasion of *Prosopis* species within the residential area of the village

entailed pruning and uprooting of some trees through the Government assistance programmes like the drought relief and *Ipelegeng*.

6. The problem of *Prosopis* invasion in the area has been a subject in various meetings that were addressed by government officials but up to date nothing in the form of assistance specifically targeting the species invasion management has materialized.
7. The seeds of the species are mainly dispersed by livestock particularly donkeys and horses which deposit intact seed with their pellets. It was indicated that ruminants like cattle and goats do not contribute in the dispersal of the species seeds because they effectively crush and digest them.
8. It was suggested that the management method that can be implemented in controlling the invasion of the species is by uprooting some individual trees.
9. There is no individual who is generating money from the species products, but pods or the whole tree can be used to produce fodder which can be used for revenue generation provided the market for the products is available.
10. The community if given an opportunity will be interested in learning ways of exploiting the *Prosopis* species to their own advantage.
11. The constraints in *Prosopis* management are mainly lack of relevant expertise, lack of market for potential products from the species and funds.
12. The disadvantages of the *Prosopis* species include the following;
    - Killing of other trees that grow within their environments
    - Depletion of underground water resources
    - Large thorns that cause tyre deflations and injure human

- Killing of livestock particularly donkeys and horses through constipation caused by overfeeding of pods produced by the *Prosopis* trees.
- Causing constipation in children who enjoy feeding on the sweet pods of some *Prosopis* species

13. The advantages of the *Prosopis* species include the following;
    a) Provision of good shade
    b) Stabilization of sand dunes
    c) Serve as wing breakers
    d) Provision of fodder resources (pods) for livestock
    e) Provision of fire wood
    f) Timber for fencing even though it was mentioned that the timber does not last for two years when untreated.

Focused group discussion held in Vaalhoek revealed the following;

1. The *Prosopis* species were introduced in Vaalhoek by the Ministry of Agriculture in 1979 through the tree planting day programme. The main purpose of introducing the species was to stabilize sand dunes in the area. It was also pointed out that the first *Prosopis* tree which was planted at the Bokspits primary school was brought into the village from South Africa in 1940.
2. The species have increased in density over the years since its introduction.
3. The disadvantages of having the species in the environment outweigh the advantages. However, it would not be desirable to control the species rather to eradicate them.
4. Initially the density of *Prosopis* species did not cause concern, but it became a cause for concern around the year 1999.
5. The management strategy that was implemented to control the invasion of *Prosopis* species within the residential area of the village entailed pruning and uprooting of some trees through the

Government assistance programmes like the drought relief and Ipelegeng.

6. The problem of *Prosopis* invasion in the area has been a subject in various meetings that were addressed by government officials but up to date nothing in the form of assistance specifically targeting the species invasion management has materialized.
7. The seeds of the species are mainly dispersed by livestock particularly donkeys and horses which deposit intact seed with their pellets. It was indicated that ruminants like cattle and goats do not contribute in the dispersal of the species seeds because they effectively crush and digest them.
14. It was suggested that the management method that can be implemented in controlling the invasion of the species is by uprooting some individual trees.
15. There is no individual who is generating money from the species products, but treated poles for fencing and pods for fodder can be used for revenue generation provided the market for the products is available. In spite of this, it was mentioned that in rare occasions, some individuals harvest the pods of the *Prosopis* species and sell them for ten Pula per bag (P10.00). Lack of market discourages those who have the desire to get involved in this business.
8. The community if given an opportunity will be interested in learning ways of exploiting the *Prosopis* species to their own advantage.
9. The constraints in *Prosopis* management are mainly lack of relevant expertise and funds.
10. The disadvantages of the *Prosopis* species include the following;
    - Killing of other trees that grow within their environments
    - Depletion of underground water resources
    - Large thorns that cause tyre deflations and injure human

- Killing of livestock particularly donkeys and horses through constipation caused by overfeeding of pods produced by the *Prosopis* trees.
- Causing constipation in children who enjoy feeding on the sweet pods of some *Prosopis* species

11. The advantages of the *Prosopis* species include the following;
    a) Provision of good shade
    b) Stabilization of sand dunes
    c) Serve as wing breakers
    d) Provision of fodder resources (pods) for livestock
    e) Provision of fire wood
    f) Timber for fencing even though the timber does not last for two years when untreated.

APPENDIX 4. Number of Individual Plant Species Found in the Sampled Quadrats.

Plot No.	Prosopis	Lyceum	H. trufuosa	Crotolaria sp sp	A.herb	A. aerio	A. Melli	Rhigozum	A leude	Aristida spp	G. Polycephala	Schemitia spp	T. terrestis	Stigrostis spp	Salsola	Eragrostis spp	C. Inflata	Scroph
1	10.00	17	5	103	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	28.00	4	0	222	1	0	0	0	1	0	0	0	0	0	0	0	0	0
3	0.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	40.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	53.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	25.00	2	0	32	2	4	0	0	0	0	0	0	0	0	0	0	0	0
7	42.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	2.00	0	1	0	0	1	0	3	0	0	0	0	0	0	0	0	0	0
9	16.00	0	0	121	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	2.00	0	0	317	0	0	0	221	0	0	0	0	0	0	0	0	0	0
11	0.00	0	0	0	0	0	0	900	0	0	0	0	0	0	0	0	0	0
12	0.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	56.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	41.00	0	0	0	1	4	0	400	0	0	0	0	0	0	0	0	0	0
15	54.00	3	0	0	0	2	0	50	0	0	0	0	0	0	0	0	0	0
16	43.00	0	0	0	0	0	0	25	0	0	1025	925	100	0	0	0	0	0
17	31.00	0	0	0	0	0	0	425	0	0	0	0	0	0	0	0	0	0
18	29.00	0	0	0	0	1	0	150	0	0	0	0	0	0	0	0	0	0
19	23.00	0	0	0	0	1	0	50	0	0	0	0	0	0	0	0	0	0
20	35.00	275	0	0	0	0	0	11025	0	975	0	1500	0	700	0	0	0	0
21	16.00	475	0	0	0	1	0	9750	0	0	0	400	0	425	1775	1075	0	0

Table 29. Cont.

22	2.00	25	0	0	1	0	0	325	0	0	0	0	0	0	0	0	0	0
23	45.00	25	0	0	0	0	1	8000	0	0	0	0	0	0	0	0	0	0
24	7.00	0	0	0	0	0	0	100	0	0	0	0	0	0	75	0	0	0
25	19.00	0	0	0	0	0	0	225	0	400	0	0	0	75	0	0	0	0
26	51.00	0	0	0	0	4	0	175	0	0	0	0	0	0	0	0	0	0
27	28.00	0	0	0	0	11	0	0	0	0	25	0	0	0	0	0	0	0
28	18.00	0	0	0	0	0	0	150	0	300	0	0	0	0	0	0	75	0
29	24.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	724
30	29.00	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	400
31	24.00	0	0	0	0	1	0	25	0	0	0	0	0	25	0	0	0	0
32	19.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	36.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	19.00	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
35	122.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	68.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	54.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	39.00	0	0	0	0	0	0	375	0	0	0	0	0	0	0	0	0	0
39	38.00	0	0	0	0	4	0	50	0	0	300	0	0	6	0	0	0	0
40	37.00	0	0	0	0	1	0	2100	0	0	1075	0	0	0	0	0	0	0
41	0.00	0	0	0	0	3	0	400	0	0	0	0	0	0	0	0	0	0
42	0.00	0	0	0	1	4		125	0	0	0	0	0	0	0	0	0	0
43	5.00	0	0	0	0	3	0	150	0	0	0	0	0	0	0	0	0	0

APPENDIX 5. Data for Soil Samples Collected Under Class 1 *Prosopis* Trees.

