IMPACT OF THE TSUMEB SMELTER WASTE ON PLANT SPECIES DIVERSITY AND STRUCTURE IN TSUMEB, NORTH-CENTRAL NAMIBIA

A thesis submitted in partial fulfilment of the requirements for the degree of
Master of Science in Biodiversity Management and Research at the
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ABSTRACT

The objective of this study was to determine the impact of the smelter waste on plant species diversity and structure in the Tsumeb area. The most important sources of contamination are solid and gaseous emissions from the Tsumeb Smelter, airborne particles from the Tsumeb tailings pond and airborne particles from slag mill waste. Six sites: Inside Smelter Site, Outside Smelter Site, Abattoir Hill Site, Transnamib Site, Nomtsoub Site and Airport Site were selected and ten 10 m x 10 m plots were randomly demarcated at each site for soil and plant sampling. All 10 m x 10 m plots were used for sampling trees, nested within them were 5 m x 5 m and 2 m x 2 m plots which were used for sampling shrubs and grasses respectively. Top soils were sampled and analysed for concentration of arsenic, cadmium and lead. All trees (basal circumference >15 cm) as well as selected trees species, *Combretum apiculatum* and *Terminalia prunioides* were identified, counted and their heights as well as basal circumferences were measured. All shrubs, saplings and seedlings as well as a selected shrub, *Dichrostachys cinerea,* were identified, counted and their heights were measured. Grasses were identified and total grass cover was visually determined. Plant species diversity, richness, composition, woody cover and plant densities were determined. The results indicated high concentrations of arsenic, cadmium and lead at sites closer to the smelter. There were significant differences in plant species diversity (F=8.227, df=59, p<0.001), richness (F=9.073, df=59, p<0.001) and tree density (H=35.75, df=5, p<0.001) amongst the sites. There was no significant difference in shrub density (H=8.430, df=5, p=0.128) amongst the sites. The hierarchical cluster analysis on species presence/absence data separated the vegetation into five types. Indirect gradient analysis indicated a complex interaction of gradients which have influence the pattern in species composition; however, the direct gradient analysis indicated that heavy metal pollution, disturbance and geology accounted for a significant variation in species composition. High heavy metal concentrations at the Inside Smelter Site and Outside Smelter Site were due to proximity of these sites to the smelter while high concentrations at Abattoir Hill Site were because this site was in the direction of the prevailing wind directions. Differences in species diversity, richness and composition were due to wood cutting and pollution. Differences in vegetation structure can be attributed to a complexity of factors including pollution and wood clearing. Heavy metal toxicity contributed to poor plant development, poor recruitment and as a result there were very few small trees at the polluted sites. Geology also contributed to difference in species composition. It was concluded that heavy metal pollution influenced species composition and vegetation structure.

Key words: gradient analysis, heavy metals, Namibia, pollution, species composition, species diversity, Tsumeb, vegetation structure.

DEDICATION

This thesis is dedicated to my parents Chris Nunes and Lelie-Saima Nunes, for they made me who I am today. Was it not for their unconditional love, tireless effort and commitment in giving me proper guidance during my childhood, perhaps I would not be writing this thesis.

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DECLARATION

This is a thesis prepared in partial fulfilment of the requirements for the degree of Master of Science in Biodiversity Management and Research at the University of Namibia (UNAM) in Windhoek, Namibia. This thesis is the original work of the author and it has not been submitted for a degree elsewhere. The views and opinions stated therein are those of the author and not necessarily those of the institution.

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ACRONYMYS

ABA	Abattoir Hill Site
AIR	Airport Site
FAO	Food and Agriculture Organisation
INS	Inside Smelter Site
MET	Ministry of Environment and Tourism
MME	Ministry of Mines and Energy
NOM	Nomtsoub Site
OMPL	Ongopolo Mining and Processing Limited
SME	Outside Smelter Site
TCL	Tsumeb Corporation Limited
TRA	Transnamib Site
UNEP	United Nations Environmental Programme
UNESCO	United Nations Educational Scientific and Cultural Organisation
UNSDEM	United Nations Sustainable Development and Environmental Management
USEPA	United States Environmental Protection Agency
WHO	World Health Organisation

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Mining, alongside agriculture, represents one of human's earliest endeavours, the two being fundamental to development and continuation of civilisation. Mining is one of the major activities in the exploitation of natural resources (Wang, 2001). However, as a consequence of mining, pollution for the environment occurs, creating new constraints to the sustainable development of the world (Wang, 2001).

In resource rich countries the creation of wealth through the development of mineral resources is of prime importance to the overall economy of the country (Klugman, 1998). Almost all the processes of mining may give rise to the pollution of the environment. A study of the negative impact of mining becomes one of urgent tasks of scientists in the protection of the mining environment and the optimal utilization of mineral resources (Wang, 2001).

Pollution can be defined as '*the direct or indirect introduction, as a result of human activity, of substances, vibrations, heat, radiation or noise into the air, water or land which may be harmful to human health or well-being or the quality of the environment, or impair or interfere with amenities and other legitimate uses of the environment*' (Ministry of Environment and Tourism, 2001). Heavy metals and other toxic compounds such as sulphur and phosphorus oxide may contaminate the air, soil and water. This deteriorates the air, soil and water quality.

Many countries around the world have long mining histories and mining has been a major contributor to their economies for many years (Klugman, 1998). However, the mining industry, world wide, has not had a good environmental track record due to the pollution left behind after the closure of the mines or during the life of the mining operation (Klugman, 1998).

Mining pollution, as a result of poor environmental management, prompted international organisations such as United Nations Environmental Programme (UNEP) to oppose any disturbance of the environment (Klugman, 1998). In 1992, governments agreed to the Rio Declaration, the general principles, and to an action plan, Agenda 21 (Klugman, 1998). The Rio Declaration confirms that sustainable development requires that environmental protection constitutes an integral part of the development process. A variety of guidelines have been produced by various international agencies including United Nations specialist agencies UNEP, WHO & UNSDEM (Klugman, 1998). These guidelines are relevant to environmental management within the mining sector of both developed and developing countries (Klugman, 1998).

In Namibia, historical links between mining and abuse of the environment are clear (Barnard, 1998). Groundwater is the primary concern for pollution in Namibia (Ministry of Environment and Tourism, 2001). Amongst the polluting sources, mines constitute a serious point source for groundwater pollution because of minerals they extract or chemicals used in the extraction process (Ministry of Environment and Tourism, 2001). Those mines located in karst or other rocky aquifers are more of a threat than those located in sandy soils, because of the connections between the groundwater channels and the extent that contaminants can move (Ministry of Environment and Tourism, 2001).

The mining town of Tsumeb is situated in Oshikoto Region, north central part of Namibia. Tsumeb Corporation Limited (TCL) has been mining copper and lead since the early 1900s. The mine comprises a mining area and a smelter complex for processing these minerals. According to WSP Walmsley Environmental Consultants (2004), in 1998, the TCL was liquidated and taken over by Ongopolo Mining & Processing Limited (OMPL), and the smelter was re-commissioned.

The Tsumeb Smelter, like many other smelters in the world, produces waste materials that may degrade the environment around it.   Environmental pollution, harmful to both plant and animal communities, could possibly occur at the smelter complex and its surrounding area. For example, some species that cannot tolerate high levels of heavy elements may die completely (Mapani, 2001).   However, little is known about the impacts of mining on plant diversity within the Tsumeb area. Work has mainly focussed on underground water resources, which is mainly used for human consumption at the town.

1.2 Problem statement

The Tsumeb smelter complex is situated in dolomitic country rock, which has a high permeability and so any hazardous or other pollutants that enter the groundwater could potentially move far (Ministry of Environment and Tourism, 2001). Moreover, arsenic and cadmium compounds, both toxic, have been recovered in the smelting process and thus can be present in small amounts in stack emissions and in tailings (Ministry of Environment and Tourism, 2001). This situation can be complicated by the fact that background levels of these compounds are high since they both occur naturally in the country rock together with the mineralization. The country's rocks consist of an extraordinary diversity of minerals including lead, copper, zinc, silver, arsenic, cadmium, cobalt, antinomy, germanium, gallium, iron, mercury molybdenum, nickel, tin as well as vanadium (WSP Walmsley Environmental Consultants, 2004).

The smelter waste has a low pH – which means that it is highly acidic and it is very toxic in nature (Geo-Consult, 1996). The toxic substances can migrate via different pathways, for example through smelter – air – soil – biosphere, to the environmental resources and give rise to certain risks. Environmental resources may be plants or animals living in the areas surrounding the smelter complex. Some plant species may die completely while some species may tend to accumulate certain elements like arsenic (Mapani, 2001). In humans, arsenic can cause skin cancer, when exposure is through contact with the skin (Mapani, 2006).

Woody plant communities are generally important to both humans and animal species. Plants form an essential part of the environment. According to Burke (2005) plants provide essential goods (for example: wood products such as charcoal, food such as berries, medicine and cultural values) and services such as soil fertility and stability, climate regulation and waste assimilation. Plants help regulate local climatic conditions, capture carbon, stabilise soil, suppress dust and are essential elements of all landscapes giving these a particular character (Burke, 2005). Each living thing has a role to play in the environment. The removal of trees may increases the concentration of carbon dioxide in the atmosphere (Campbell, 1996).

There is a continual influx of heavy metal contaminants and pollutants into the biosphere from both natural and anthropogenic sources. This study was aimed at studying the impact of the Tsumeb smelter waste on the diversity and structure of plants in the vicinity of the smelter. The findings can be used by OPML as a foundation for improved decision-making based on the extent of pollution and to minimize environmental deterioration in areas most affected by pollution. The OPML can use the findings of this study as additional information to their ongoing environmental monitoring program. The government ministries such as Ministry of Mines and Energy (MME) and Ministry of Environment and Tourism (MET) can also use the findings to put emphasis on its efforts to coordinate environmental management, promote public awareness and assist public service in environmental control for sustainable development.

1.3 Objectives, questions and hypotheses

The overall objective of this study was to determine the impact of the smelter waste on plant species diversity and structure in Tsumeb area.

The specific objectives were to:

a. determine and compare concentrations of heavy metals (arsenic, cadmium, and lead) in soils from the selected sites.

b. quantify and compare plant species diversity and richness among the selected sites.
c. determine and compare plant species composition among the selected sites.
d. determine individual tree, shrub and stem densities among the site and compare tree, shrub and stem density among the selected sites.
e. assess and compare vegetation structural attributes (basal area, height, vegetation cover) among the sites.
f. use the results to make recommendations on the biodiversity around the smelter as well as the management of smelter outputs.

The study sought to answer the following questions:

a. What are the heavy metal concentrations in the soil and how do the concentrations of heavy metals in soils differ among the sites?
b. What is the plant species diversity and richness and what are the differences (if any) in plant species diversity and richness among the sites?
c. How does plant species composition differ among the sites?
d. What are the individual tree, shrub and stem densities? What are the differences in individual tree and shrub densities and stem densities among the sites?
e. How does vegetation structural attributes (vegetation cover, height, basal area) differ among the sites?

The hypotheses for the study were:

a. Concentrations of heavy metals would be higher in soil taken from sites close to the smelter than at sites further away from the smelter due to processes of copper smelting which produces heavy metals as waste material.

b. Plant diversity and richness will be lower closest to the smelter compared to areas further away due to higher pollution in the smelter area.
c. Plant species composition would differ among the sites; as some plant species may disappear from the polluted sites due to the harshness of the heavy metals on the plants.
d. Density of trees, shrub and stems would differ among the sites, with low densities expected at polluted sites and high densities expected at less polluted sites.
e. The vegetation structural attributes (height, basal area, canopy cover) of individual plants would vary significantly among the sites, with higher values expected in less polluted sites.

CHAPTER 2

LITERATURE REVIEW

2.1 Mining activities and pollution

Mining can have severe effects on the environment (Aucamp, 2003). In 1992, polluted mine water, from the Wheal Jane Mine in the United Kingdom flowed into two river systems at a rate of 8 to 20 million litres a day (Klugman, 1998). The toxic waters entered the surrounding coastal areas threatening the fishing industries and local well-water supplies. Similarly, in Australia’s Mount Lyell Tin Mine, the smelting process generated large quantities of sulphur dioxide, which combined with rainfall, producing acid rain that drained into the river system (Klugman, 1998). In 1994, the tailings dam of the Harmony Gold Mine in Merrispruit, South Africa overtopped after heavy rains. The tailings flowed into the residential area causing 18 fatalities (Klugman, 1998).

In Bolivia, mining pollutes freshwater through leaching, where damaging metals enter underground water supplies (Armstrong, 1997). Mining has also caused great soil erosion, which has threatened the extinction of animals and plants in Altiplano plateaus (Armstrong, 1997). A study conducted at a copper smelter which is characterised by arsenic emission (100-300 tons per year), in Russia, found arsenic contents in mushrooms and berries growing nearby the smelter (Petrov *et al.*, 2007). Arsenic content in the recycle water from some concentrators around this smelter was up to 400 ppm (Petrov *et al.*, 2007).

Wang (2001) undertook a study, in China, to determine the relationship between mining and the environment, with particular emphasis on the negative impacts of mining. In his study, Wang (2001) concluded that pollution from mine waste waters was very common and severe – the water was highly acidic with pH of 2-4, hardness >7.5 and high concentration of 2000mg/L. Wang (2001) also found that soils and vegetations around the mining area had high contents of heavy metals, such as molybdenum, lead and cadmium.

In the same region, Xiangdong *et al*. (2001) undertook a study in Hong Kong to determine the heavy metal contamination in the soil. Xiangdong *et al*. (2001) found out that soils in Hong Kong had elevated concentrations of cadmium, copper, lead and zinc. In Korea, Jung (2001) studied the extent, in terms of distance, of metal contamination in soils and waters in and around the Imcheon Au-Ag mine. Jung (2001) concluded that there was high contamination of Au-Ag around the mine and the metal concentration decreased with increasing distance from the mine.

The Kabwe lead mine in Zambia – which is no longer operational, contaminated the air, soil and vegetation with heavy metals because there were no pollution laws regulating emission (Black Smith Institute, unknown). In South Africa, a survey conducted by Rösner *et al*. (1998) in Aucamp (2003) showed that gold-mining activities in Gauteng were polluting the surrounding environment by increasing the acidity, salinisation and heavy-metal contents in soils, water and groundwater bodies. Evans (1990) in Aucamp (2003) found trace-element pollution caused by acid-mine drainage generation in a wetland adjacent to a tailings dam. The Witswatersrand

Goldfield, near Johannesburg, has been mining gold for more than a century (Chevrel *et al*., 2006). The large tailings dams of this mine have caused severe regional environmental problems and disseminate toxic materials (heavy metals) into the environment (Chevrel *et al*., 2006).

2.2 Impacts of mining activities on Biodiversity

Unless adequate precautions are taken, mining can be accompanied by serious negative impacts on the environment. According to UNEP (1991), mining can change landscapes, alter water tables, disrupt the local ecology, generate serious air and water pollution, and degrade large areas of land. Many studies have been conducted on the effect of heavy metal contamination in soils, plants waters and sediments from mines throughout the world.

Alexeyev (1995) undertook a study in the Kola Peninsula, Europe, to observe terrestrial ecosystems where large copper-nickel smelters were functioning. The results indicated plant damage by air and soil pollutants. The results also indicated that plants that were weakened by natural stresses had lower thresholds of sensitivity to airborne pollutants (Alexeyev, 1995). A study conducted at the Yellowstone National Park, Montana, USA, indicated trace metal levels frequently exceed acceptable concentrations for agricultural soils at sampling points (Stoughton & Marcus, 2000). This study also showed that metals and acidity associated with tailings affected plant biomass, density and diversity.