SAMP ID	pH	EC (µs/cm)	Na (cmol/kg)	K (cmol/kg)	Ca (cmol/kg)	Mg (cmol/kg)	N (mg/kg)	C (mg/kg)	C:N Ratio
YBVS1	7.78	294	0.1398	0.1507	3.081	0.1935	3112.2	31125	10.00
YBVS2	8.3	135	0.1382	0.0996	1.333	0.109	125.9	3525	28.00
YBVS3	8.44	252	0.1704	0.2252	2.986	0.2643	863.9	9731	11.26
YBVS4	8.56	208	0.164	0.1888	2.654	0.2142	859	7976	9.29
YBVS5	8.34	289	0.1456	0.1657	1.426	0.1207	429.8	4977	11.58
YBVS6	8.39	200	0.1547	0.1991	2.44	0.2371	722.2	8207	11.36
YBVS7	7.77	285	0.1416	0.1384	1.798	0.1622	1090.7	10846	9.94
YBVS8	8.63	110.2	0.1403	0.1044	1.134	0.0889	488.3	3588	7.35
YBVS9	7.57	170.5	0.1353	0.0708	0.852	0.0638	519.3	3637	7.00
YBVS10	8.25	115.4	0.1374	0.0848	0.956	0.0888	422.3	2742	6.49
YBVS11	7.92	170.7	0.1417	0.0822	0.981	0.0885	649.9	5075	7.81
YBVS12	8.46	159.2	0.1818	0.1092	0.767	0.0815	545.7	3365	6.17
YBVS13	8.29	2180	0.6525	0.0895	1.155	0.0867	4860	680.8	0.14
YBVS14	8.61	152.2	0.1369	0.1297	1.002	0.083	187.2	2334	12.47
YBVS15	8.55	110.8	0.1329	0.0618	0.86	0.054	2423	76.9	0.03
YSTS1	8.48	113	0.1263	0.0954	1.016	0.0723	1806.5	2237	1.24
YSTS2	8.2	219	0.1587	0.1551	1.313	0.1374	769.6	8534	11.09
YSTS3	8.26	302	0.1594	0.2257	2.969	0.3061	1696.6	17235	10.16
YSTS4	8.43	139.3	0.1461	0.1155	1.701	0.1384	380.2	4534	11.93
YSTS5	8.1	244	0.1434	0.1159	1.818	0.1608	1052.3	9230	8.77
YSTS6	8.36	160.3	0.1419	0.1244	1.786	0.1701	845.6	7447	8.81
YSTS7	8.31	181	0.1676	0.1978	1.171	0.1196	569.1	4415	7.76
YSTS8	8.47	136.6	0.1331	0.1224	1.093	0.1007	514	3769	7.33
YSTS9	8.14	138.7	0.1364	0.0887	0.819	0.078	206.6	2616	12.66
YSTS10	8.19	122.6	0.1448	0.0818	0.884	0.0901	118.7	2532	21.33
YSTS11	7.93	158.7	0.1302	0.1023	1.154	0.108	440.8	4018	9.12
YSTS12	8.66	161.6	0.1376	0.1405	1.303	0.1253	590.5	4375	7.41
YSTS13	8.36	106.8	0.1388	0.0517	0.919	0.0503	ND	1663	-
YSTS14	8.51	82.2	0.1441	0.0587	0.624	0.0597	791	979	1.24
YSTS15	8.14	133.2	0.1424	0.0839	0.792	0.0876	ND	2618	-

Y – Class 1; M – Class 2; S – Class 3

BV – Bokspits/Valhoek ST- Struizendam

S- Sample

APPENDIX 6. Data for Soil Samples Collected Under Class 2 *Prosopis* Trees.

SAMP ID	pH	EC (µs/cm)	Na (cmol/Kg)	K (cmol/Kg)	Ca (cmol/Kg)	Mg (cmol/Kg)	N (mg/Kg)	C (mg/Kg)	C:N Ratio
MBVS1	7.79	395	0.1361	0.1195	1.826	0.1366	1742.2	16960	9.73
MBVS2	8.27	186.9	0.148	0.0907	1.01	0.0934	397.9	3049	7.66
MBVS3	8.44	205	0.1387	0.2355	2.128	0.2189	1074.9	8843	8.23
MBVS4	8.21	259	0.147	0.2124	2.693	0.2494	1318.8	9020	6.84
MBVS5	8.21	186	0.1447	0.1636	0.658	0.118	364.9	3428	9.39
MBVS6	7.94	248	0.1492	0.1429	1.66	0.1848	1037.2	7720	7.44
MBVS7	8.24	243	0.1366	0.1601	1.672	0.1676	1135.3	6377	5.62
MBVS8	8.2	170	0.1277	0.1182	1.594	0.1229	675.2	6206	9.19
MBVS9	8.12	148.4	0.1429	0.0791	0.922	0.0725	453.4	4477	9.87
MBVS10	8.24	177.7	0.1309	0.0818	1.087	0.0937	322.4	3476	10.78
MBVS11	8.23	141.3	0.1412	0.0952	0.977	0.0985	ND	2669	-
MBVS12	7.47	298	0.17	0.1539	1.125	0.105	735.3	5361	7.29
MBS13	8.29	195.5	0.1973	0.084	0.756	0.0764	500.3	2891	5.78
MBVS14	8.35	148.1	0.1341	0.0629	0.603	0.0534	136.5	1981	14.51
MBVS15	8.26	193.4	0.1533	0.0896	1.101	0.0773	5127	302.6	0.06
MSTS1	8.57	130.4	0.1406	0.1505	0.824	0.0834	170.5	2489	14.60
MSTS2	8.03	179.3	0.1606	0.1532	1.255	0.1335	255	4284	16.80
MSTS3	8.35	150	0.1357	0.2048	2.867	0.286	1653.4	17241	10.43
MSTS4	8.03	287	0.1415	0.1347	1.707	0.1533	706.2	7885	11.17
MSTS5	8.4	204	0.1557	0.1769	1.814	0.1774	892.3	7511	8.42
MSTS6	8.04	215	0.1387	0.1088	1.441	0.1337	774.6	6795	8.77
MSTS7	7.85	181.6	0.1367	0.0787	0.845	0.0817	677.9	4908	7.24
MSTS8	8.17	130.7	0.143	0.116	1.207	0.1354	744.2	5244	7.05
MSTS9	8.03	166.3	0.1442	0.1206	0.99	0.0934	325.9	3394	10.41
MSTS10	8.28	140.5	0.1349	0.0785	0.796	0.0764	413	2183	5.29
MSTS11	8.25	146.1	0.1336	0.0902	1.091	0.1041	626.7	4546	7.25
MSTS12	8.44	148.6	0.1624	0.1849	1.196	0.1226	238.6	3774	15.82
MSTS13	8.3	129.1	0.137	0.0644	0.577	0.0453	232	1355	5.84
MSTS14	8.29	119.1	0.1299	0.073	0.658	0.0435	15.4	1800	116.88
MSTS15	8.47	121.4	0.1359	0.0989	1.385	0.1204	218.7	3257	14.89

Y – Class 1; M – Class 2; S – Class 3

BV – Bokspits/Valhoek ST- Struizendam

S- Sample

APPENDIX 7. Data for Soil Samples Collected Under Class 3 *Prosopis* Trees.