On the other hand, Bell (2001) reported that the impact of mining depends on many factors, especially the type of mining and the size of the operation. Bell (2001) further stated that the impact of mining may be a disturbed land, changes in topography and affected hydrogeological conditions.

In Australia, Taylor & Fox (2001) examined the effects of atmospheric fluoride pollution on the lizard fauna and the open forest of coastal dunes in New South, Wales. The results indicated that fluoride pollution resulted in significant changes to canopy cover, understorey vegetation density and ground cover (Taylor & Fox, 2001). There was significantly higher species richness and total lizard abundance, where fluoride levels were low in unmined forest (Taylor & Fox, 2001).

In Argentina, in a region of Patagonia, impacts of mining include soil disturbance, interference with animal migration and interference with local fauna and flora (Pawlowski, 1997). Pawlowski (1997) further stated that toxic wastes added to the environment may kill vegetation or destroy part of it, such as forestry canopy.

Most pollutants are harmful to plants and animal life, some when present at high concentration can cause disease and death (Cole & Smith, 1984). The uptake of pollutants through the leaves is predominantly controlled by the cuticle and the stomata which control the rate at which pollutants diffuse into individual leaves (Mansfield & Freer-Smith, 1984). Once the pollutant has penetrated into the mesophyll cell surface, it may be metabolised or excreted (Barnes *et al.*, 1999). Plants have a detoxification/repair system that helps with the excretion of pollutants and where pollutants uptake exceeds the capacity of the detoxification/repair system to prevent damage, there may be a host of adverse consequences on plant physiology resulting in death of plant tissue (Barnes *et al.*, 1999).

Plants of heavy metal soils cannot prevent the influx of heavy metals into their cell; it is necessary for the protoplasm to have a resistance against heavy metals (Ernst, 1972 in Hamunyela, 2006). However, there are plant species that have mechanisms to withstand the impact of high heavy metal concentrations (Ernst, 1972 in Hamunyela, 2006). Tolerance of a plant species to heavy metals depends on whether or not the plant species has the physiological capability of withstanding the sudden high increase in the concentration of heavy metals within the plants.

2.3 Tsumeb Smelter and Environment

Geo-Consult (1996) undertook an environmental audit aimed at determining the impact the Tsumeb smelter poses on the receiving environment. The findings indicated an environmental impact spread over an area greater than 1000 km^2 (Geo-Consult, 1996). The intensity of the impact decreases by varying degrees specific to a given element compound as the distance from the smelter complex grows (Geo-Consult, 1996). According to Geo-Consult (1996), the tailings represent a mass of million tons of fine-grained material with average concentration of:

- 0.46 % copper (Cu)
- 0.90 % lead (Pb) and
- 16 ppm silver (Ag) associated with harmful inorganic components (such as arsenic, cadmium etc).

Harmful impacts on the receiving environment were in particular caused via the following paths:

- smelter – air – biosphere
- smelter – air – soil – biosphere
- tailings dam – air – soil – biosphere (Geo-Consult, 1996).

Geo-Consult (1996) established that in dry periods the fine-grained materials, with concentration of copper, lead and silver from the tailing dams are blown out by wind erosion. Formation and migration of (toxic) gases by chemical reactions may also occur in the tailings dam (Geo-Consult, 1996).

The arsenate minerals occurring in the tailings will, if treated with acid, form "arsine gas" which is extremely toxic (Geo-Consult, 1996). Limited attempts have been made to contain surface water pollution (Ministry of Environment and Tourism, 2001). Walmsely Environmental Consultants (1998) reported that metal contamination has occurred up to 2 metres below the tailing dam, with the most pronounced effects being in the first metre below the dam. Due to the polymetallic nature of the dams, a high potential for water pollution can occur (Walmsely Environmental Consultants, 1998).

Walmsely Environmental Consultants (1998) stated that there is a building up of metals in the soils underlying and surrounding the tailing dam. Walmsely Environmental Consultants (1998) further reported that dust emanating from the dumps, particularly the respirable fraction, represents a human health hazard in the immediate vicinity of the dumps, as well as in the wind blown direction. The hot dry climatic conditions exacerbate the dust potential (Walmsely Environmental Consultants, 1998). The results of a study by Walmsley Environmental Consultants (2001) indicated that the sources of contamination in the Tsumeb Smelter Complex can be considered as follows:

- Emissions from the smelter
- Slag Mill tailing dump
- Old tailing Dams
- Contaminated farmland in the Jordan River Valley
- New tailing impoundments

A study conducted by Kříbek *et al*. (2005) indicated that especially the sulphur dioxide and dust fall-out and the dust particles contain lead and copper contaminates air and soils in the smelter surroundings. Kříbek *et al*. (2005) found out that dust from the beaches of tailings impoundments contain increased amounts of As and Cd. Flotation waste released during the failure of the old tailings impoundment dam show enrichment in Pb, Zn, Cu, Cd and Mo (Kříbek *et al.*, 2005).

Furthermore, Kříbek *et al.* (2005) established that high concentration of lead in top soil were found west and north-west of the smelter and tailing impoundment and these high contents of lead were by downwind dust and contamination. The Tsumeb Smelter is characterised by heavy metal pollution and it is therefore necessary to determine the impacts of heavy metals on the plant community in the vicinity of the Tsumeb Smelter complex.

CHAPTER 3

MATERIALS AND METHODS

3.1 Study area

3.1.1 Location

The mining town of Tsumeb is located at 19º 15’ S and 17º 42’ E and it lies 1320 m above sea level. Tsumeb is the capital of Oshikoto Region, located in north central part of Namibia (Fig. 1).

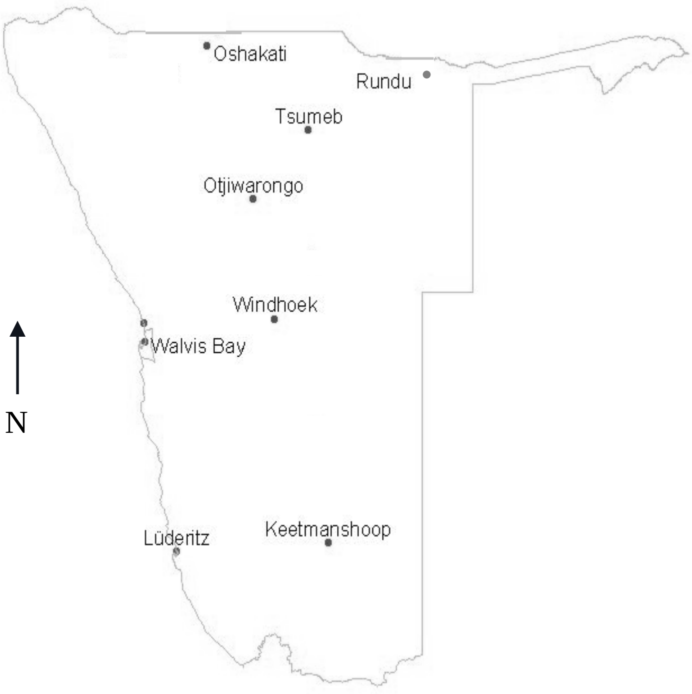

Figure 1. Map of Namibia with major towns (Ministry of Mines and Energy, 2006a).

3.1.2 Climate

The climate of Tsumeb is semi-arid to arid, with an average annual rainfall of 524 mm. The rainy season is normally in summer, from December to February. The time between May and July is regarded as winter with no or little rain. The mean annual temperature for Tsumeb is 25ºC and monthly temperature ranges between mean maximum temperature of 26ºC and mean minimum temperature of 16ºC throughout out the year (Kříbek *et al.*, 2005).

Temperatures at 08h00, 14h00 and 20h00 range from 13 ºC, 26 ºC and 18 ºC respectively between 1915 and 1998 (Kříbek *et al.*, 2005). Average relative humidity for Tsumeb at 14h00 is more than 80% in the most humid month - March (Mendelsohn *et al.*, 2002a). According to Geo-Consult (1996), the prevailing wind direction is from south-east to north-west. In January and April, northeasterly winds are more frequent (Kříbek *et al.*, 2005). Winter months are characterized by the highest frequency of easterly winds (Kříbek *et al.*, 2005).

3.1.3 Physical features

The Tsumeb region forms part of the Otavi Mountain land which has been classified into Mountain Savanna and Karstveld (Ministry of Environment and Tourism, 2004). Summit areas attain heights of 1300 to 1400 m above sea level, the bottom of intermontane basins are located at an altitude from 1220 to 1230 m (Kříbek *et al.*, 2005). The Karstveld landscape extends as narrow, raised margin that encircles the lower-lying Owambo Basin in the central northern Namibia (Mendelsohn *et al.*, 2002a). There are no major river systems in the Tsumeb region. However, the only one permanent stream in the Tsumeb region is represented by the Jordan Creek, which springs south of Tsumeb and terminates in a swampy delta area north of the town (Kříbek *et al.*, 2005).

3.1.4 Soils and geology

Soils of the Tsumeb region can be classified as calcic regosols, calcic cambisols, pelitic vertisols and arenoslos according to the FAO/Unesco (1977) classification. According to Křībek *et al.* (2005) steep slopes of elevation and carbonate platforms are usually covered by calcic regosols, foothils and slightly inclined carbonate plains are dominated by calcic cambisols. Flatlands are usually covered by pelitic vertisols and in some places; arenosols based on large fossil sand dunes occur (Křībek *et al.*, 2005).

The soils vary from loams and clays in the west and centre, to more sandy soils in the south-east, some of which are cultivated by commercial farmers (Mendelsohn *et al.*, 2002b). There are also many turf clay pans in low-lying areas (Mendelsohn *et al.*, 2002b). The soils are typically shallow on hills, lying in crevices between the rock outcrops, but deeper deposits occur around and below the hills (Mendelsohn *et al.*, 2002b).

The Karstveld lies on massive deposits of calcrete and dolomite (Menndelsohn *et al.*, 2002b). The rocks are dominated by limestone that dissolves easily in water, forming large underground caverns, lakes (Lake Otjikoto and Lake Guinas) and aquifers of underground water (Mendelsohn *et al.*, 2002a). Lake Otjikoto and Lake Guinas, according to Mendelsohn *et al.* (2002a), are in fact sinkholes which contain underground water that is now visible because the ceiling of the caverns that used to conceal the water has disappeared.

According to Kříbek *et al.* (2005) the Otavi Mountain group can be subdivided into two sub-groups:

(1) The Abenab sub-group consists mostly of laminated dolomites in the lower part, and of intercalating bedded limestone and shale with massive dolomites in the upper part,

(2) The Tsumeb sub-group is composed mostly of limestones and dolomites with horizons of spectacular diagenetic chert in the uppermost part of the unit.

3.1.5 Flora and fauna

A diverse assemblage of plants is found in the Karstveld because of the variety of topography and soils in the landscape (Mendelsohn *et al.*, 2002a). Dominant woody plants are *Colophospermum mopane* trees and shrubs, *Acacia* species and *Catophractes alexandri* (Mendelsohn *et al.*, 2002a). According to Giess (1971) the Mountain Savanna is characterised by *Kirkia acuminata*, *Gyrocarpus americanus*, *Fockea multiflora*, *Berchemia discolor*, *Pachypodium lealii*, *Croton* spp., *Moringa ovaliflora* and many more.

The flats between mountains and mountain ridges are covered with shrubs and small trees of *Combretum apiculatum, Dichrostachys cinerea,* as well as species of *Croton* and *Acacia* (Giess, 1971). The tree stratum consists mainly of *Sclerocarya birrea* subsp. *caffra, Spirostachys africana, Peltophorum africanum, Ficus cordata, F. sycomorus, F. petersii* and *Combretum imberbe,* which occur on soils with outcrops of recent surface limestone (Giess, 1971).

On sandveld patches *Philenoptera nelsii, Terminalia sericea* and *Acacia* species are common (Giess, 1971). Coarse and hard grass such as Blackfoot Brachiaria (*Brachiaria nigropedata*), Wool Grass (*Anthephora pubescens*) and Kalahari Sand Quick (*Schmiditia pappophoroides*) grow in the sandy areas while in the mountain regions bushes such as Leadwood (*Combretum imberbe*) grow along with grasses like the Armgras (*Brachiaria eruciformis*) (Geo-Consult, 1996).

According to Mendelsohn *et al*. (2002a) the most notable zones of high terrestrial diversity occur in the north-east of Namibia, in the Karstveld around Tsumeb, in highland areas in the centre ground further west of Namibia. A total of 658 species of birds have been recorded in Namibia and of these, 201-230 bird species are found around Tsumeb (Mendelsohn *et al*., 2002a). There are over 71 reptile species and 76 mammal species around the Tsumeb area (Mendelsohn *et al*., 2002a). The following mammalian species may occur around the Tsumeb area: kudu, steenbok, springbok, damara dik-dik, hyena, wild cat and other small predators (Geo-Consult, 1996).

3.1.6 Mining activities and industrial processes

Tsumeb Corporation Limited (TCL) has been mining copper and lead since the early 1900s. The mine comprises a mining area and a smelter complex for processing these minerals. Tsumeb smelter plant was originally based on the Tsumeb ore body (Geo-Consult, 1996). Geo-Consult (1996) reported that the smelter started mineral processing in 1903 to produce copper matte and crude lead for further processing outside Namibia.

Mining of the ore (copper mineral which contains 2-3% copper) happens when a hole is drilled in the ground to extract the ore. The ore then goes through the process called flotation where the copper is removed from the copper waste. A concentrate of copper (20 – 28% copper) is removed and sent to the smelter for further processing. The smelter is made up of five divisions: - Receiving bay, Copper plant, Power plant, Slag mill and Environment Department.

(i) Receiving bay

The receiving bay receives and prepares the concentrates for the Copper plant. The concentrates comes from the following mines:

- Otjihase Mine
- Kombat Mine
- A mine in Democratic Republic of Congo
- Tsumeb Mine (no more operational)
- Slag Mill (within the smelter complex)

The concentrate is transported either by train or by truck. The mines send different concentrations of copper.

(ii) Copper plant

The concentrate first goes through the primary furnace also known as reverb furnace. The furnace is 12 m wide, 27 m in length and 4 m high (Bezuidenhout[1] *pers. comm.*, 2006). The furnace is divided into two zones, the *smelting* zone as well as the *bath* zone.

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[1] Bezuidenhout Jacques is a Plant Metallurgist at Ongopolo Mining and Processing Limited. The interview was conducted on 19/05/06.

The furnace slants slightly towards the *bath* zone so that the liquid metal from the *smelting* zone moves towards the *bath* zone. In the *bath* zone, the metals separate by density, the heavy ones at the bottom and the light ones on top. The primary furnace produces sulphur dioxide-containing off-gas and heavy metal impurities which are cooled in a waste heat boiler installation (Geo-Consult, 1996). The off-gas and the impurities are finally discharged through a high stacks (Geo-Consult, 1996).

According to Bezuidenhout (*pers. comm.* 2006) copper matte (contains 40-50% copper) - the concentrate of heavy metals from the primary furnace – goes to the secondary furnace. Reverb slag (contains <1 % copper) which contain concentrations of metals from the primary furnace – slag mill - is thrown away as waste (Bezuidenhout *pers. comm.*, 2006). Slag mill waste is made out of fine grained particles of metals such as lead, zinc, germanium and gallium (Křîbek *et al.*, 2005).

The secondary furnace (also known as converter) has a cylindrical shape with an open mouth as well as holes that allows air to move in and it can rotate 360º. The matte is added to the converter through the mouth. The matte then reacts with oxygen and a mushy substance that floats on top of the matte is produced. The converter then turns and the mushy substances fall out. The mushy substance (consist of 2–3% copper) goes to slag mill as waste.

(iii) Power plant

The entire smelting process uses 100 tonnes of coal per day and that is about 27 mega watts (mW) of energy (Bezuidenhout *pers. comm.*, 2006). That in itself is a lot of energy and it can not be wasted. Therefore, this chemical energy is converted into electrical energy which is used by the entire smelter complex.

(iv) Environment

The stacks release gaseous emissions such as sulphur dioxide and dust-fallout. The dust particles contain lead, copper and other metals, which depending on their size and mass, are deposited on the ground. Air pollutants emitted by smelter stacks are transported by atmospheric flows and dissipated by turbulent current. Other sources of contamination are airborne particles from the Tsumeb tailings pond, airborne particles from slag mill waste, and flotation wastes released to a watercourse during the failure of a dam of the old tailings impoundment.

The Analytical Department at the Smelter is responsible for monitoring the dust particles released through the stacks. Monitoring is done by sampling, analysing and processing the data; and it is done in the following aspects:

- Air quality monitoring
    - Sulphur Dioxide Monitoring – sulphur dioxide concentration in the air
    - Fallout Monitoring – coarse windborne particles
    - Total Suspended Particles – all dust particles including coarse and fine dust
    - PM10 monitoring of fine material <2.5 microns in the air
- Groundwater quality monitoring

Monitoring is done at 14 stations; in and around the smelter complex.

3.2 Selection of sites and demarcation of plots

Sites close to the 14 monitoring stations were identified (Fig. 2). The study sites were selected such that they covered a presumed gradient from heavy pollution inside the smelter complex to areas without pollution (airport site), but close enough to act as acceptable controls.

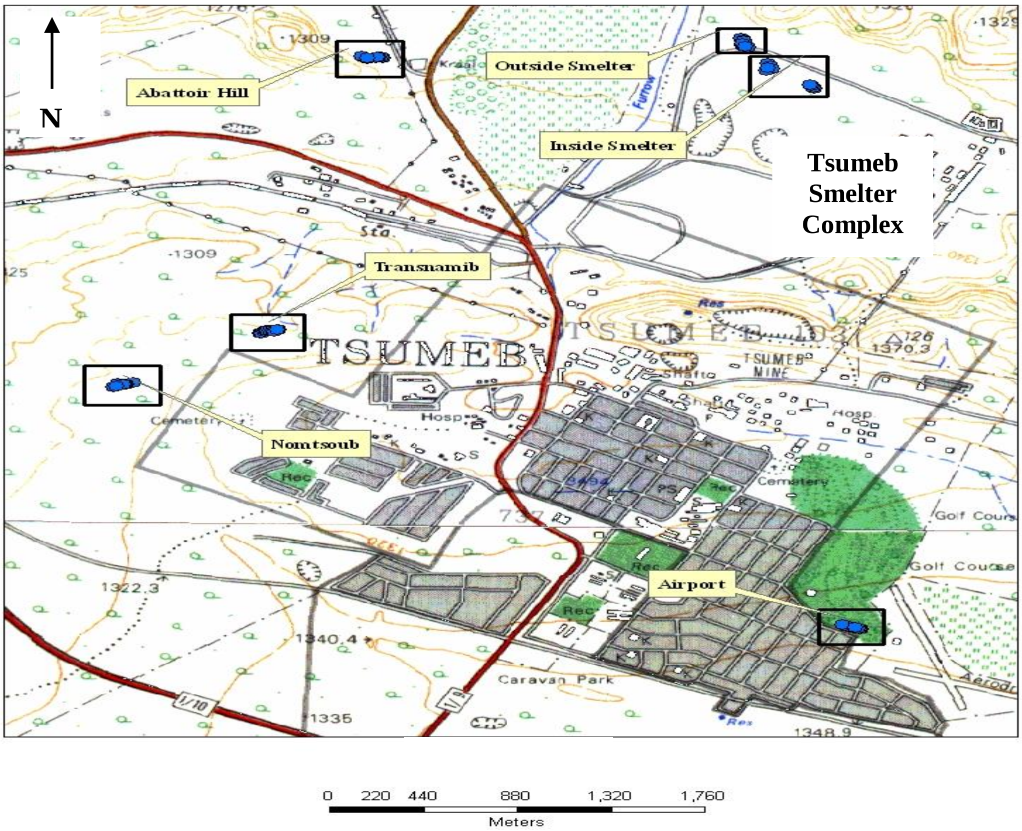

Figure 2. Map of Tsumeb showing the six study sites (Ministry of Mines and Energy, 2006a).

The six study sites were:

I) Inside Smelter Site (INS)

II) Outside Smelter Site (SME)

III) Abattoir Hill Site (ABA)

IV) Transnamib Site (TRA)

V) Nomtsoub Site (NOM)

VI) Airport Site (AIR)

After the identification of the study sites, ten plots were randomly demarcated at each study site. Stratified random sampling design was used to select plots within the study sites (Barbour *et al*., 1999). A stratified random design allows the fieldworker to subdivide the survey area – or any given stand- into several homogeneous regions, and then locate the samples randomly within each homogeneous region (Barbour *et al*., 1999). Barbour *et al*. (1999) stated that this design ensures that samples will be dispersed throughout the entire survey area and it does not compromise the concept of random sampling.

Nested plots were used to determine the minimal plot area. It is necessary to determine the minimal area – the smallest area within which the species of the community are adequately represented (Barbour *et al*., 1999; Weger, 1972). The minimal area may be determined by a species-area curve (Barbour *et al*., 1999).

This was achieved by placing larger and larger quadrats on the ground in such a way that each larger quadrat encompasses all the smaller ones, an arrangement known as nested quadrats (Barbour *et al*., 1999). The number of species encountered in each quadrat was plotted against quadrat area (m^2) to produce a species area curve. The point on the curve where the slope most rapidly approaches the horizontal is called the minimal area (Barbour *et al*., 1999; Weger, 1972). The minimal area for this specific study was 100 m^2. Therefore, each plot had a dimension of 10 m x 10 m.

The 10 m x 10 m plots were used for sampling trees, defined as woody plants with a basal circumference of more than 15 cm (Anderson & Walker, 1974).

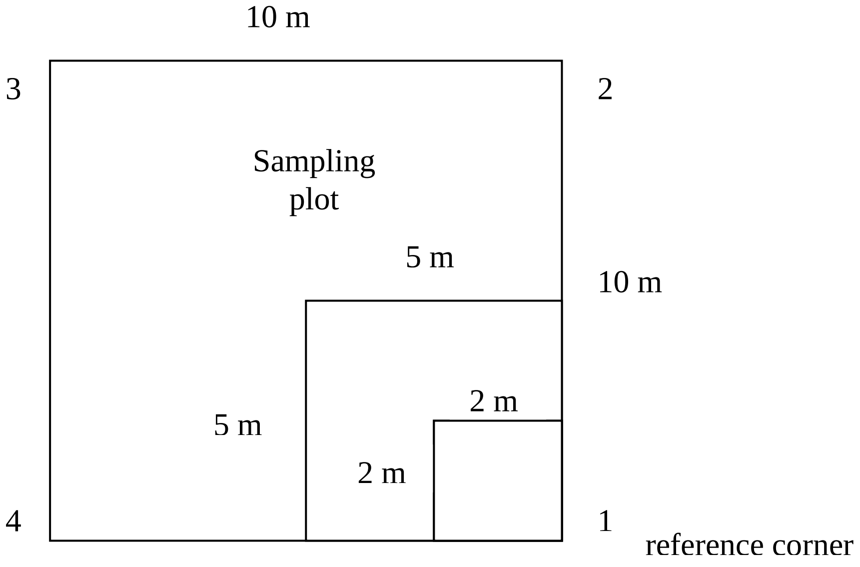

Figure 3. An illustration of a sampling plot (10 m x 10 m) with subplots, indicating a reference corner (1). (not drawn to scale)

The 10 m x 10 m plot had a 5 m x 5 m subplot in one corner, so that its reference corner was the same as the one for the 10 m x 10 m plot (Bonham, 1989). The 5 m x 5 m plot was used for sampling shrubs, seedlings and saplings, defined as woody plants with a basal circumference of less than or equal to 15 cm (Anderson & Walker, 1974).

A 2 m x 2 m subplot was nested within the 5 m x 5 m subplot, so that its reference corner was the same as the one for both the 5 m x 5 m and 10 m x 10 m (Bonham, 1989). Grasses were assessed within the 2 m x 2 m plots. The Global Positioning System (GPS) was used to record the position of each reference corner. Measuring tape was used to demarcate the plots. Metal pegs were used to mark the corners of the plots.

3.3 Measurement of plant attributes

All the trees, within each plot, were identified (Appendix 2) and counted. Their heights as well as basal circumferences were measured and recorded. Height was measured with the aid of a ranging pole, which was placed against the tree's trunk. Basal circumference was measured with a tape measure just above the base of the tree. This was done with an assumption that all the stems were circular. Each stem of multi-stemmed trees was measured and recorded separately. Basal circumference and height were measured for all trees in general and for specific tree species; *Combretum apiculatum* and *Terminalia prunioides*. *C. apiculatum* and *T. prunioides* were selected because they were common in the study area.

All the shrubs, seedlings and saplings, were identified (Appendix 2) and counted, as well as a specific shrub *Dichrostachys cinerea*. The specific shrub was selected since it was common among the study sites. Their heights as well as the number of stems were recorded for each individual. Height was measured with a ranging pole, which was placed against the plant’s trunk. The stems of each plant were counted and recorded on a field sheet.

Grass species were identified (Appendix 2). Total grass cover was visually determined and ranked according to cover classes of Braun-Blanquet (Barbour *et al.*, 1999). Unidentified woody and grass species were collected and identified at the National Botanical Research Institute. Collection of unidentified plant species was done by cutting-off with a pair of secateurs a minimum amount of plant specimen that was useful for identification. The plant specimens were pressed with a plant press and preserved for identification purposes.

3.4 Determination of woody cover

At each site, five 50 m line transects were randomly set up to determine canopy cover. Randomising was achieved by an approach known as random walk, which involved walking for a number of paces and selecting a point as well as a direction (Wilson, 2005).

The line was stretched taut at a height to contact the vegetation canopy and the length of each plant intercept was measured (Bonham, 1989; Wilson, 2005). The proportion of the total length of transect intercepted by a species gives measure of the cover of that species (Greig-Smith, 1983). A measuring tape was used.

3.5 Assessment of disturbance

Disturbance was assessed at each site. The assessment was done as follows; no disturbance if no trees were cut down, moderate disturbance if less than five trees were cut down and heavy disturbance if more than five trees were cut down.

3.6 Soil sampling

From each plot, a composite sample of surface soil was collected from depth 0 – 3 cm, after removal of litter on the surface (Kříbek *et al*., 2005). A composite sample was prepared by blending soil samples taken from the corners and in the central point of the 10 m x 10 m plot (Kříbek *et al*., 2005). A garden shovel was used to collect the soil samples. At most, 500 grams of the soil were collected into a bag. Each bag was properly labelled with the name of the site and plot number.

3.7 Chemical analysis of soil samples

All the soil samples were sun dried and sieved to 0.7 mm fraction. A portable x-ray fluorescence (XRF) machine, Niton XLt 700 Series Environmental Analyser, was used to analyse the soil samples (Ministry of Mines and Energy, 2006b). This device uses a standardized United State Environmental Protection Agency (USEPA) Method 6200. The soil samples were analysed for concentrations of arsenic, lead and cadmium. The analysis was done at the Geological Survey of Namibia, Ministry of Mines and Energy.

3.8 Data manipulation and analysis

A Kolmogorov-Smirnov test for normality indicated that arsenic (As), cadmium (Cd) and lead (Pb) concentrations in the soil were not normally distributed ($p < 0.001$). A Kruskal-Wallis test was used to test whether there was a significant difference in the concentrations of these heavy metals (arsenic, cadmium and lead) found in soil samples among the sites. A Mann-Whitney U test – was used to determine where the significant difference was (Le Blanc, 2004).

Plant species diversity for each plot at the different sites was calculated by means of Shannon-Wiener Diversity Index (H'):

$$H' = -\sum_{i=1}^{s} (p_i * \ln p_i)$$

where p_i was the proportion of individuals found in the i-th species (Pielou 1975). The Shannon-Wiener index takes into account species richness as well as evenness which are good indications of species diversity. The Kolmogorov-Smirnov test was used to test whether the diversity index (H') followed a normal distribution. The Kolmogorov-Smirnov test indicated that the diversity (H') was normally distributed ($p = 0.200$).

To test whether plant species diversity differed among the sites, one-way Analysis of Variance (ANOVA) test was used. ANOVA is a simultaneous test used to determine with a single test of significance whether any of three or more population means for a single variable differ from each other (Le Blanc, 2004). If there was a significant difference in plant species diversity (H') between the sites, a multiple comparison test- Tukey's *post hoc* range tests - can determine which means differ.

A one-way ANOVA was used to determine whether there was a significant difference in species richness among the sites. The Kolmogorov-Smirnov test indicated that the richness was normally distributed ($p = 0.25$).

Density was based on a simple formula:

$$D=N/A$$

where D is the density, N the number of sampled trees or stems and A the size of the plot from which the plants were sampled (Pielou, 1975). Density was calculated for individual trees as well as stems and expressed in number per hectare. Density was calculated for trees and shrubs. Density was calculated for specific tree species; *Terminalia prunioides* and *Combretum apiculatum,* and specific shrub species, *Dichrostachys cinerea.*

A Kolmogorov-Smirnov test for normality indicated that the individual tree density and stem density for trees were not normally distributed ($p < 0.01$). Furthermore, the Kolmogorov-Smirnov test for normality indicated that the individual shrub density and stem density for shrubs were not normally distributed ($p < 0.05$).

Kolmogorov-Smirnov test for normality indicated that the individual tree density for *Terminalia prunioides* was not normally distributed ($p < 0.01$) while stem density was normally distributed ($p = 0.200$). Kolmogorov-Smirnov test for normality indicated that the individual tree density and stem density for *Combretum apiculatum* was not normally distributed ($p < 0.001$) and the individual shrub density for

Dichrostachys cinerea was not normally distributed ($p < 0.001$) as well as the stem density ($p < 0.001$).

A Kruskal-Wallis test was used to test for significant differences in the density data that were not normally distributed and a *post hoc* test - Mann-Whitney U test – was used to determine where the significant differences were, where applicable. One-way ANOVA was used to test for significant differences of the density data that were normally distributed and a *post hoc* test – Tukey's honestly significant difference (HSD) test – was used to determine where the significant differences were.

A two sample (paired) t-test was used to determine whether the individual tree density differed from stem density at each site for trees, shrubs and specific tree species; *Combretum apiculatum* and *Terminalia prunioides* well as specific shrub species, *Dichrostachys cinerea.*

The basal area of each plant was calculated from basal circumference using the formula:

$$BA = c^2/(4*\pi)$$

where BA was the basal area and c was the basal circumference. The basal area formula was used with an assumption that the stems were circular. The heights and basal areas were categorised in classes. The basal area was categorised into the following basal area classes (cm^2); 17-50.99, 51-84.99, 85-118.99, 119-152.99, 153-186.99, 187-220.99, ≥221. A Chi-squared test was used to test for differences in basal area distribution patterns among the sites.