SAMP ID	pH	EC (µs/cm)	Na (cmol/kg)	K (cmol/kg)	Ca (cmol/kg)	Mg (cmol/kg)	N (mg/kg)	C (mg/kg)	C:N Ratio
SBVS1	7.66	364	0.1363	0.0991	1.381	0.1092	1209.6	11223	2.24
SBVS2	8.06	185	0.1441	0.1375	1.235	0.1165	606.5	5014	0.62
SBVS3	8.29	229	0.1357	0.182	2.414	0.2574	812.4	8039	0.80
SBVS4	8.03	347	0.1565	0.346	2.354	0.2370	1022.1	10006	0.73
SBVS5	7.66	377	0.1559	0.2327	1.674	0.1811	1614.8	13727	2.06
SBVS6	7.91	241	0.1202	0.1511	1.908	0.1982	728.4	6664	0.85
SBVS7	8.07	233	0.1386	0.1398	1.791	0.1783	975.7	7836	1.41
SBVS8	8.01	174.6	0.1391	0.0935	1.198	0.0874	773.3	5567	0.61
SBVS9	8.01	186.2	0.1197	0.0992	1.386	0.1005	938.6	9154	2.11
SBVS10	7.88	285	0.1468	0.1154	1.182	0.0965	17857	4329	0.44
SBVS11	7.83	1098	0.2871	0.1774	1.610	0.152	1039	9782	2.13
SBVS12	8.39	266	0.1957	0.1925	1.194	0.1182	453.6	4593	1.63
SBVS13	7.88	154	0.1404	0.0852	0.832	0.0712	1162.2	2826	1.00
SBVS14	8.09	173.5	0.1465	0.0855	0.657	0.067	345.1	2817	0.66
SBVS15	8.22	189.6	0.1438	0.0909	1.100	0.0956	203.7	4248	0.72
SSTS1	8.2	201	0.1714	0.1931	1.506	0.1633	412.7	5922	0.63
SSTS2	8.25	431	0.1569	0.2417	1.594	0.1566	1166.9	9396	0.60
SSTS3	8.05	426	0.1355	0.2139	2.641	0.2542	1676	15716	1.73
SSTS4	7.88	300	0.1714	0.1539	1.378	0.138	802.8	9092	0.92
SSTS5	8.31	205	0.1446	0.2488	2.561	0.2422	926.4	9885	2.24
SSTS6	8.26	181.5	0.1365	0.1238	0.997	0.103	562.5	4407	0.87
SSTS7	8.28	201	0.1482	0.1335	1.724	0.1589	826.8	5067	1.22
SSTS8	8	197.5	0.1411	0.1291	0.914	0.0978	549.5	4150	1.00
SSTS9	8.18	194.8	0.1352	0.1131	0.751	0.08	511.6	4167	1.27
SSTS10	8.17	190	0.14	0.1392	1.055	0.0976	391.6	3292	0.58
SSTS11	8.06	200	0.1409	0.1211	1.53	0.1419	594.2	5675	1.72
SSTS12	8.06	170.6	0.1414	0.1016	1.256	0.1312	501.7	3309	2.99
SSTS13	8.47	109.7	0.1509	0.0709	0.912	0.0542	ND	1108	0.74
SSTS14	8.39	169	0.1452	0.0778	0.571	0.0531	17.9	1490	0.34
SSTS15	8.24	179.9	0.1349	0.0884	1.151	0.0946	487.4	4319	-

Y – Class 1; M – Class 2; S – Class 3

BV – Bokspits/Valhoek ST- Struizendam

S- Sample

APPENDIX 8. Soil pH Data Used for Soil-*Prosopis* Correlations.

Sample ID	pH	Sample ID	pH	Sample ID	pH	Sample ID	pH
S1C 0-20	8.58	S1C 60-80	9.15	S1N 0-20	8.76	S1N 60-80	9.11
S2C 0-20	8.67	S2C 60-80	8.95	S2N 0-20	8.83	S2N 60-80	8.65
S3C 0-20	7.39	S3C 60-80	8.46	S3N 0-20	8.26	S3N 60-80	9.03
S4C 0-20	8.08	S4C 60-80	8.88	S4N 0-20	7.74	S4N 60-80	8.99
S5C 0-20	8.11	S5C 60-80	8.34	S5N 0-20	8	S5N 60-80	8.11
S6C 0-20	7.56	S6C 60-80	NS	S6N 0-20	7.29	S6N 60-80	NS
S7C 0-20	7.72	S7C 60-80	9.23	S7N 0-20	7.7	S7N 60-80	8.82
S8C 0-20	7.44	S8C 60-80	9.06	S8N 0-20	7.83	S8N 60-80	8.67
S10C 0-20	7.31	S10C 60-80	NS	S10N 0-20	7.67	S10N 60-80	NS
S11C 0-20	7.23	S11C 60-80	9.12	S11N 0-20	7.57	S11N 60-80	9.21
S12C 0-20	7.62	S12C 60-80	7.59	S12N 0-20	8.53	S12N 60-80	8.96
S13C 0-20	7.48	S13C 60-80	8.38	S13N0-20	8.59	S13N 60-80	8.65
S14C 0-20	8.34	S14C 60-80	8.74	S14N 0-20	8.67	S14N 60-80	8.56
S15C 0-20	7.73	S15C 60-80	8.4	S15N 0-20	7.68	S15N 60-80	8.58
S16C 0-20	7.55	S16C 60-80	8.89	S16N 0-20	7.94	S16N 60-80	8.89
S17C 0-20	8.43	S17C 60-80	8.19	S17N 0-20	8.56	S17N 60-80	8.54
S18C 0-20	8.31	S18C 60-80	8.82	S18N 0-20	8.69	S18N 60-80	8.84
S19C 0-20	7.39	S19C 60-80	9.07	S19N 0-20	8.08	S19N 60-80	8.39
S20C 0-20	7.16	S20C 60-80	8.96	S20N 0-20	7.79	S20N 60-80	8.73
S21C 0-20	7.15	S21C 60-80	8.36	S21N 0-20	7.64	S21N 60-80	8.63
S22C 0-20	7.65	S22C 60-80	8.56	S22N 0-20	8.6	S22N 60-80	7.96
S23C 0-20	7.62	S23C 60-80	8.18	S23N 0-20	7.81	S23N 60-80	8.19
S24C 0-20	7.79	S24C 60-80	9.02	S24N 0-20	8.72	S24N 60-40	8.64
S25C 0-20	8.2	S25C 60-80	8.5	S25N 0-20	7.86	S25N 60-80	8.23
S26C 0-20	8.59	S26C 60-80	8.33	S26N 0-20	7.93	S26N 60-80	8.54
S27C 0-20	7.34	S27C 60-80	8.25	S27N 0-20	7.77	S27N 60-80	8.69
S28C 0-20	8.04	S28C 60-80	8.77	S28N 0-20	8.4	S28N 60-80	8.99
S29C 0-20	7.62	S29C 60-80	8.8	S29N 0-20	8.34	S29N 60-80	9.14
S30C 0-20	7.5	S30C 60-80	8.39	S30N 0-20	8.08	S30N 60-80	8.63
S31C 0-20	7.79	S31C 60-80	9.77	S31N 0-20	8.53	S31N 60-80	9.41
S32C 0-20	7.35	S32C 60-80	9.04	S32N 0-20	8.45	S32N 60-80	8.86
S33C 0-20	7.77	S33C 60-80	8.97	S33N0-20	7.97	S33N 60-80	8.97
S34C 0-20	7.4	S34C 60-80	8.51	S34N 0-20	7.51	S34N 60-80	8.55

NS- Not Sampled

APPENDIX 9. Electrical Conductivity (EC) Data Used for Soil-*Prosopis* Correlations.