The basal area of all individual trees in the plot were added together to give total basal area per plot and was then expressed per hectare. The Kolmogorov-Smirnov test for normality indicated that the total basal area per plot for trees were normally distributed ($p = 0.200$). A one-way ANOVA was used to test for significant differences for total basal area between the sites.

The heights of individual trees, as well as for *Combretum apiculatum* and *Terminalia prunioides* were categorised into the following height classes (m); <2.0, 2.0-2.9, 3.0-3.9, 4.0-4.9, ≥5. The heights of shrubs and *Dichrostachys cinerea* were categorised into the following height classes (m); ≤1, 1.1-1.5, 1.6-2.0, 2.1-2.5, 2.6-3.0, >3.0. A Chi-squared test was used to test for differences in height distribution among the sites.

A Kruskal-Wallis test was used to test whether there was a difference in tree canopy cover and grass cover amongst the sites. A Mann-Whitney U test was used to determine where the significant difference was.

SPSS Version 14 for Windows package (Norusis, 2004) was used for the Kolmogorov Smirnov test for normality and *post hoc* tests. GenStat for Windows Discovery Edition 2 was used for the Kruskal Wallis test, t-test and ANOVA.

For species composition, a Hierarchical Cluster Analysis (HCA) was used to determine whether there were differences in species composition among the sites. Hierarchical Cluster Analysis using between groups linkage method (Van Tongeren,

1995) was performed on a matrix of 60 plots by 25 plant species (excluding grasses), using species presence/absence data (Appendix 3). Preliminary analysis indicated no significant differences between a matrix with grasses and a matrix without grasses. HCA was done to produce a classification using similarities among plots based on species composition. SPSS Version 14 for Windows package (Norusis, 2004) was used for the cluster analysis.

Detrended Correspondence Analysis (DCA) (Ter Braak & Prentice, 1988) was applied to the presence/absence species data for all the sites, excluding the grasses. Preliminary analysis indicated no significant differences between a matrix with grasses and a matrix without grasses. According to Bowyer-Bower *et al.* (1996) the DCA procedure gives a two dimension spatial plot of site numbers, the spatial proximity of each data point indicating the degree of correspondence in species present. Preliminary analysis can be made using an indirect gradient analysis – DCA - to check the magnitude of change in species composition along the first ordination axis (Vetaas & Chadaudhary, 1998).

According to Ter Braak & Prentice (1988), in indirect gradient analysis attention is first focused on the major pattern of variation in community composition; the environmental basis of this pattern is to be established later. The DCA method ensures that at any point along the first ordination axis, the mean value of the site scores on subsequent axes is approximated to zero (Ter Braak & Prentice, 1988).

Canonical Correspondence Analysis (CCA) was used to test for relationships between species composition (excluding grasses) and explanatory variables. The explanatory data set consisted of five variables as follows: (i) arsenic concentration (ppm) (ii) lead concentration (ppm) (iii) cadmium concentration (ppm) (iv) geology as 1, 2, 3, 4 (thin-bedded light dolomite, superficial deposits, massive light dolomite, laminated dark dolomite) (v) disturbance as 0, 1 or 2 (none, moderate, heavy).

The geology at the Inside Smelter Site and Outside Smelter Site is superficial deposits of the Kalahari system; the geology at the Abattoir Hill Site is the massive light dolomite; the geology at the Transnamib Site and Nomtsoub Site is thin-bedded light dolomite and at the Airport Site, the geology, is laminated dark dolomite. The geology was determined with the use of the simplified geological map of the Tsumeb area (Ministry of Mines and Energy, 2006b). CCA aims to visualise (i) a pattern of community variation, as in standard ordination (ii) the main features of species' distribution along the environmental variables (Ter Braak, 1987). CANOCO was used for this analysis. CCA was performed on the same species data set as for DCA. Monte Carlo permutation test was used to test for significant influence of each explanatory variable. CANOCO Version 4.5 for Windows package (Ter Braak & Smilauer, 2002) was used for analysing CCA and DCA.

CHAPTER 4

RESULTS

4.1 Heavy metal contamination in the soil

4.1.1 Arsenic (As)

The concentration of arsenic ranged from 126.0 to 4129.0 mg/kg at the Inside Smelter Site, from 228.0 to 4387.0 mg/kg at the Outside Smelter Site, from 53.2 to 286.0 mg/kg at the Abattoir Hill Site, from 14.7 to 133.0 mg/kg at the Transnamib Site, from 15.1 to 35.8 mg/kg at the Nomtsoub Site and from 5.9 to 36.1 mg/kg at the Airport Site.

The lowest mean concentration was 17.0 mg/kg and the highest mean concentration was 2079.03 mg/kg (Table 1). The Kruskal-Wallis test indicated a significant difference in arsenic concentration among the sites ($H = 49.23$, $df = 5$, $p < 0.001$).

The Mann-Whitney U test indicated that arsenic concentration at Inside Smelter Site was significantly higher than at Abattoir Hill Site ($p < 0.01$), Transnamib Site, Nomtsoub Site and Airport Site ($p < 0.001$). The arsenic concentration at Outside Smelter Site was significantly higher than Abattoir Hill Site, Transnamib Site, Nomtsoub Site and Airport Site ($p < 0.001$). The arsenic concentration at Abattoir Hill Site was significantly higher than at the Transnamib Site ($p < 0.01$), Nomtsoub Site and Airport Site ($p < 0.001$). The arsenic concentration at the Airport Site was significantly lower than at the Transnamib Site and Nomstoub Site ($p < 0.05$).

There was no significant difference in arsenic concentration between Inside Smelter Site and Outside Smelter Site ($p > 0.05$). There was no significant difference between Transnamib Site and Nomtsoub Site ($p > 0.05$).

Table 1. The mean concentrations of heavy metals (cadmium, lead and arsenic) in soil samples taken from the six sites as well as the guideline values and the probable effect limit (Mapani 2006). (The shaded blocks represent the metal concentration higher than the probable effect limit.)

Soil samples at Tsumeb Area			
Site	Cadmium (ppm) ± standard error	Lead (ppm) ± standard error	Arsenic (ppm) ± standard error
Inside Smelter	88.4±24.3	6024.5±1523.7	2074.0±511.9
Outside Smelter	44.4±12.5	5059.5±1068.5	1702.4±367.2
Abattoir Hill	0	852.6±147.4	169.2±24.5
Transnamib	0	375.4±102.9	52.3±12.5
Nomtsoub	0	134.1±20.2	24.1±2.3
Airport	0	37.3±3.6	17.0±2.7
	International Sediment Quality Guidelines (ISQG) in ppm		
	0.6	35	5.8
	Probable effect limit (PEL) in ppm		

	3.5	91.3	17

4.1.2 Cadmium (Cd)

The concentration of cadmium ranged from 0 to 172.62 mg/kg at the Inside Smelter Site and from 0 to 137.51 mg/kg at the Outside Smelter Site. The concentration of cadmium for the other sites (Abattoir Hill Site, Transnamib Site, Nomtsoub Site and Airport Site) was below detection limit.

The lowest mean concentration was 0 mg/kg and the highest mean concentration was 88.88 mg/kg (Table 1). The Kruskal-Wallis test indicated a significant difference in cadmium concentration among the sites ($H = 22.13$, $df = 5$, $p < 0.001$).

The Mann-Whitney U test indicated that cadmium concentrations at the Inside Smelter Site and Outside Smelter Site were significantly higher than at Abattoir Hill Site, Transnamib Site, Nomtsoub Site as well as Airport Site ($p < 0.01$). There was no significant difference in cadmium concentration between Inside Smelter Site and Outside Smelter Site.

4.1.3 Lead (Pb)

The concentration of lead ranged from 130.61 to 11881.0 mg/kg at the Inside Smelter Site, from 801 to 13072.0 mg/kg at the Outside Smelter Site, from 49.33 to 1584.00 mg/kg at the Abattoir Hill Site, from 61.72 to 942.8 mg/kg at the Transnamib Site, from 65.9 to 239.19 mg/kg at the Nomtsoub Site and from 17.54 to 57.56 mg/kg at the Airport Site.

The lowest mean concentration was 37.27 mg/kg and the highest mean concentration was 6024.48 mg/kg (Table 1). The Kruskal-Wallis test indicated a significant difference in lead concentration among the sites ($H = 45.77$, $df = 5$, $p < 0.001$).

The Mann-Whitney U test indicated that lead concentrations at Inside Smelter Site was significantly higher than at Transnamib Site, Nomtsoub Site ($p < 0.01$) and Airport Site ($p < 0.001$). The lead concentration at Outside Smelter Site was significantly higher than at the Abattoir Hill Site ($p < 0.01$), Transnamib Site, Nomtsoub Site and Airport Site ($p < 0.001$). The lead concentration at the Abattoir Hill Site was significantly higher than at the Transnamib Site, Nomtsoub Site ($p < 0.05$) and Airport Site ($p < 0.001$). The lead concentration at the Airport Site was significantly lower than at the Transnamib Site and Nomstoub Site ($p < 0.001$).

There was no significant difference in lead concentration between Inside Smelter Site and Outside Smelter Site ($p > 0.05$). There was no significant difference between Transnamib Site and Nomstoub Site ($p > 0.05$).

4.2 Species diversity and richness

The species diversity (H’) ranged between 0.38 and 2.34, with the lowest diversity recorded at the Airport Site and the highest diversity recorded at the Transnamib Site.

The lowest mean species diversity was 0.897 and the highest mean species diversity was 1.741. The one-way ANOVA indicated a significant difference in species diversity among the sites ($F = 8.227$, $df = 59$, $p < 0.001$).

The multiple comparison test – Tukey's honestly significant difference (Tukey's HSD) test- indicated that the species diversity at the Airport Site was significantly lower than at the Inside Smelter Site ($p < 0.05$), Outside Smelter Site ($p < 0.01$), Transnamib Site and Nomtsoub Site ($p < 0.001$). The species diversity at Abattoir Hill Site was significantly lower than at Transnamib Site ($p < 0.05$).

Table 2. The mean Shannon-Wiener diversity index and mean species richness of plant species sampled at six sites. (Shaded area indicates highest values.)

Site	Mean Shannon-Wiener Diversity Index (H') ± standard error	Mean Species Richness ± standard error
Inside Smelter	1.38 ± 0.11	5.40 ± 0.54
Outside Smelter	1.44 ± 0.11	5.30 ± 0.42
Abattoir Hill	1.23 ± 0.12	4.70 ± 0.54
Transnamib	1.74 ± 0.10	7.10 ± 0.50
Nomtsoub	1.68 ± 0.11	6.80 ± 0.70
Airport	0.90 ± 0.09	3.00 ± 0.21

There were no significant differences between the Inside Smelter Site, Outside Smelter, Transnamib Site and Nomtsoub Site ($p > 0.05$). There was no significant difference between Abattoir Hill Site and Airport Site ($p > 0.05$). The species diversity at the Abattoir Hill Site was not significantly different from the species diversity at the Inside Smelter Site, Outside Smelter Site and Nomstoub Site ($p > 0.05$).

The species richness ranged between 2 and 11 species per plot. A one-way ANOVA indicated significant differences in species richness between the sites (F = 9.073, df = 59, $p < 0.001$). The species richness at the Airport Site was significantly lower than at the Inside Smelter Site and Outside Smelter Site ($p < 0.05$) as well as at Transnamib Site and Nomtsoub Site ($p < 0.001$). The species richness at the Abattoir Hill Site was significantly lower than at the Transnamib Site ($p < 0.05$).

There were no significant differences in species richness between the Inside Smelter Site, Outside Smelter, Transnamib Site and Nomtsoub Site ($p > 0.05$). There was no significant difference in species richness between Abattoir Hill Site and Airport Site ($p > 0.05$). The species richness at the Abattoir Hill Site was not significantly different from the species richness at the Inside Smelter Site, Outside Smelter Site and Nomstoub Site ($p > 0.05$).

4.3 Plant densities

4.3.1 All trees

The density of individual trees ranged from 0 to 1000 trees per hectare at the Inside Smelter Site; from 800 to 1400 trees per hectare at the Outside Smelter Site and from 600 to 1000 trees per hectare at the Abattoir Hill Site. The individual tree density ranged from 700 to 1400 trees per hectare at the Transnamib Site, from 400 to 1600 trees per hectare at the Nomstoub Site and from 0 to 300 trees per hectare at the Airport Site.

The density of stems ranged from 900 to 1800 stems per hectare at the Inside Smelter Site; from 1500 to 3500 stems per hectare at the Outside Smelter Site; from 1000 to 2300 stems per hectare at the Abattoir Site. The stem density ranged from 1700 to 3000 stems per hectare at the Transnamib Site, from 1400 to 2900 stems per hectare at the Nomstoub Site and from 0 to 1000 stems per hectare at the Airport Site.

The mean individual tree density varied from 160 to 1080 trees per hectare, whereas, mean stem density varied from 290 to 2230 stems per hectare (Fig. 4). The lowest mean tree density per hectare as well as the stem density, for trees, was recorded at the Airport Site (160 trees per hectare and 290 stems per hectare). The highest mean tree density per hectare was recorded at both the Outside Smelter Site and Transnamib Site (1080 trees per hectare) while highest mean stem density per hectare, for trees, was recorded at Transnamib Sites (2230 stems per hectare).

The Kruskal-Wallis test for individual trees indicated that there was a significant difference in the tree density among the sites ($H = 35.75$, $df = 5$, $p < 0.001$) and there was a significant difference in stem density among sites ($H = 37.27$, $df = 5$, $p < 0.001$).

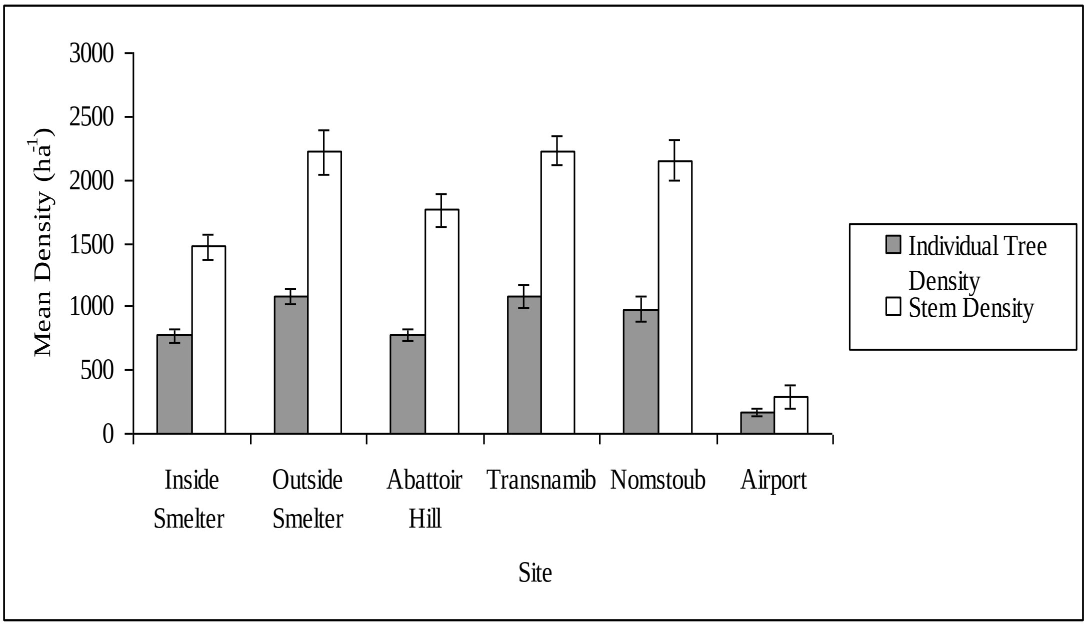

Figure 4. Mean tree and mean stem densities at the six study sites with standard error bars.