SAMP ID	EC(µs/cm)	Sample ID	EC(µs/cm)	Sample ID	EC(µs/cm)	Sample ID	EC(µs/cm)
S1C 0-20	123	S1C 60-80	226	S1N 0-20	110.3	S1N 60-80	259
S2C 0-20	143.9	S2C 60-80	145.4	S2N 0-20	159.7	S2N 60-80	243
S3C 0-20	373	S3C 60-80	180	S3N 0-20	762	S3N 60-80	184.2
S4C 0-20	230	S4C 60-80	217	S4N 0-20	310	S4N 60-80	370
S5C 0-20	330	S5C 60-80	158.8	S5N 0-20	191	S5N 60-80	143.5
S6C 0-20	350	S6C 60-80	NS	S6N 0-20	360	S6N 60-80	NS
S7C 0-20	404	S7C 60-80	193.8	S7N 0-20	261	S7N 60-80	192.1
S8C 0-20	318	S8C 60-80	96.4	S8N 0-20	189.1	S8N 60-80	82.1
S10C 0-20	282	S10C 60-80	NS	S10N 0-20	201	S10N 60-80	NS
S11C 0-20	313	S11C 60-80	83.8	S11N 0-20	656	S11N 60-80	548
S12C 0-20	317	S12C 60-80	447	S12N 0-20	90.3	S12N 60-80	151.3
S13C 0-20	313	S13C 60-80	177.2	S13N0-20	86.6	S13N 60-80	136
S14C 0-20	161.4	S14C 60-80	212	S14N 0-20	125.5	S14N 60-80	83.8
S15C 0-20	244	S15C 60-80	134.5	S15N 0-20	247	S15N 60-80	101.6
S16C 0-20	355	S16C 60-80	115	S16N 0-20	169.4	S16N 60-80	193
S17C 0-20	132.2	S17C 60-80	257	S17N 0-20	83.4	S17N 60-80	131.6
S18C 0-20	130.6	S18C 60-80	96.3	S18N 0-20	76.6	S18N 60-80	86.3
S19C 0-20	562	S19C 60-80	266	S19N 0-20	260	S19N 60-80	161.1
S20C 0-20	390	S20C 60-80	104.4	S20N 0-20	180	S20N 60-80	110
S21C 0-20	421	S21C 60-80	130	S21N 0-20	249	S21N 60-80	113.7
S22C 0-20	274	S22C 60-80	111.5	S22N 0-20	92.5	S22N 60-80	187
S23C 0-20	282	S23C 60-80	206	S23N 0-20	252	S23N 60-80	393
S24C 0-20	224	S24C 60-80	217	S24N 0-20	105.6	S24N 60-40	262
S25C 0-20	259	S25C 60-80	479	S25N 0-20	342	S25N 60-80	711
S26C 0-20	281	S26C 60-80	494	S26N 0-20	270	S26N 60-80	432
S27C 0-20	768	S27C 60-80	385	S27N 0-20	359	S27N 60-80	386
S28C 0-20	306	S28C 60-80	202	S28N 0-20	267	S28N 60-80	322
S29C 0-20	365	S29C 60-80	160.2	S29N 0-20	184.4	S29N 60-80	239
S30C 0-20	269	S30C 60-80	128	S30N 0-20	159.6	S30N 60-80	145.7
S31C 0-20	238	S31C 60-80	191	S31N 0-20	87.5	S31N 60-80	171.1
S32C 0-20	388	S32C 60-80	179.6	S32N 0-20	117	S32N 60-80	158.4
S33C 0-20	347	S33C 60-80	163.5	S33N0-20	207	S33N 60-80	154
S34C 0-20	293	S34C 60-80	122.2	S34N 0-20	171.2	S34N 60-80	168.3

NS- Not Sampled

APPENDIX 10. Soil Calcium (Ca) Data Used for Soil-*Prosopis* Correlations.

SAMP ID	Ca (cmol/kg)	Sample ID	Ca (cmol/kg)	Sample ID	Ca (cmol/kg)	Sample ID	Ca (cmol/kg)
S1C 0-20	17.13	S1C 60-80	23.25	S1N 0-20	16.45	S1N 60-80	24.43
S2C 0-20	14.73	S2C 60-80	21.81	S2N 0-20	19.51	S2N 60-80	14.64
S3C 0-20	22.53	S3C 60-80	21.02	S3N 0-20	25.57	S3N 60-80	16.56
S4C 0-20	29.18	S4C 60-80	30.73	S4N 0-20	31.78	S4N 60-80	19.28
S5C 0-20	12.78	S5C 60-80	13.67	S5N 0-20	16.48	S5N 60-80	10.78
S6C 0-20	14.28	S6C 60-80	NS	S6N 0-20	15.82	S6N 60-80	NS
S7C 0-20	16.69	S7C 60-80	17.43	S7N 0-20	15.82	S7N 60-80	19.16
S8C 0-20	8.70	S8C 60-80	21.93	S8N 0-20	8.05	S8N 60-80	18.61
S10C 0-20	6.68	S10C 60-80	NS	S10N 0-20	5.64	S10N 60-80	NS
S11C 0-20	7.56	S11C 60-80	11.14	S11N 0-20	11.02	S11N 60-80	11.57
S12C 0-20	6.87	S12C 60-80	21.92	S12N 0-20	8.97	S12N 60-80	21.12
S13C 0-20	10.54	S13C 60-80	14.24	S13N0-20	12.38	S13N 60-80	15.36
S14C 0-20	12.14	S14C 60-80	14.63	S14N 0-20	18.29	S14N 60-80	13.01
S15C 0-20	10.25	S15C 60-80	13.97	S15N 0-20	14.31	S15N 60-80	15.12
S16C 0-20	11.98	S16C 60-80	20.25	S16N 0-20	12.81	S16N 60-80	17.56
S17C 0-20	13.80	S17C 60-80	15.54	S17N 0-20	8.85	S17N 60-80	18.16
S18C 0-20	10.39	S18C 60-80	18.61	S18N 0-20	10.60	S18N 60-80	16.39
S19C 0-20	21.57	S19C 60-80	13.70	S19N 0-20	20.39	S19N 60-80	15.72
S20C 0-20	7.11	S20C 60-80	19.58	S20N 0-20	8.25	S20N 60-80	20.18
S21C 0-20	8.86	S21C 60-80	12.04	S21N 0-20	11.87	S21N 60-80	13.58
S22C 0-20	12.96	S22C 60-80	11.32	S22N 0-20	14.78	S22N 60-80	14.51
S23C 0-20	12.72	S23C 60-80	25.69	S23N 0-20	23.49	S23N 60-80	20.75
S24C 0-20	15.39	S24C 60-80	18.37	S24N 0-20	14.76	S24N 60-40	19.81
S25C 0-20	41.29	S25C 60-80	24.06	S25N 0-20	35.51	S25N 60-80	26.71
S26C 0-20	37.81	S26C 60-80	23.37	S26N 0-20	34.52	S26N 60-80	25.19
S27C 0-20	37.20	S27C 60-80	27.75	S27N 0-20	28.43	S27N 60-80	20.88
S28C 0-20	33.29	S28C 60-80	27.43	S28N 0-20	33.67	S28N 60-80	30.63
S29C 0-20	29.34	S29C 60-80	28.20	S29N 0-20	29.57	S29N 60-80	25.81
S30C 0-20	11.56	S30C 60-80	21.62	S30N 0-20	13.65	S30N 60-80	13.08
S31C 0-20	9.79	S31C 60-80	7.07	S31N 0-20	13.22	S31N 60-80	15.18
S32C 0-20	14.12	S32C 60-80	31.51	S32N 0-20	14.10	S32N 60-80	22.96
S33C 0-20	20.22	S33C 60-80	17.04	S33N0-20	18.20	S33N 60-80	14.42
S34C 0-20	9.58	S34C 60-80	8.86	S34N 0-20	9.33	S34N 60-80	9.49

NS- Not Sampled

APPENDIX 11. Soil Magnesium (Mg) Data Used for Soil-*Prosopis* Correlations.

SAMP ID	Mg (cmol/kg)	Sample ID	Mg (cmol/kg)	Sample ID	Mg (cmol/kg)	Sample ID	Mg (cmol/kg)
S1C 0-20	3.92	S1C 60-80	4.24	S1N 0-20	2.39	S1N 60-80	3.11
S2C 0-20	2.09	S2C 60-80	3.18	S2N 0-20	4.79	S2N 60-80	2.84
S3C 0-20	5.33	S3C 60-80	6.61	S3N 0-20	5.11	S3N 60-80	2.48
S4C 0-20	8.95	S4C 60-80	5.80	S4N 0-20	6.90	S4N 60-80	4.87
S5C 0-20	3.70	S5C 60-80	3.41	S5N 0-20	2.21	S5N 60-80	6.78
S6C 0-20	2.58	S6C 60-80	NS	S6N 0-20	5.65	S6N 60-80	NS
S7C 0-20	6.07	S7C 60-80	3.05	S7N 0-20	2.71	S7N 60-80	3.86
S8C 0-20	2.54	S8C 60-80	2.69	S8N 0-20	1.23	S8N 60-80	1.40
S10C 0-20	1.72	S10C 60-80	NS	S10N 0-20	4.00	S10N 60-80	NS
S11C 0-20	2.73	S11C 60-80	1.57	S11N 0-20	2.85	S11N 60-80	1.15
S12C 0-20	1.38	S12C 60-80	2.58	S12N 0-20	2.11	S12N 60-80	2.18
S13C 0-20	6.89	S13C 60-80	2.48	S13N0-20	3.86	S13N 60-80	4.01
S14C 0-20	3.08	S14C 60-80	3.54	S14N 0-20	2.03	S14N 60-80	1.39
S15C 0-20	1.18	S15C 60-80	1.36	S15N 0-20	2.43	S15N 60-80	1.03
S16C 0-20	2.26	S16C 60-80	5.76	S16N 0-20	7.14	S16N 60-80	3.78
S17C 0-20	2.45	S17C 60-80	4.13	S17N 0-20	2.11	S17N 60-80	2.00
S18C 0-20	4.22	S18C 60-80	2.51	S18N 0-20	7.28	S18N 60-80	2.82
S19C 0-20	9.10	S19C 60-80	3.89	S19N 0-20	6.50	S19N 60-80	3.46
S20C 0-20	3.15	S20C 60-80	3.23	S20N 0-20	1.32	S20N 60-80	2.34
S21C 0-20	1.73	S21C 60-80	2.34	S21N 0-20	6.75	S21N 60-80	3.36
S22C 0-20	2.59	S22C 60-80	8.99	S22N 0-20	1.71	S22N 60-80	3.82
S23C 0-20	2.05	S23C 60-80	8.87	S23N 0-20	2.97	S23N 60-80	3.65
S24C 0-20	2.36	S24C 60-80	5.23	S24N 0-20	1.65	S24N 60-40	3.56
S25C 0-20	8.47	S25C 60-80	11.17	S25N 0-20	9.23	S25N 60-80	9.51
S26C 0-20	6.83	S26C 60-80	12.21	S26N 0-20	5.54	S26N 60-80	11.76
S27C 0-20	7.07	S27C 60-80	6.92	S27N 0-20	4.55	S27N 60-80	10.60
S28C 0-20	7.29	S28C 60-80	10.78	S28N 0-20	6.97	S28N 60-80	9.21
S29C 0-20	5.88	S29C 60-80	8.82	S29N 0-20	4.62	S29N 60-80	6.54
S30C 0-20	1.46	S30C 60-80	3.46	S30N 0-20	2.90	S30N 60-80	2.23
S31C 0-20	6.16	S31C 60-80	1.40	S31N 0-20	4.98	S31N 60-80	2.14
S32C 0-20	2.97	S32C 60-80	7.52	S32N 0-20	9.13	S32N 60-80	4.75
S33C 0-20	3.62	S33C 60-80	3.11	S33N0-20	2.86	S33N 60-80	3.39
S34C 0-20	4.11	S34C 60-80	1.47	S34N 0-20	1.06	S34N 60-80	2.03

NS- Not Sampled

APPENDIX 12. Soil Potassium (K) Data Used for Soil-*Prosopis* Correlations.