The Mann-Whitney U test indicated that individual tree density at the Airport Site was significantly lower than all the other five sites ($p < 0.001$). The tree density at the Inside Smelter Site was significantly lower than at the Outside Smelter Site ($p < 0.01$), Transnamib Site and Nomtsoub Site ($p < 0.05$). Tree density at the Abattoir Hill Site was significantly lower than at the Outside Smelter Site, Transnamib Site and Nomtsoub Site ($p < 0.05$).

There was no significant difference in tree density between the Inside Smelter Site and Abattoir Hill Site. There was also no significant difference between the Outside Smelter Site, Transnamib Site and Nomtsoub Site.

The Mann-Whitney U test indicated that stem density at the Airport Site was significantly lower than all the other five sites ($p < 0.001$). The stem density at the

Inside Smelter Site was significantly lower than at the Outside Smelter Site ($p < 0.05$), Transnamib Site ($p < 0.001$) and Nomtsoub Site ($p < 0.01$). The stem density at the Abattoir Hill Site was significantly lower than at the Outside Smelter and Transnamib Site ($p < 0.05$).

There was no significant difference in stem density between Outside Smelter Site, Transnamib Site and Nomstoub Site ($p > 0.05$). There was no significant difference between Abattoir Hill Site and Nomtsoub Site ($p > 0.05$).

The paired t-test indicated that the individual tree density was significantly lower than the stem density at all sites: Inside Smelter ($t = -7.72$, df = 9, $p < 0.001$), Outside Smelter ($t = -7.64$, df = 9, $p < 0.001$), Abattoir Hill Site ($t = -8.65$, df = 9, $p < 0.001$), Transnamib ($t = -16.00$, df = 9, $p < 0.001$), Nomtsoub Site ($t = -9.45$, df = 9, $p < 0.001$), Airport Site ($t = -1.45$, df = 9, $p < 0.001$).

4.3.2 Selected tree species

Combretum apiculatum

The individual tree density of *C. apiculatum* ranged from 0 to 300 trees per hectare at the Inside Smelter Site; from 0 to 500 trees per hectare at the Outside Smelter Site; from 0 to 200 trees per hectare at the Abattoir Hill Site. The individual tree density ranged from 0 to 400 trees per hectare at the Transnamib Site, from 0 to 500 trees per hectare at the Nomstoub Site and from 0 to 200 trees per hectare at the Airport Site.

The stem density of *C. apiculatum* ranged from 0 to 800 stems per hectare at the Inside Smelter Site; from 0 to 1000 stems per hectare at the Outside Smelter Site; from 0 to 300 stems per hectare at the Abattoir Site. The stem density ranged from 100 to 1200 stems per hectare at the Transnamib Site, from 0 to 1400 stems per hectare at the Nomstoub Site and from 0 to 300 stems per hectare at the Airport Site.

The mean individual tree density for *C. apiculatum* varied from 20 to 270 trees per hectare, whereas, mean stem density varied from 30 to 700 stems per hectare (Fig. 5). The lowest mean tree density per hectare as well as the mean stem density, for *C. apiculatum*, was recorded at the Airport Site (20 trees per hectare and 30 stems per hectare). The highest mean tree density per hectare as well as the mean stem density, for *C. apiculatum*, was recorded at the Nomtsoub Site (270 trees per hectare and 700 stems per hectare).

The Kruskal-Wallis test for *C. apiculatum* indicated that there was a significant difference in the tree density among the sites ($H = 20.09$, $df = 5$, $p < 0.001$) as well as in stem density among the sites ($H = 22.81$, $df = 5$, $p < 0.001$).

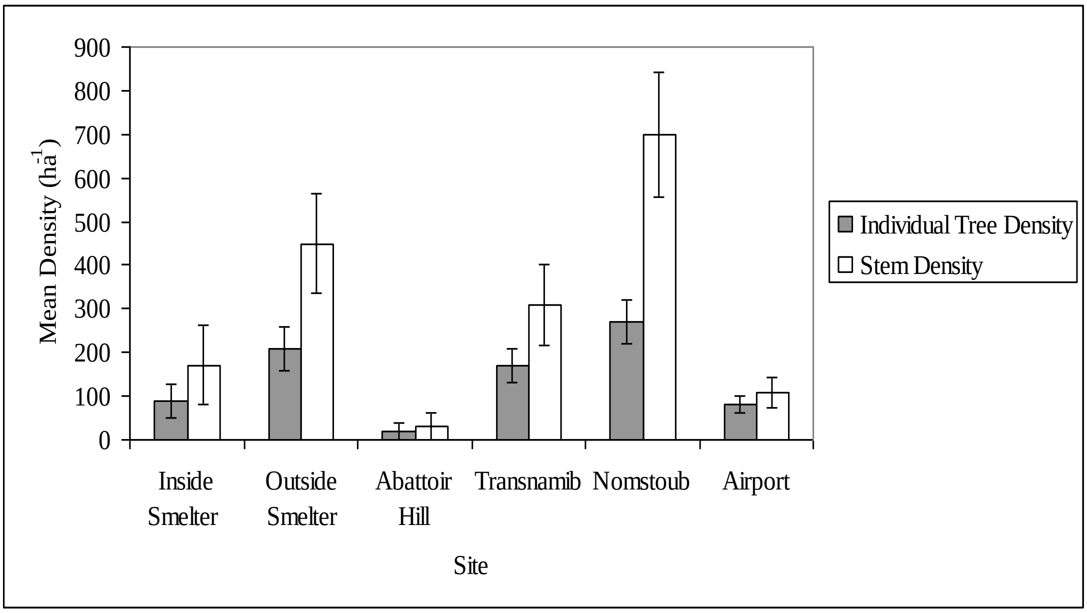

Figure 5. Mean tree and mean stem densities of *Combretum apiculatum* at the six study sites with standard error bars.

The Mann-Whitney U test indicated that individual tree density of *C. apiculatum* at Abattoir Hill Site was significantly lower than at the Outside Smelter Site, Transnamib Site, Nomstoub Site ($p < 0.01$) and Airport Site ($p < 0.05$). The tree density of *C. apiculatum* at the Outside Smelter was significantly higher than at the Inside Smelter Site ($p < 0.05$) and Airport site ($p < 0.01$).

The Mann-Whitney U test indicated that there was no significant difference in tree density of *C. apiculatum* between Nomstoub Site, Transnamib Site and Outside Smelter Site. There was no significant difference in tree density of *C. apiculatum* between Inside Smelter Site and Airport Site.

The Mann-Whitney U test indicated that the stem density of *C. apiculatum* at the Abattoir Hill Site was significant lower than at the Outside Smelter Site, Transnamib Site ($p < 0.01$), Nomstoub Site ($p < 0.001$) and Airport Site ($p < 0.05$). The stem density of *C. apiculatum* at the Nomstoub Site was significantly higher than at the Inside Smelter Site and Airport Site ($p < 0.01$). The stem density of *C. apiculatum* at the Outside Smelter Site was significantly higher than at the Airport Site ($p < 0.05$).

The Mann-Whitney U test indicated that there was no significant difference in stem density of *C. apiculatum* between Outside Smelter Site, Transnamib Site and Nomstoub Site. The insignificant differences were due to high variations in mean stem density of *C. apiculatum* at the Nomstoub Site, which subsequently affected the stem density of *C. apiculatum* at that site. There was also no significant difference in stem density of *C. apiculatum* between Inside Smelter Site and Abattoir Hill Site. Insignificant differences were due to high variations in mean stem density of *C. apiculatum* at the Inside Smelter Site.

The paired t-test indicated that the individual tree density was significantly lower than the stem density at the following sites: Outside Smelter ($t = -3.42$, $df = 9$, $p < 0.05$) and Nomtsoub Site ($t = -4.00$, $df = 9$, $p < 0.01$). The test indicated no differences between individual tree density and stem density at the Inside Smelter ($t = -1.44$, $df = 9$, $p = 0.182$), Abattoir Hill Site ($t = -1.00$, $df = 9$, $p = 0.343$), Transnamib ($t = -1.18$, $df = 9$, $p < 0.268$) and Airport Site ($t = -1.41$ $df = 9$, $p = 0.193$).

Terminalia prunioides

The individual tree density of *T. prunioides* ranged from 0 to 400 trees per hectare at the Inside Smelter Site; from 200 to 600 trees per hectare at the Outside Smelter Site;

from 200 to 700 trees per hectare at the Abattoir Hill Site. The individual tree density ranged from 100 to 800 trees per hectare at the Transnamib Site, from 0 to 600 trees per hectare at the Nomstoub Site and from 0 to 100 trees per hectare at the Airport Site.

The stem density of *T. prunioides* ranged from 0 to 700 stems per hectare at the Inside Smelter Site; from 400 to 1300 stems per hectare at the Outside Smelter Site; from 400 to 1600 stems per hectare at the Abattoir Site. The stem density ranged from 100 to 1200 stems per hectare at the Transnamib Site, from 0 to 1100 stems per hectare at the Nomstoub Site and from 0 to 200 stems per hectare at the Airport Site.

The mean individual tree density for *T. prunioides* varied from 20 to 440 trees per hectare, whereas, mean stem density varied from 30 to 1080 stems per hectare (Fig. 6). The lowest mean tree density per hectare as well as the mean stem density, for *T. prunioides*, was recorded at the Airport Site (20 trees per hectare and 30 stems per hectare). The highest mean tree density per hectare as well as the mean stem density, for *T. prunioides*, was recorded at the Abattoir Site (440 trees per hectare and 1800 stems per hectare).

The Kruskal-Wallis test for *T. prunioides* indicated that there was a significant difference in the tree density among the sites (H = 30.09, df = 5, $p < 0.001$) while the one-way ANOVA test indicated a significant difference in stem density among the sites (F = 31.681, df = 5, $p < 0.001$).

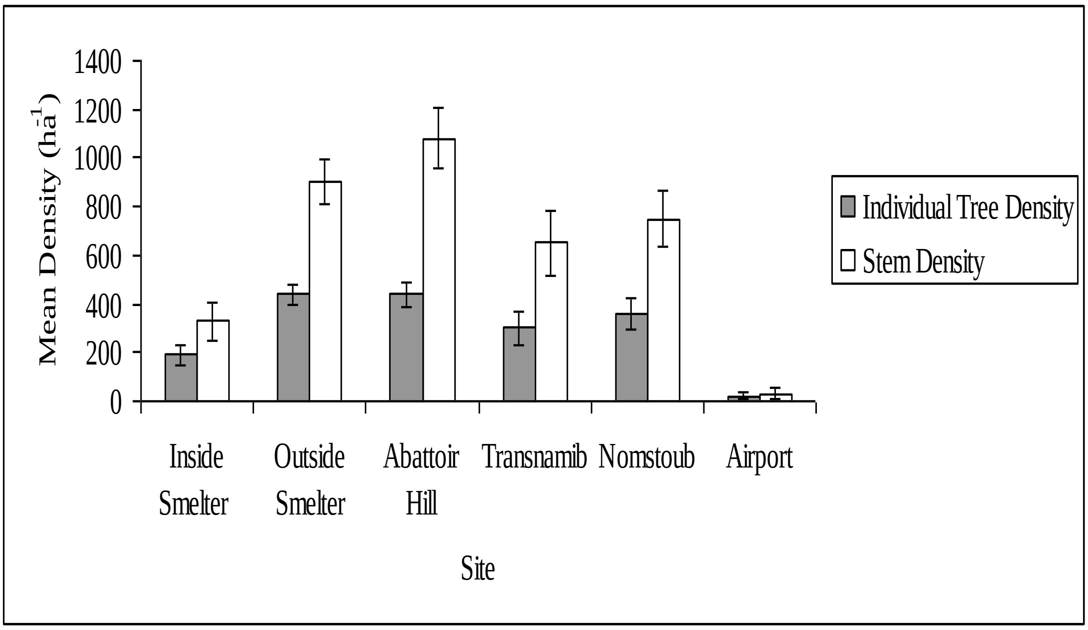

Figure 6. Mean tree and mean stem densities of *Terminalia prunioides* at the six study sites with standard error bars.

The Mann-Whitney U test indicated that individual tree density of *T. prunioides* at the Airport Site was significantly lower than at the Inside Smelter Site ($p < 0.01$), Outside Smelter Site, Abattoir Hill Site, Transnamib Site ($p < 0.001$) and Nomtsoub Site ($p < 0.01$). The tree density of *T. prunioides* at Inside Smelter Site was significantly lower that at the Outside Smelter Site, Abattoir Hill Site ($p < 0.01$) and Nomstoub Site ($p < 0.05$).

There was no significant difference in tree density of *T. prunioides* between Outside Smelter Site, Abattoir Hill Site, Transnamib Site and Nomtsoub Site. There was no significant difference in tree density of *T. prunioides* between Inside Smelter Site and Transnamib Site.

The Tukey's HSD test indicated that the stem density of *T. prunioides* at the Inside Smelter Site was significantly lower than at the Outside Smelter Site ($p < 0.01$) and

Abattoir Hill Site ($p < 0.001$). The stem density at the Abattoir Hill Site was significantly higher than at the Transnamib Site ($p < 0.05$). The stem density at the Airport Site was significantly lower than at the Outside Smelter Site, Abattoir Hill Site and Nomtsoub Site ($p < 0.001$) as well as at the Transnamib Site ($p < 0.01$).

The Tukey's HSD test indicated that there was no significant difference in stem density of *T. prunioides* between Outside Smelter and Abattoir Hill Site. There was also no significant difference in stem density of *T. prunioides* between Transnamib Site and Nomstoub Site.

The paired t-test indicated that the individual tree density was significantly lower than the stem density at the following sites: Inside Smelter ($t = -3.28$, $df = 9$, $p < 0.05$), Outside Smelter ($t = -6.70$, $df = 9$, $p < 0.001$), Abattoir Hill Site ($t = -6.86$, $df = 9$, $p < 0.001$), Transnamib ($t = -4.01$, $df = 9$, $p < 0.01$), Nomtsoub Site ($t = -7.13$, $df = 9$, $p < 0.001$). The test indicated no difference between individual tree density and stem density at the Airport Site ($t = -1.00$, $df = 9$, $p = 0.343$).

4.3.3 All shrubs

The density of individual shrubs ranged from 0 to 6000 shrubs per hectare at the Inside Smelter Site; from 0 to 2000 shrubs per hectare at the Outside Smelter Site; from 0 to 3600 shrubs per hectare at the Abattoir Hill Site. The individual shrub density ranged from 0 to 3200 shrubs per hectare at the Transnamib Site, from 0 to 2800 shrubs per hectare at the Nomstoub Site and from 400 to 4800 shrubs per hectare at the Airport Site.

The density of shrub stems ranged from 0 to 22 000 stems per hectare at the Inside Smelter Site, from 0 to 13200 stems per hectare at the Outside Smelter Site and at the Abattoir Site it was from 0 to 22400 stems per hectare. The stem density ranged from 0 to 16800 stems per hectare from 0 to 22400 stems per hectare at the Transnamib Site, from 0 to 20 800 stems per hectare at the Nomstoub Site and from 0 to 69 200 stems per hectare at the Airport Site.

The mean individual shrub density varied from 880 to 2680 shrubs per hectare, whereas, mean stem density varied from 4480 to 15960 stems per hectare (Fig. 7). The lowest mean shrub densities as well as the stem density were recorded at the Transnamib Site (880 shrubs per hectare and 4480 stems per hectare). The highest mean shrub density was recorded at Inside Smelter Site (2680 shrubs per hectare) while the highest mean stem density was recorded at Airport Site (15960 stems per hectare).

The Kruskal-Wallis test indicated that there was no significant difference in the shrub density among the sites (H = 8.430, df = 5, p = 0.128). There was no significant difference in stem density among sites (H = 4.979, df = 5, p = 0.414). The insignificant differences were due to high variations in mean stem density of shrubs at the Airport Site.

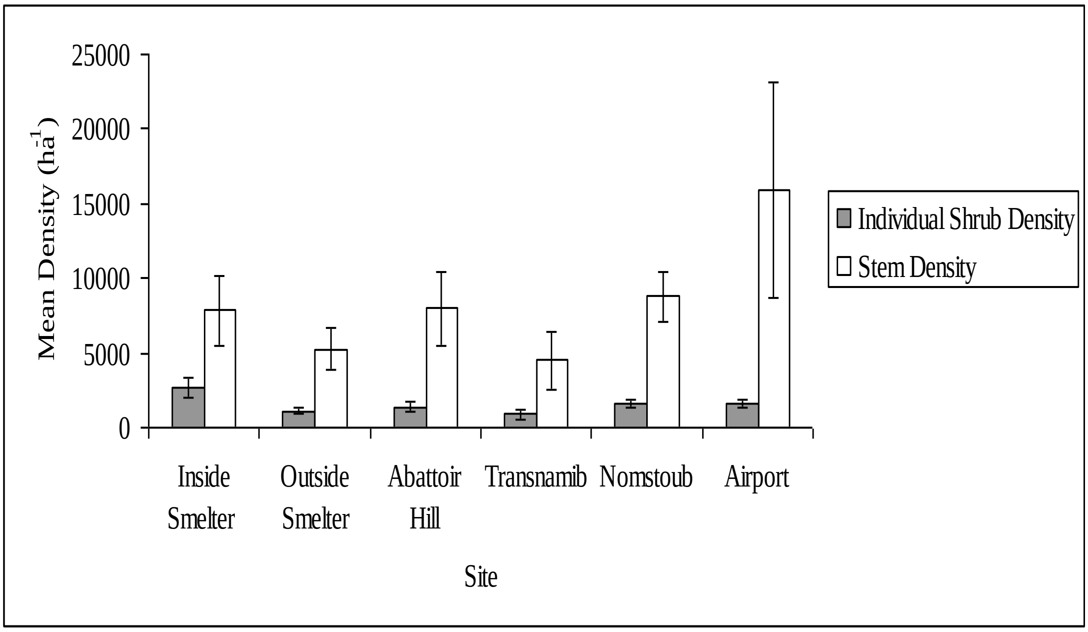

Figure 7. Mean shrub and mean stem densities at the six study sites with standard error bars.

The paired t-test indicated that the individual shrub density was significantly lower than the stem density at all sites: Inside Smelter (t = -2.77, df = 9, $p < 0.05$), Outside Smelter (t = -3.56, df = 9, $p < 0.01$), Abattoir Hill Site (t = -3.05, df = 9, $p < 0.05$), Transnamib (t = -2.77, df = 9, $p < 0.05$), Nomtsoub Site (t = -4.82, df = 9, $p < 0.001$) and Airport Site (t = -5.11, df = 9, $p < 0.001$).

4.3.4 Selected shrub species

Dichrostachys cinerea

The individual shrub density of *D. cinerea* ranged from 0 to 6000 shrubs per hectare at the Inside Smelter Site; from 0 to 1600 shrubs per hectare at the Outside Smelter Site; from 0 to 1200 shrubs per hectare at the Abattoir Hill Site. The individual shrub density ranged from 0 to 1200 shrubs per hectare at the Transnamib Site, from

0 to 800 shrubs per hectare at the Nomstoub Site and from 0 to 1200 shrubs per hectare at the Airport Site.

The stem density of *D. cinerea* ranged from 0 to 14400 stems per hectare at the Inside Smelter Site; from 0 to 7600 stems per hectare at the Outside Smelter Site; from 0 to 3600 stems per hectare at the Abattoir Site. The stem density ranged from 0 to 7200 stems per hectare at the Transnamib Site, from 0 to 4400 stems per hectare at the Nomstoub Site and from 0 to 19200 stems per hectare at the Airport Site.

The mean individual shrub density for *D. cinerea* varied from 120 to 1800 shrubs per hectare, whereas, mean stem density varied from 360 to 5800 stems per hectare (Fig. 8). The lowest mean shrub densities as well as the mean stem density, for *D. cinerea*, were recorded at the Abattoir Site (120 shrubs per hectare and 360 stems per hectare). The highest mean shrub density, for *D. cinerea*, was recorded at the Inside Smelter Site (1800 shrubs per hectare) while the highest mean stem density was recorded at Airport Site (5800 stems per hectare).

The Kruskal-Wallis test for *D. cinerea*, indicated a significant difference in shrub density among the sites ($H = 18.89$, $df = 5$, $p < 0.001$) as well as in stem density among sites ($H = 16.42$, $df = 5$, $p < 0.01$).

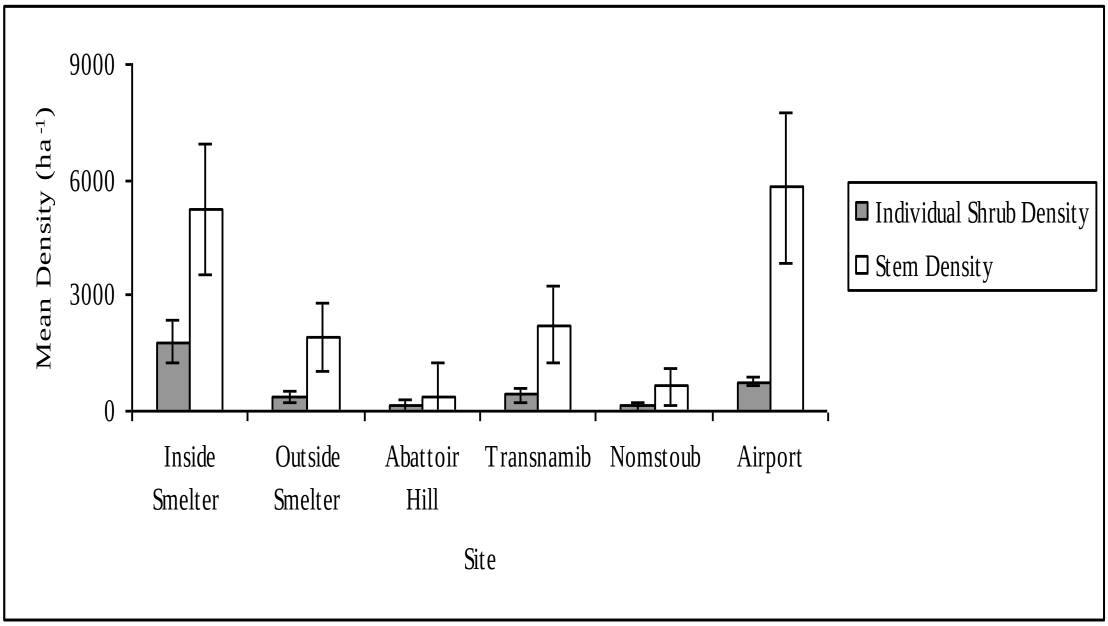

Figure 8. Mean shrub and mean stem densities of *Dichrostachys cinerea* at the six study sites with standard error bars.

The Mann-Whitney U test indicated that the individual shrub density of *D. cinerea* at the Inside Smelter Site was significantly higher than at the Outside Smelter Site ($p < 0.05$), Abattoir Hill Site ($p < 0.01$), Transnamib Site ($p < 0.05$) and Nomtsoub Site ($p < 0.01$). The individual shrub density of *D. cinerea* at Airport Site was significantly higher than at the Outside Smelter Site ($p < 0.05$), Abattoir Hill Site and Nomtsoub Site ($p < 0.01$).

The Mann-Whitney U test indicated that there was no significant difference in individual shrub density of *D. cinerea* between Inside Smelter Site and Airport Site ($p > 0.05$). There was no significant difference in individual shrub density of *D. cinerea* between Outside Smelter Site, Abattoir Hill Site, Transnamib Site, Nomtsoub Site and Airport Site ($p > 0.05$).

The Mann-Whitney U test indicated that stem density was significantly higher at Airport Site than at the Abattoir Hill Site and Nomtsoub Site ($p < 0.01$). The Mann-Whitney U test indicated that the stem density of *D. cinerea* at the Inside Smelter Site was significantly higher than at the Abattoir Hill Site and Nomtsoub Site ($p < 0.01$).

The Mann-Whitney U test indicated that there was no significant difference in stem density of *D. cinerea* between Airport Site, Transnamib Site and Inside Smelter Site ($p > 0.05$). High variations in mean stem density of *D. cinerea* at the Inside Smelter Site and Airport Site contributed to the insignificant differences. There was also no significant difference between Outside Smelter Site, Abattoir Hill Site and Nomstoub Site ($p > 0.05$). The insignificant differences were due to high variations in mean stem density of *D. cinerea* at the Outside Smelter Site.

The paired t-test indicated that the individual shrub density was significantly lower than the stem density at the following sites: Inside Smelter Site ($t = -2.69$, $df = 9$, $p < 0.05$) and Airport Site ($t = -2.72$, $df = 9$, $p < 0.05$). The test indicated no significant difference between individual tree density and stem density at the Outside Smelter Site ($t = -2.05$, $df = 9$, $p = 0.07$), Abattoir Hill Site ($t = -1.00$, $df = 9$, $p = 0.343$), Transnamib ($t = -2.20$, $df = 9$, $p = 0.06$) and Nomtsoub Site ($t = -1.38$, $df = 9$, $p = 0.20$).

4.4 Vegetation structural attributes

4.4.1 Basal area distribution patterns

4.4.1.1 All trees

Tree basal area ranged from 20.37 to 1034 cm^2 at the Inside Smelter Site; from 20.37 to 764.26 cm^2 at the Outside Smelter Site; from 20.37 to 911.08 cm^2 at the Abattoir Hill Site; from 20.37 to 764.26 cm^2 at the Transnamib Site; from 20.37 to 945.46 cm^2 at the Nomtsoub Site and from 52.20 to 795.77 cm^2 at the Airport Site.

The basal area class 153-186.99 cm^2 and 187-220.99 cm^2 recorded the lowest proportion of trees between the sites (Fig. 9). The basal area distribution patterns indicated higher proportion of trees in the class 17-50.99 cm^2 than in other classes. The Airport site recorded no trees in the basal area class 17-50.99 cm^2 and 153-186.99 cm^2.

There were significant differences in the basal area distribution patterns among the sites ($\chi^2 = 61.76$, df = 30, $p < 0.01$). The differences were mainly due to much lower expected frequency than observed at Outside Smelter Site for class 17-50.99 cm^2, Abattoir Hill Site for class 17-50.99 cm^2 and for class 51-84.99 cm^2, Nomstoub Site for class 85-118.99 cm^2 and Airport Site for class ≥221 cm^2.

Much higher expected frequencies than observed were recorded at Outside Smelter Site for class 85-118.99 cm^2, Transnamib Site for class 17-50.99 cm^2 and Airport Site for class 17-50.99 cm^2.

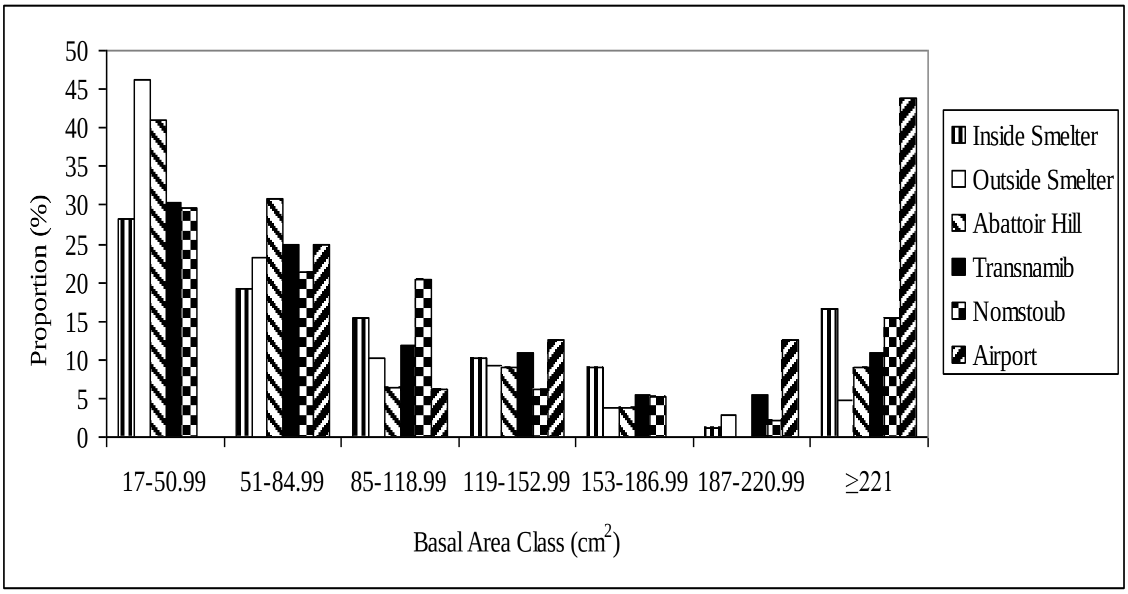

Figure 9. Comparison of basal area frequency distribution patterns of all trees among the six sites.

4.4.1.2 Selected tree species

Combretum apiculatum

Basal area for *C. apiculatum* trees ranged from 25.78 to 133.77 cm^2 at the Inside Smelter Site; from 25.78 to 124.30 cm^2 at the Outside Smelter Site; from 31.83 to 57.61 cm^2 at the Abattoir Hill Site; from 23.00 to 240.72 cm^2 at the Transnamib Site; from 20.37 to 199.74 cm^2 at the Nomtsoub Site and from 52.50 to 223.85 cm^2 at the Airport Site.

The basal area distribution patterns indicated higher proportion of *C. apiculatum* in the class 17-50.99 cm^2 and very low proportion in class 153-186.99 cm^2 (Fig. 10). There was no significant difference in the basal area distribution patterns among the sites for *C. apiculatum* trees (χ^2 = 37.12, df = 30, p = 0.174).

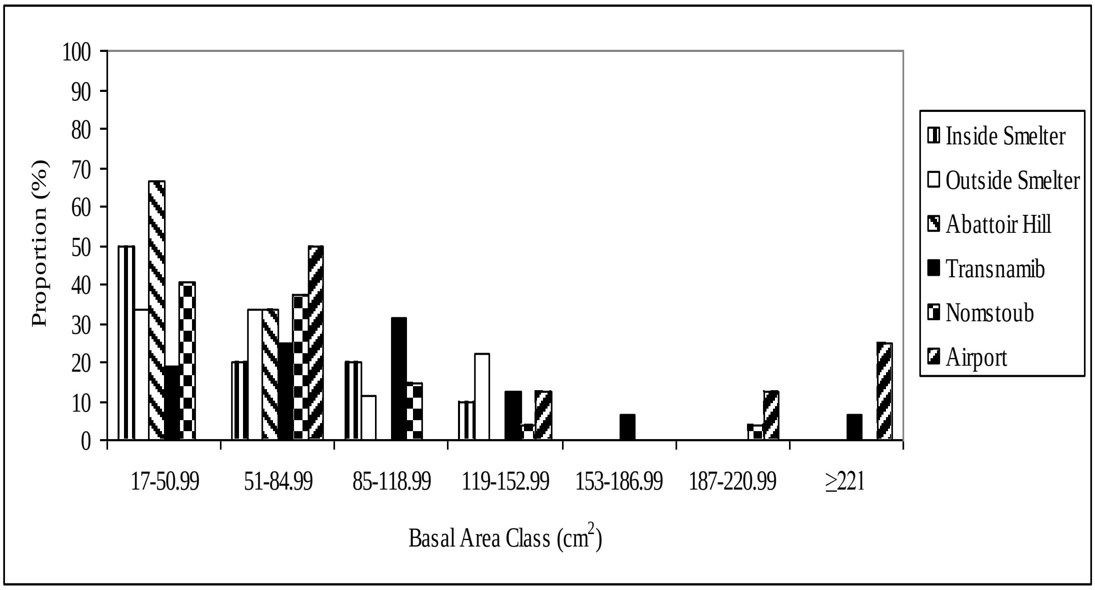

Figure 10. Comparison of basal area frequency distribution patterns of *Combretum apiculatum* trees among the six sites.