Sample ID	K (cmol/kg)	Sample ID	K (cmol/kg)	Sample ID	K (cmol/kg)	Sample ID	K (cmol/kg)
S1C 0-20	0.63	S1C 60-80	0.57	S1N 0-20	0.47	S1N 60-80	0.48
S2C 0-20	0.75	S2C 60-80	0.25	S2N 0-20	0.70	S2N 60-80	0.36
S3C 0-20	1.55	S3C 60-80	0.61	S3N 0-20	0.81	S3N 60-80	0.36
S4C 0-20	1.63	S4C 60-80	0.72	S4N 0-20	1.45	S4N 60-80	0.79
S5C 0-20	1.38	S5C 60-80	0.43	S5N 0-20	0.60	S5N 60-80	0.45
S6C 0-20	0.75	S6C 60-80	NS	S6N 0-20	0.71	S6N 60-80	NS
S7C 0-20	1.19	S7C 60-80	0.47	S7N 0-20	0.50	S7N 60-80	0.41
S8C 0-20	0.37	S8C 60-80	0.35	S8N 0-20	0.24	S8N 60-80	0.39
S10C 0-20	0.34	S10C 60-80	NS	S10N 0-20	0.43	S10N 60-80	NS
S11C 0-20	0.56	S11C 60-80	0.92	S11N 0-20	1.04	S11N 60-80	1.78
S12C 0-20	0.62	S12C 60-80	0.98	S12N 0-20	0.44	S12N 60-80	0.63
S13C 0-20	0.72	S13C 60-80	0.44	S13N0-20	0.43	S13N 60-80	0.44
S14C 0-20	0.60	S14C 60-80	0.29	S14N 0-20	0.30	S14N 60-80	0.31
S15C 0-20	0.33	S15C 60-80	0.24	S15N 0-20	0.29	S15N 60-80	0.24
S16C 0-20	0.38	S16C 60-80	0.69	S16N 0-20	0.62	S16N 60-80	0.47
S17C 0-20	0.59	S17C 60-80	0.56	S17N 0-20	0.32	S17N 60-80	0.32
S18C 0-20	0.48	S18C 60-80	0.34	S18N 0-20	0.54	S18N 60-80	0.39
S19C 0-20	1.39	S19C 60-80	0.56	S19N 0-20	1.13	S19N 60-80	0.51
S20C 0-20	0.41	S20C 60-80	0.59	S20N 0-20	0.20	S20N 60-80	0.29
S21C 0-20	0.41	S21C 60-80	0.36	S21N 0-20	0.49	S21N 60-80	0.38
S22C 0-20	0.57	S22C 60-80	0.46	S22N 0-20	0.51	S22N 60-80	0.30
S23C 0-20	0.63	S23C 60-80	0.84	S23N 0-20	0.76	S23N 60-80	1.28
S24C 0-20	0.51	S24C 60-80	0.72	S24N 0-20	0.50	S24N 60-40	0.55
S25C 0-20	2.03	S25C 60-80	1.49	S25N 0-20	1.56	S25N 60-80	1.82
S26C 0-20	1.41	S26C 60-80	2.32	S26N 0-20	1.38	S26N 60-80	1.82
S27C 0-20	2.37	S27C 60-80	0.61	S27N 0-20	1.34	S27N 60-80	0.91
S28C 0-20	1.89	S28C 60-80	1.28	S28N 0-20	2.06	S28N 60-80	1.38
S29C 0-20	1.17	S29C 60-80	0.80	S29N 0-20	1.51	S29N 60-80	0.80
S30C 0-20	0.30	S30C 60-80	0.25	S30N 0-20	0.44	S30N 60-80	0.31
S31C 0-20	0.51	S31C 60-80	2.32	S31N 0-20	0.48	S31N 60-80	1.28
S32C 0-20	0.98	S32C 60-80	0.53	S32N 0-20	1.01	S32N 60-80	0.40
S33C 0-20	0.77	S33C 60-80	0.37	S33N0-20	0.57	S33N 60-80	0.36
S34C 0-20	0.50	S34C 60-80	0.39	S34N 0-20	0.28	S34N 60-80	0.33

NS- Not Sampled

APPENDIX 13. Soil Sodium (Na) Data Used for Soil-*Prosopis* Correlations.

Sample ID	Na (cmol/kg)	Sample ID	Na (cmol/kg)	Sample ID	Na (cmol/kg)	Sample ID	Na (cmol/kg)
S1C 0-20	0.49	S1C 60-80	1.56	S1N 0-20	0.05	S1N 60-80	1.84
S2C 0-20	0.04	S2C 60-80	0.24	S2N 0-20	0.59	S2N 60-80	0.21
S3C 0-20	0.61	S3C 60-80	1.50	S3N 0-20	3.21	S3N 60-80	0.46
S4C 0-20	3.94	S4C 60-80	1.97	S4N 0-20	0.49	S4N 60-80	2.41
S5C 0-20	0.05	S5C 60-80	0.71	S5N 0-20	0.02	S5N 60-80	0.68
S6C 0-20	0.02	S6C 60-80	NS	S6N 0-20	0.66	S6N 60-80	NS
S7N 0-20	0.17	S7C 60-80	1.32	S7C 0-20	1.10	S7N 60-80	0.86
S8C 0-20	0.50	S8C 60-80	0.27	S8N 0-20	0.13	S8N 60-80	0.20
S10C 0-20	0.36	S10C 60-80	NS	S10N 0-20	0.68	S10N 60-80	NS
S11C 0-20	0.35	S11C 60-80	0.52	S11N 0-20	0.22	S11N 60-80	0.61
S12C 0-20	0.46	S12C 60-80	0.69	S12N 0-20	0.07	S12N 60-80	0.17
S13C 0-20	2.87	S13C 60-80	0.98	S13N0-20	0.73	S13N 60-80	0.55
S14C 0-20	0.07	S14C 60-80	0.54	S14N 0-20	0.14	S14N 60-80	0.40
S15C 0-20	0.14	S15C 60-80	0.19	S15N 0-20	0.16	S15N 60-80	0.24
S16C 0-20	0.18	S16C 60-80	0.14	S16N 0-20	1.43	S16N 60-80	0.29
S17C 0-20	0.14	S17C 60-80	0.38	S17N 0-20	0.13	S17N 60-80	0.17
S18C 0-20	0.71	S18C 60-80	0.14	S18N 0-20	1.93	S18N 60-80	0.43
S19C 0-20	1.91	S19C 60-80	1.83	S19N 0-20	1.46	S19N 60-80	0.45
S20C 0-20	0.10	S20C 60-80	0.11	S20N 0-20	0.16	S20N 60-80	0.00
S21C 0-20	0.14	S21C 60-80	0.72	S21N 0-20	1.42	S21N 60-80	0.61
S22C 0-20	0.11	S22C 60-80	0.96	S22N 0-20	0.02	S22N 60-80	0.32
S23C 0-20	0.12	S23C 60-80	0.75	S23N 0-20	0.23	S23N 60-80	0.74
S24C 0-20	0.14	S24C 60-80	1.60	S24N 0-20	0.16	S24N 60-40	0.98
S25C 0-20	1.06	S25C 60-80	2.98	S25N 0-20	1.35	S25N 60-80	2.32
S26C 0-20	1.95	S26C 60-80	1.89	S26N 0-20	0.91	S26N 60-80	2.77
S27C 0-20	0.05	S27C 60-80	1.44	S27N 0-20	0.24	S27N 60-80	2.78
S28C 0-20	0.17	S28C 60-80	2.24	S28N 0-20	0.42	S28N 60-80	3.22
S29C 0-20	0.07	S29C 60-80	1.73	S29N 0-20	0.76	S29N 60-80	2.67
S30C 0-20	0.17	S30C 60-80	0.42	S30N 0-20	1.04	S30N 60-80	0.24
S31C 0-20	0.50	S31C 60-80	0.67	S31N 0-20	0.52	S31N 60-80	0.41
S32C 0-20	0.21	S32C 60-80	1.53	S32N 0-20	1.39	S32N 60-80	0.80
S33C 0-20	0.05	S33C 60-80	1.41	S33N0-20	0.53	S33N 60-80	1.23
S34C 0-20	0.91	S34C 60-80	0.14	S34N 0-20	0.14	S34N 60-80	0.61

NS- Not Sampled

APPENDIX 14. Soil Organic Carbon (C) Data Used for Soil-*Prosopis* Correlations.