Terminalia prunioides

Basal area of *T. prunioides* trees ranged from 20.37 to 249.55 cm^2 at the Inside Smelter Site; from 20.37 to 232.05 cm^2 at the Outside Smelter Site; from 20.37 to 911.08 cm^2 at the Abattoir Hill Site; from 20.37 to 764.26 cm^2 at the Transnamib Site; from 20.37 to 412.53 cm^2 at the Nomtsoub Site and from 249.55 to 283.06 cm^2 at the Airport Site.

The basal area distribution patterns indicated higher proportions of *T. prunioides* in the class 17-50.99 cm^2 than in other classes (Fig. 11). The Airport Site recorded *T. prunioides* in the basal area class ≥221 cm^2 only.

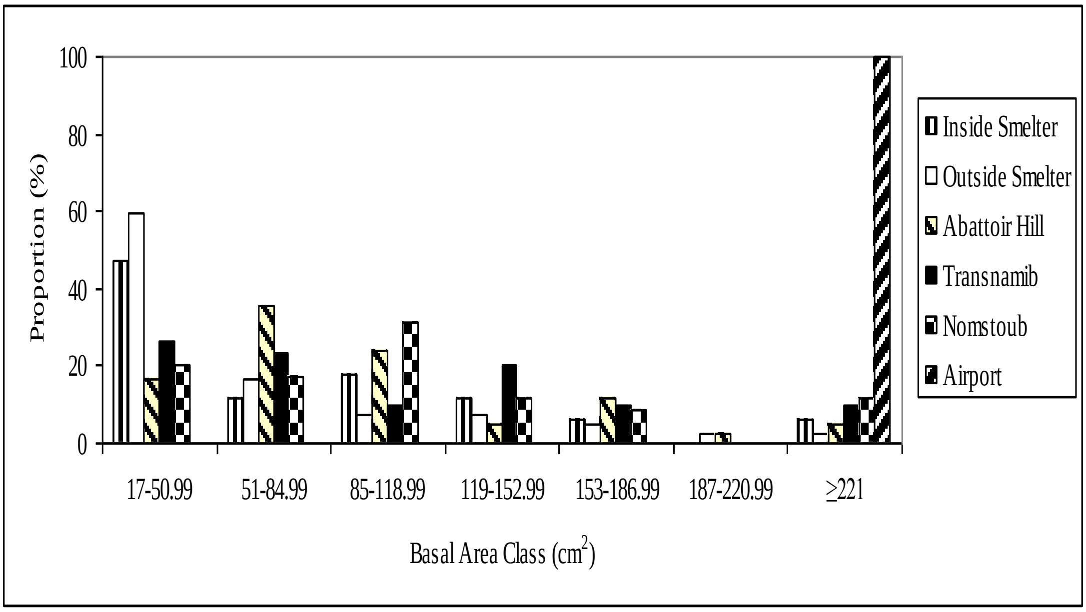

Figure 11. Comparison of basal area frequency distribution patterns of *Terminalia prunioides* trees among the six sites.

There were significant differences in the basal area distribution patterns among the sites for *T. prunioides* trees ($\chi^2 = 63.99$, df = 30, $p < 0.001$). The differences were mainly due to much lower expected frequency than observed recorded at Outside Smelter Site for class 17-50.99 cm^2, Abattoir Hill Site for class 51-84.99 cm^2 and Nomstoub Site for class 85-118.99 cm^2. Much higher expected frequencies than observed was recorded at Outside Smelter Site for class 85-118.99 cm^2 and Abattoir Hill Site for class 17-50.99 cm^2.

4.4.2 Total basal area

Total basal area ranged from 5.32 to 16.25 m^2/ha at the Inside Smelter Site; from 4.76 to 15.33 m^2/ha at the Outside Smelter Site; from 4.42 to 14.60 m^2/ha at the Abattoir Hill Site; from 6.62 to 23.83 m^2/ha at the Transnamib Site; from 2.86 to 20.78 m^2/ha at the Nomtsoub Site and from 0 to 9.58 m^2/ha at the Airport Site.

The one-way ANOVA test indicated a significant difference in total basal areas among the sites ($F = 6.528$, $df = 5$, $p < 0.001$). The highest mean basal area was 12.95 m^2/ha and the lowest mean basal area was 3.54 m^2/ha (Fig. 12).

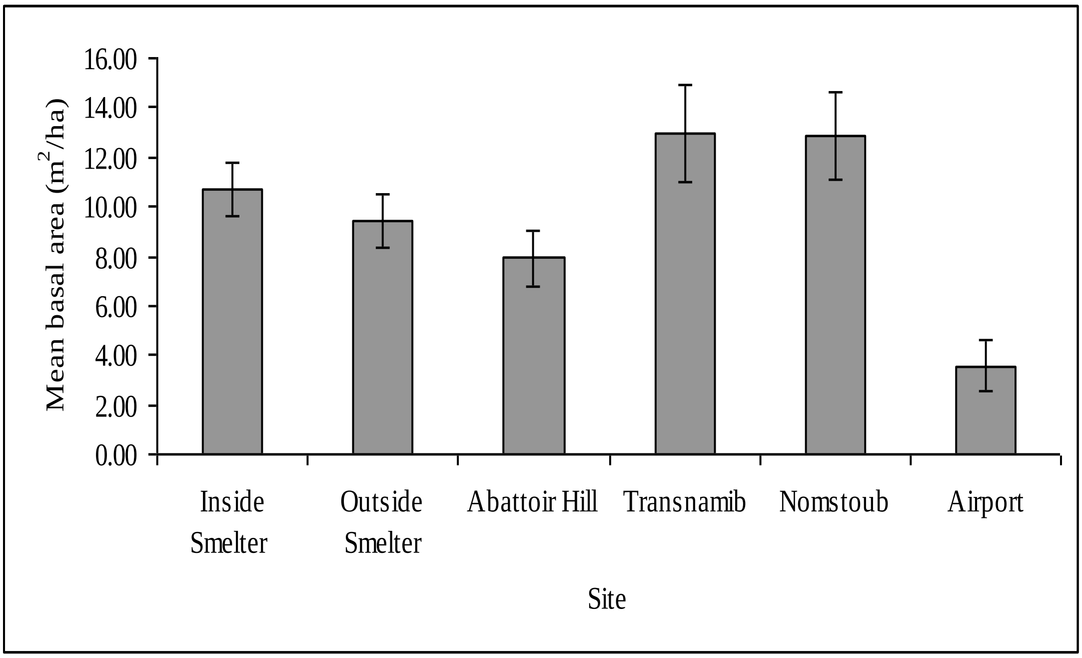

Figure 12. Mean total basal area of each site with error bars indicating standard error.

The Tukey's HSD test indicated that total basal area at the Airport Site was significantly lower than at the Inside Smelter Site and Nomtsoub Site ($p < 0.01$), Outside Smelter Site ($p < 0.05$) and Transnamib Site ($p < 0.001$).

The Tukey's HSD test indicated that total basal area at the Airport Site was not significantly different from the total basal area at Abattoir Hill Site ($p > 0.05$). There was no significant difference in total basal area between Inside Smelter Site, Outside Smelter Site, Abattoir Hill Site, Nomtsoub Site and Transnamib Site ($p > 0.05$).

4.4.3 Height distribution patterns

4.4.3.1 All trees

Tree heights ranged from 1.5 to >5 m at the Inside Smelter Site; from 1.2 to >5 m at the Outside Smelter Site; from 1.5 to >5 m at the Abattoir Hill Site; from 1.2 to >5 m at the Transnamib Site; from 1.2 to >5 m at the Nomtsoub Site and from 1.7 to >5 m at the Airport Site. The height distribution patterns indicated higher proportions of trees in the classes 2.0-2.9 m and 3.0-3.9 m and very low proportion in class 4.0-4.9 m (Fig. 13).

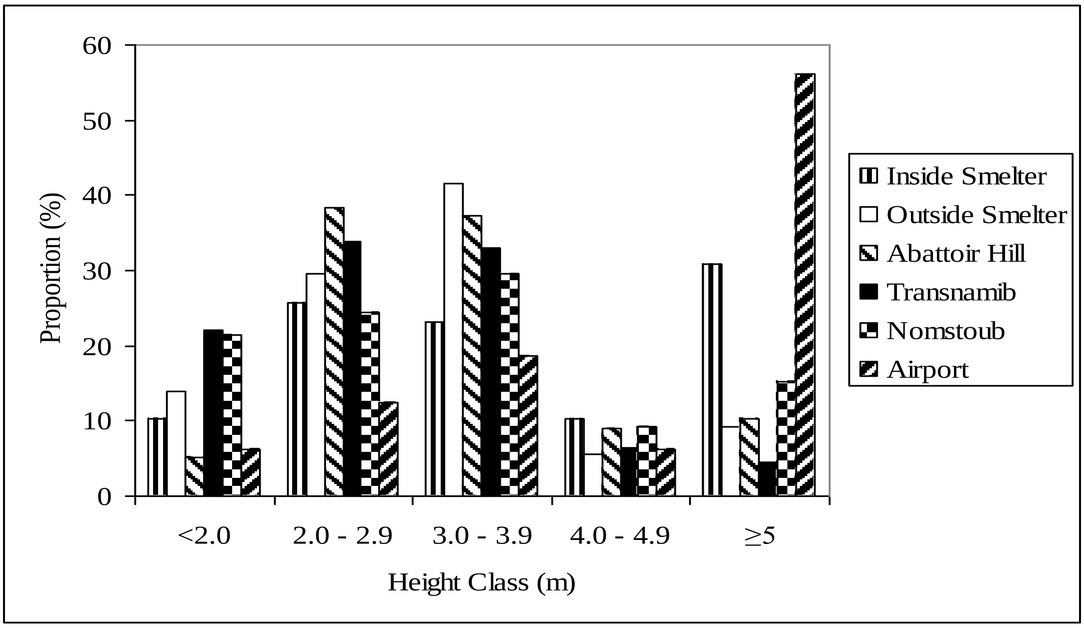

Figure 13. Comparison of height frequency distribution patterns of all trees among the six sites.

There was a significant difference in the height distribution patterns among the sites for trees ($\chi^2 = 71.24$, df = 20, $p < 0.001$). The differences were mainly due to much lower expected frequency than observed at Inside Smelter Site for class ≥5 m, Outside Smelter Site for class 3.0-3.9 m, Abattoir Hill Site for class 2.0-2.9 m as well as class 3.0-3.9 m, Nomtsoub Site for class <2.0 m, Transnamib for class <2.0 m and Airport Site for class ≥5 m.

Much higher expected frequencies than observed were recorded at Inside Smelter Site for class 3.0-3.9 m, Abattoir Hill Site for class <2.0 m, Transnamib Site for class ≥5 m and Nomtsoub Site for class 2.0-2.9 m.

4.4.3.2 Selected tree species

Combretum apiculatum

The heights of *C. apiculatum* trees ranged from 1.8 to >5 m at the Inside Smelter Site; from 2.1 to >5 m at the Outside Smelter Site; from 2.5 to 3 m at the Abattoir Hill Site; from 1.2 to 3.7 m at the Transnamib Site; from 1.3 to 4 m at the Nomtsoub Site and from 2.5 to >5 m at the Airport Site. The height distribution patterns indicated higher proportion for *C. apiculatum* trees in the class 2.0-2.9 m and 3.0-3.9 m (Fig 14).

There was a significant difference in the height distribution patterns among the sites for *C. apiculatum* trees ($\chi^2 = 39.94$, df = 20, $p < 0.01$). The difference was due to much lower expected frequency than observed at Outside Smelter Site 2.0-2.9 m.

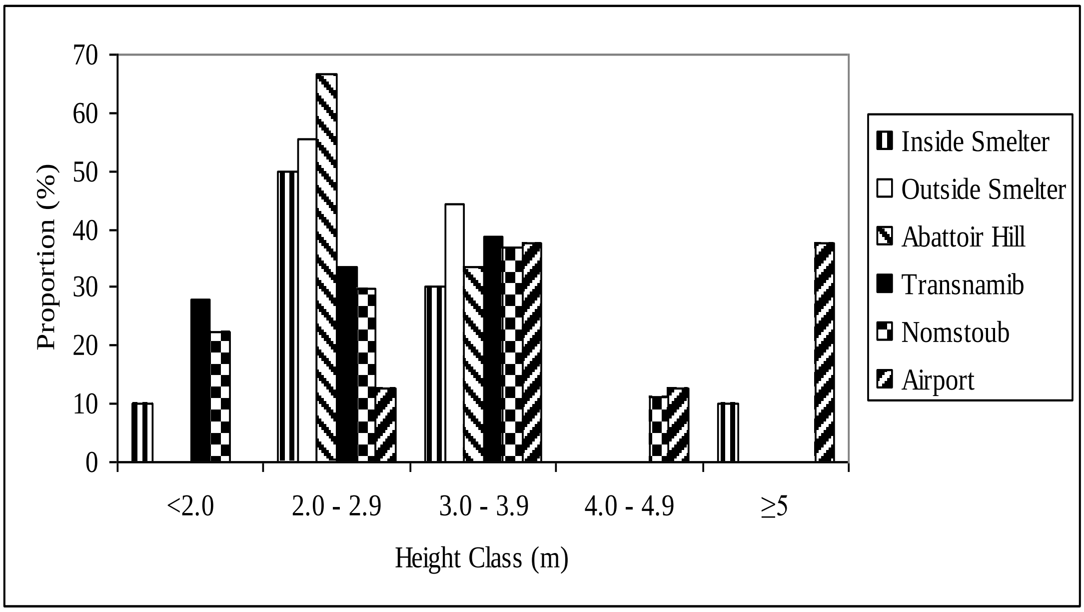

Figure 14. Comparison of height frequency distribution patterns of *Combretum apiculatum* trees among the six sites.

Terminalia prunioides

The heights of *T. prunioides* trees ranged from 1.5 to >5 m at the Inside Smelter Site; from 1.2 to >5 m at the Outside Smelter Site; from 1.5 to >5 m at the Abattoir Hill Site; from 1.4 to >5 m at the Transnamib Site; from 1.2 to >5 m at the Nomtsoub Site.

The Airport Site had *T. prunioides* trees of >5 m only. The height distribution patterns indicated higher proportion for *T. prunioides* trees in the class 2.0-2.9 m and 3.0-3.9 m (Fig. 15).