SAMP ID	C (mg/kg)	Sample ID	C (mg/kg)	Sample ID	C (mg/kg)	Sample ID	C (mg/kg)
S1C 0-20	2088	S1C 60-80	3731	S1N 0-20	2203	S1N 60-80	3956
S2C 0-20	2692	S2C 60-80	2878	S2N 0-20	4853	S2N 60-80	3083
S3C 0-20	4482	S3C 60-80	726.1	S3N 0-20	4470	S3N 60-80	3065
S4C 0-20	3879	S4C 60-80	10869	S4N 0-20	10396	S4N 60-80	4860
S5C 0-20	7791	S5C 60-80	2809	S5N 0-20	4573	S5N 60-80	1560
S6C 0-20	4547	S6C 60-80	NS	S6N 0-20	6705	S6N 60-80	NS
S7N 0-20	2330	S7C 60-80	3098	S7C 0-20	4411	S7N 60-80	2032
S8C 0-20	1685	S8C 60-80	5313	S8N 0-20	1032	S8N 60-80	2413
S10C 0-20	415	S10C 60-80	NS	S10N 0-20	848	S10N 60-80	NS
S11C 0-20	1767	S11C 60-80	790	S11N 0-20	3242	S11N 60-80	10099
S12C 0-20	289.4	S12C 60-80	8469	S12N 0-20	1387	S12N 60-80	7708
S13C 0-20	3006	S13C 60-80	5563	S13N0-20	2184	S13N 60-80	4914
S14C 0-20	1861	S14C 60-80	3710	S14N 0-20	3981	S14N 60-80	2087
S15C 0-20	70.1	S15C 60-80	2128	S15N 0-20	1538	S15N 60-80	1901
S16C 0-20	2802	S16C 60-80	5770	S16N 0-20	1881	S16N 60-80	5541
S17C 0-20	2522	S17C 60-80	2756	S17N 0-20	1216	S17N 60-80	2785
S18C 0-20	1437	S18C 60-80	180.6	S18N 0-20	1294	S18N 60-80	4255
S19C 0-20	371.5	S19C 60-80	7647	S19N 0-20	2898	S19N 60-80	1800
S20C 0-20	2159	S20C 60-80	2383	S20N 0-20	721	S20N 60-80	2005
S21C 0-20	2427	S21C 60-80	2159	S21N 0-20	1228	S21N 60-80	3140
S22C 0-20	2989	S22C 60-80	2387	S22N 0-20	2391	S22N 60-80	4704
S23C 0-20	4747	S23C 60-80	23576	S23N 0-20	7725	S23N 60-80	17464
S24C 0-20	3272	S24C 60-80	9191	S24N 0-20	1580	S24N 60-40	9394
S25C 0-20	9760	S25C 60-80	10099	S25N 0-20	6763	S25N 60-80	8180
S26C 0-20	7750	S26C 60-80	9165	S26N 0-20	5686	S26N 60-80	9829
S27C 0-20	10010	S27C 60-80	5391	S27N 0-20	6505	S27N 60-80	6484
S28C 0-20	10076	S28C 60-80	7331	S28N 0-20	7906	S28N 60-80	7684
S29C 0-20	4741	S29C 60-80	12571	S29N 0-20	5128.00	S29N 60-80	12176
S30C 0-20	1904	S30C 60-80	2407	S30N 0-20	1314	S30N 60-80	2264
S31C 0-20	2462	S31C 60-80	3617	S31N 0-20	1450	S31N 60-80	2706
S32C 0-20	2509	S32C 60-80	7359	S32N 0-20	3125	S32N 60-80	4398
S33C 0-20	2212	S33C 60-80	1744	S33N0-20	1931	S33N 60-80	2128
S34C 0-20	701	S34C 60-80	1800	S34N 0-20	373	S34N 60-80	506

NS- Not Sampled

APPENDIX 15. Soil Total Nitrogen (N) Data Used for Soil-*Prosopis* Correlations.

SAMP ID	N (mg/kg)	Sample ID	N (mg/kg)	Sample ID	N (mg/kg)	Sample ID	N (mg/kg)
S1C 0-20	99.40	S1C 60-80	ND	S1N 0-20	ND	S1N 60-80	100.50
S2C 0-20	19.40	S2C 60-80	ND	S2N 0-20	ND	S2N 60-80	ND
S3C 0-20	3170.00	S3C 60-80	7842.00	S3N 0-20	713.70	S3N 60-80	ND
S4C 0-20	ND	S4C 60-80	540.90	S4N 0-20	674.80	S4N 60-80	ND
S5C 0-20	1128.00	S5C 60-80	237.60	S5N 0-20	211.60	S5N 60-80	4578.80
S6C 0-20	337.90	S6C 60-80	NS	S6N 0-20	424.60	S6N 60-80	NS
S7N 0-20	ND	S7C 60-80	22.10	S7C 0-20	311.50	S7N 60-80	997.10
S8C 0-20	ND	S8C 60-80	127.30	S8N 0-20	ND	S8N 60-80	321.60
S10C 0-20	1117.00	S10C 60-80	NS	S10N 0-20	275.20	S10N 60-80	NS
S11C 0-20	ND	S11C 60-80	N D	S11N 0-20	26.80	S11N 60-80	503.50
S12C 0-20	2417.00	S12C 60-80	ND	S12N 0-20	ND	S12N 60-80	132.40
S13C 0-20	193.20	S13C 60-80	ND	S13N0-20	ND	S13N 60-80	ND
S14C 0-20	ND	S14C 60-80	ND	S14N 0-20	ND	S14N 60-80	135.10
S15C 0-20	1712.00	S15C 60-80	170.70	S15N 0-20	ND	S15N 60-80	ND
S16C 0-20	16.40	S16C 60-80	ND	S16N 0-20	ND	S16N 60-80	ND
S17C 0-20	ND	S17C 60-80	459.00	S17N 0-20	361.10	S17N 60-80	ND
S18C 0-20	ND	S18C 60-80	463.00	S18N 0-20	914.20	S18N 60-80	300.00
S19C 0-20	5328.00	S19C 60-80	68.00	S19N 0-20	ND	S19N 60-80	261.50
S20C 0-20	213.50	S20C 60-80	89.20	S20N 0-20	6.30	S20N 60-80	71.10
S21C 0-20	ND	S21C 60-80	ND	S21N 0-20	ND	S21N 60-80	396.50
S22C 0-20	189.10	S22C 60-80	192.30	S22N 0-20	290.10	S22N 60-80	51.50
S23C 0-20	298.10	S23C 60-80	ND	S23N 0-20	ND	S23N 60-80	ND
S24C 0-20	ND	S24C 60-80	74.60	S24N 0-20	ND	S24N 60-40	31.50
S25C 0-20	1031.20	S25C 60-80	503.50	S25N 0-20	642.60	S25N 60-80	121.70
S26C 0-20	822.40	S26C 60-80	332.30	S26N 0-20	357.60	S26N 60-80	333.30
S27C 0-20	1003.60	S27C 60-80	ND	S27N 0-20	944.30	S27N 60-80	299.40
S28C 0-20	864.90	S28C 60-80	ND	S28N 0-20	750.80	S28N 60-80	192.70
S29C 0-20	478.00	S29C 60-80	811.00	S29N 0-20	536.50	S29N 60-80	121.30
S30C 0-20	266.60	S30C 60-80	ND	S30N 0-20	0.90	S30N 60-80	282.10
S31C 0-20	146.70	S31C 60-80	207.10	S31N 0-20	ND	S31N 60-80	ND
S32C 0-20	378.60	S32C 60-80	177.60	S32N 0-20	193.20	S32N 60-80	ND
S33C 0-20	292.60	S33C 60-80	437.00	S33N0-20	ND	S33N 60-80	170.70
S34C 0-20	ND	S34C 60-80	261.50	S34N 0-20	ND	S34N 60-80	108.30

NS- Not Sampled *ND – Not Detected/ Below detection limit*

APPENDIX 16. Soils C:N ratio based on data Used for Soil-*Prosopis* Correlations.

SAMP ID	C:N Ratio	Sample ID	C:N Ratio	Sample ID	C:N Ratio	Sample ID	C:N Ratio
S1C 0-20	21.01	S1C 60-80	-	S1N 0-20	-	S1N 60-80	39.36
S2C 0-20	138.76	S2C 60-80	-	S2N 0-20	-	S2N 60-80	-
S3C 0-20	1.41	S3C 60-80	0.09	S3N 0-20	6.26	S3N 60-80	-
S4C 0-20	-	S4C 60-80	20.09	S4N 0-20	15.41	S4N 60-80	-
S5C 0-20	6.91	S5C 60-80	11.82	S5N 0-20	21.61	S5N 60-80	0.34
S6C 0-20	13.46	S6C 60-80	-	S6N 0-20	15.79	S6N 60-80	-
S7N 0-20	-	S7C 60-80	140.18	S7C 0-20	14.16	S7N 60-80	2.04
S8C 0-20	-	S8C 60-80	41.74	S8N 0-20	-	S8N 60-80	7.50
S10C 0-20	0.37	S10C 60-80	-	S10N 0-20	3.08	S10N 60-80	-
S11C 0-20		S11C 60-80	-	S11N 0-20	120.97	S11N 60-80	20.06
S12C 0-20	0.12	S12C 60-80	-	S12N 0-20	-	S12N 60-80	58.22
S13C 0-20	15.56	S13C 60-80	-	S13N0-20	-	S13N 60-80	-
S14C 0-20	-	S14C 60-80	-	S14N 0-20	-	S14N 60-80	15.45
S15C 0-20	0.04	S15C 60-80	12.47	S15N 0-20	-	S15N 60-80	-
S16C 0-20	170.85	S16C 60-80	-	S16N 0-20	-	S16N 60-80	-
S17C 0-20	-	S17C 60-80	0.06	S17N 0-20	3.37	S17N 60-80	-
S18C 0-20	-	S18C 60-80	0.04	S18N 0-20	1.42	S18N 60-80	14.18
S19C 0-20	0.07	S19C 60-80	112.46	S19N 0-20	-	S19N 60-80	6.88
S20C 0-20	10.11	S20C 60-80	26.72	S20N 0-20	114.44	S20N 60-80	28.20
S21C 0-20	-	S21C 60-80	-	S21N 0-20	-	S21N 60-80	7.92
S22C 0-20	15.81	S22C 60-80	12.41	S22N 0-20	8.24	S22N 60-80	91.34
S23C 0-20	15.92	S23C 60-80	-	S23N 0-20	-	S23N 60-80	-
S24C 0-20	-	S24C 60-80	123.20	S24N 0-20	-	S24N 60-40	298.22
S25C 0-20	9.46	S25C 60-80	20.06	S25N 0-20	10.52	S25N 60-80	67.21
S26C 0-20	9.42	S26C 60-80	27.58	S26N 0-20	15.90	S26N 60-80	29.49
S27C 0-20	9.97	S27C 60-80	-	S27N 0-20	6.89	S27N 60-80	21.66
S28C 0-20	11.65	S28C 60-80	-	S28N 0-20	10.53	S28N 60-80	39.88
S29C 0-20	9.92	S29C 60-80	0.16	S29N 0-20	9.56	S29N 60-80	100.38
S30C 0-20	7.14	S30C 60-80	-	S30N 0-20	1460.00	S30N 60-80	8.03
S31C 0-20	16.78	S31C 60-80	17.46	S31N 0-20	-	S31N 60-80	-
S32C 0-20	6.63	S32C 60-80	41.44	S32N 0-20	16.17	S32N 60-80	-
S33C 0-20	7.56	S33C 60-80	0.04	S33N0-20	-	S33N 60-80	12.47
S34C 0-20	-	S34C 60-80	6.88	S34N 0-20	-	S34N 60-80	4.67

APPENDIX 17. Data on *Prosopis* Seed Bank Assessment (No. of seed m^{-2})

Villages	RZC 0-5cm	RZI 0-5cm	RZC 5-10cm	SC 0-5cm	SI 0-5cm	SC 5-10cm
Bokspits	22960±2368	48±32	656±400	128±64	224±128	0
	912±48	0±16	0±16	656±176	0±16	416±96
	400±288	32±32	0±16	80±64	144±80	48±32
	112±80	48±48	112±32	112±64	0	0±16
	528±192	0±16	32±32	544±96	0±16	208±144
	1408±320	32±48	32±48	240±272	0±16	336±112
	1488±416	48±48	48±48	80±80	224±48	0±16
	3856±1584	80±64	192±128	560±288	0±16	192±144
	1216±480	0±16	208±64	416±416	0	144±48
	2448±672	0	80±80	48±32	0	0±16
Rappelspan	0	0	0	112±80	0	112±64
	0	0	0	224±96	16±16	0±16
	0	0	0	112±64	64±48	32±16
	0	0	0	16±16	0±16	0
	0	0	0	160±64	0	208±80
	0	0	0	176±96	0±16	272±64
	0	0	0	16±16	0±16	0±16
	0	0	0	64±48	352±80	48±32
	0	0	0	80±48	0	0±16
	0	0	0	160±160	0±16	0±16
Vaalhoek	976±192	0±16	832±224	496±96	0±16	208±48
	0±16	32±32	96±48	80±48	32±16	80±32
	0	0	0±16	1920±208	16±16	656±112
	32±32	0±16	80±32	400±112	304±128	48±32
	208±64	16±0	0	0±16	0	0±16
	816±272	0	0±16	144±32	0±16	0
	176±64	160±64	0±16	48±32	16±16	16±16
	128±80	0	0±16	304±80	112±64	0±16
	128±48	80±32	0±16	96±16	0	48±32
	144±64	0±16	0	96±64	0±16	32±16
Struizendam	0±16	0±16	0±16	0±16	0±16	0±16
	48±32	0	32±32	48±32	0	32±32
	304±64	0±16	432±64	304±64	0±16	432±64
	0±16	112±48	144±64	0±16	112±48	144±64
	432±112	192±64	368±64	432±112	192±64	368±64
	144±64	176±64	192±48	144±64	176±64	192±48
	0±16	80±32	128±64	0±16	80±32	128±64
	32±16	48±16	48±32	32±16	48±16	48±32
	0±16	0±16	16±16	0±16	0±16	16±16
	0±16	0	48±80	0	0	48±80