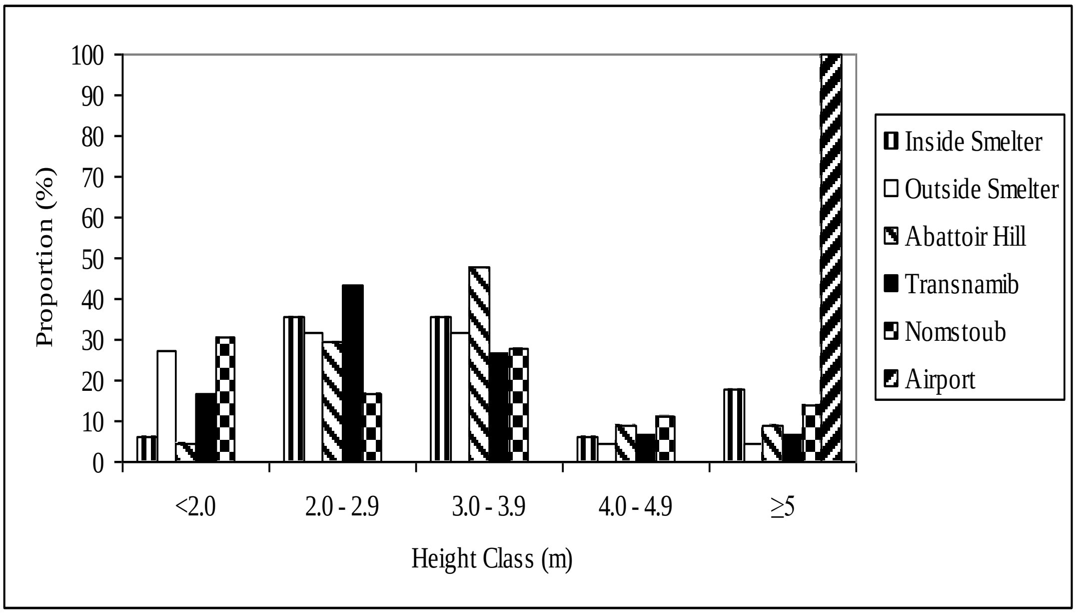

Figure 15. Comparison of height frequency distribution patterns of *Terminalia prunioides* trees among the six sites.

There was a significant difference in the height distribution patterns among the sites for *T. prunioides* trees ($\chi^2 = 40.44$, df = 25, $p < 0.05$). The differences were due to much lower expected frequency than observed at Outside Smelter Site for class <2.0 m, Abattoir Hill Site for class 3.0-3.9 m, Transnamib Site for class 2.0-3.9 m and Nomtsoub Site for class <2.0 m. Much higher expected frequencies than observed were recorded at Abattoir Hill Site for class <2.0 m and Nomtsoub Site for class 2.0-2.9 m.

4.4.3.3 All shrubs

Heights of shrubs ranged from <1 to 3.5 m at the Inside Smelter Site; from <1 to 3.5 m at the Outside Smelter Site; from <1 to 3 m at the Abattoir Hill Site; from <1 to 2.3 m at the Transnamib Site; from <1 to 2.5 m at the Nomtsoub Site and from <1 to 2 m at the Airport Site.

High proportions were recorded in the height class ≤1 m as well as in class 1.1-1.5 m (Fig. 16). However, low proportions were recorded in height class 2.6-3 m and in class >3.0 m.

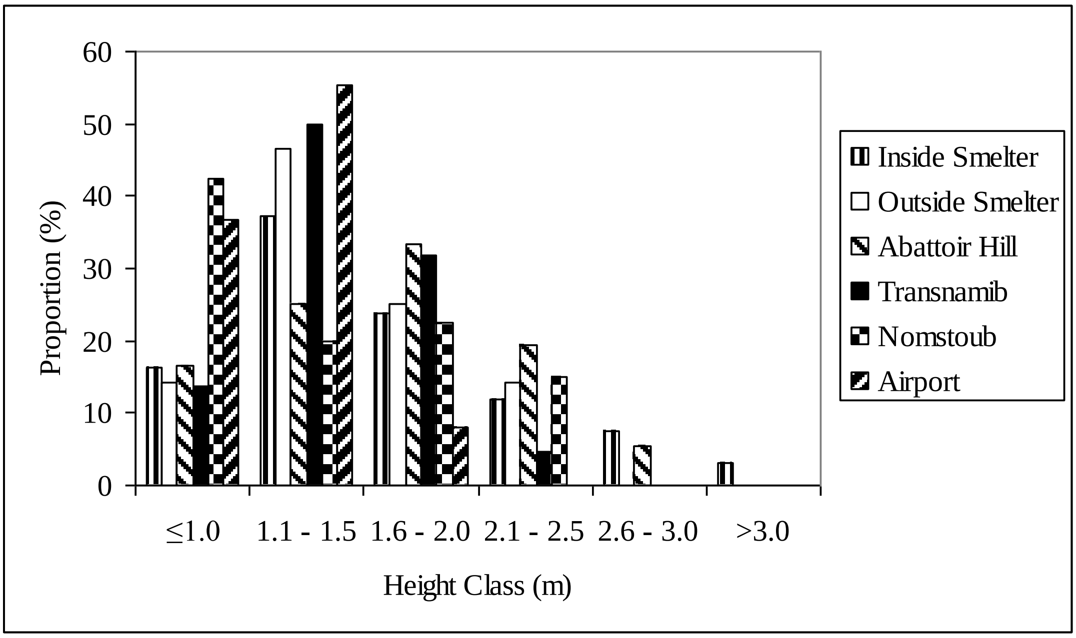

Figure 16. Comparison of height frequency distribution patterns of all shrubs among the six sites.

There was a significant difference in the height distribution patterns among the sites for shrubs ($\chi^2 = 50.42$, df = 25, $p < 0.01$). The difference was due to high expected frequency than observed at Nomtsoub Site for class 1.1-1.5 m and Airport Site for class 1.6-2.0 m. Low expected frequencies than observed were recorded at Abattoir Hill Site for class 2.1-2.5 m, Nomtsoub Site for class ≤1 m and Airport Site for class ≤1 m as well as class 1.1-1.5 m.

4.4.3.4 Selected shrub species

Dichrostachys cinerea

Heights of *D. cinerea* ranged from <1 to 3.5 m at the Inside Smelter Site; from <1 to 3.5 m at the Outside Smelter Site; from 1.5 to 2.0 m at the Abattoir Hill Site; from <1 to 2.0 m at the Transnamib Site; from 1 to 2.5 m at the Nomtsoub Site and from <1 to 1.7 m at the Airport Site. High proportions were recorded in the height class 1.1-1.5 m as well as in class 1.6-2.0 m. Low proportions were recorded in height class 2.6-3.0 m (Fig. 17).

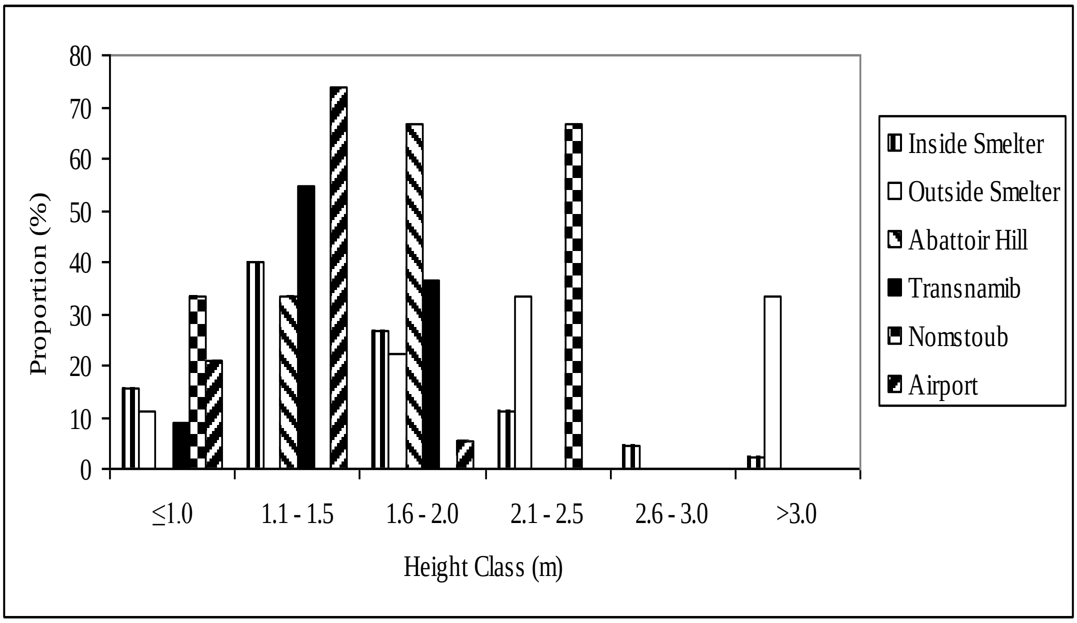

Figure 17. Comparison of height distribution patterns of *Dichrostachys cinerea* shrubs among the six sites.

There was a significant difference in the height distribution patterns among the sites for *D. cinerea* ($\chi^2 = 55.39$, df = 25, $p < 0.001$). The difference was due to high expected frequencies than observed at Outside Smelter Site for class 1.1-1.5 m. Lower expected frequencies than observed were recorded at Outside Smelter Site for class 2.1-2.5 m and class >3.0 m, Nomtsoub Site for class 2.1-2.5 m and Airport Site for class 1.1-1.5 m.

4.4.4 Vegetation cover

The Kruskal-Wallis test indicated a significant difference in woody cover (H = 23.39, df = 5, p < 0.001) and grass cover (H = 31.99, df = 5, p < 0.001) among the sites. The lowest mean woody cover was 20% which was recorded at the Airport Site while the highest mean woody cover was 60% which was recorded at the Nomstoub Site (Fig. 18). The lowest mean grass cover was 21% which was recorded at the Transnamib Site while the highest mean grass cover was 81.5% which was recorded at the Airport Site.

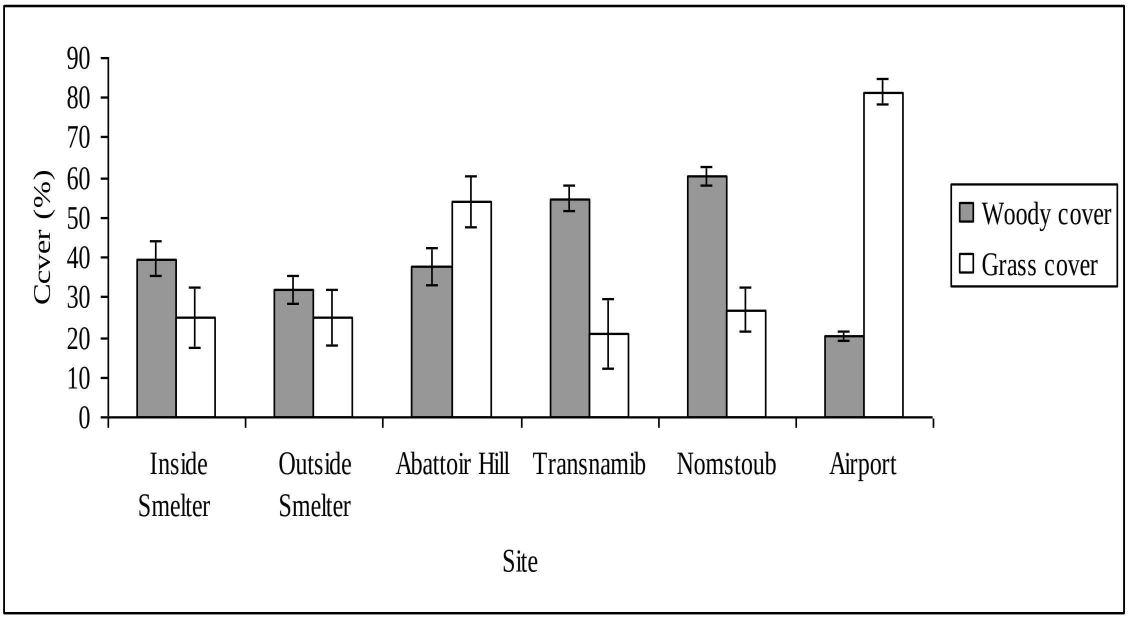

Figure 18. Variation in mean woody cover and mean grass cover at six sites with standard error bars.

The Mann-Whitney U test indicated that woody cover at the Airport Site was significantly lower than at the Inside Smelter Site (p < 0.01), Outside Smelter (p < 0.05), Abattoir Hill Site, Transnamib Site and Nomtsoub Site (p < 0.01). The woody cover at the Transnamib Site was significantly higher than at the Inside Smelter Site (p < 0.01), Outside Smelter Site (p < 0.01) and Abattoir Hill Site (p < 0.05). The woody cover at the Nomtsoub Site was significantly higher than at the Inside Smelter Site ($p < 0.05$), Outside Smelter site ($p < 0.01$) and Abattoir Hill Site ($p < 0.01$).

The Mann-Whitney U test indicated that there was no significant difference in woody cover between Inside Smelter Site, Outside Smelter Site and Abattoir Hill Site. The woody cover at Nomstoub Site was not significantly different from the woody cover at the Transnamib Site ($p > 0.05$).

The Mann-Whitney U test indicated that grass cover was significantly higher at the Airport Site than at the Inside Smelter Site, Outside Smelter Site ($p < 0.001$), Abattoir Hill Site ($p < 0.01$), Transnamib Site and Nomtsoub Site ($p < 0.001$). The grass cover at the Abattoir Hill Site was significantly higher than at the Inside Smelter Site, Outside Smelter Site, Transnamib Site ($p < 0.05$) and Nomtsoub Site ($p < 0.01$). There was no significant difference in grass cover among Inside Smelter Site, Outside Smelter Site, Transnamib Site and Nomtsoub Site ($p > 0.05$).

4.5 Determinants of vegetation structure and composition

4.5.1 Species composition

Hierarchical Cluster Analysis (HCA) separated the vegetation into five floristic associations based on variations in the woody and shrub species composition. *Combretum apiculatum, Dichrostachys cinerea* and *Terminalia prunioides* were the most common species. The five associations are described below:

Cluster 1. The vegetation that was common in this cluster was generally *D. cinerea, T. prunioides* as well as *Combretum* spp. This open-shrubland was found on shallow sand consisting mainly of *D. cinerea* shrubs of up to 3 m and it occurs mainly at the Airport Site as well as at some plots within the Inside Smelter Site and Outside Smelter Site. This plots were clustered together because of the presence of *Commiphora angolensis* and *Helinus integrifolius* .

Cluster 2. This shrubland was confined mainly to the Inside Smelter Site and it differed from Cluster 1 because of the presence of *Diospyrous lycioides* and *Leucaena leucocephala* trees. The vegetation composition of this cluster was dominated by *D. cinerea, C. apiculatum* and *T. prunioides*. Soils were deep red sand with sparse to bare grass cover.

Cluster 3. This woodland was confined mainly to Abattoir Hill Site as well as some plots within the Transnamib Site and Nomstoub Site. This cluster differed from cluster 1 and 2 because of the presence of *Acacia erioloba* and *Acacia tortilis* trees.

Cluster 4. This shrubland was confined to some plots within the Nomstoub Site. Common shrubs included *Grewia* spp. and *Boscia albitrunca*. These plots were clustered together because of the presence of both *Grewia flavescens* and *Terminalia prunioides* trees in all the plots.

Cluster 5. This woodland was confined to only one plot within the Transnamib Site. Geology was dolomite rocky. This cluster was different from other clusters because it was the only plot with the presence of both *Diospyros lycioides* and *Ximenia caffra* trees.

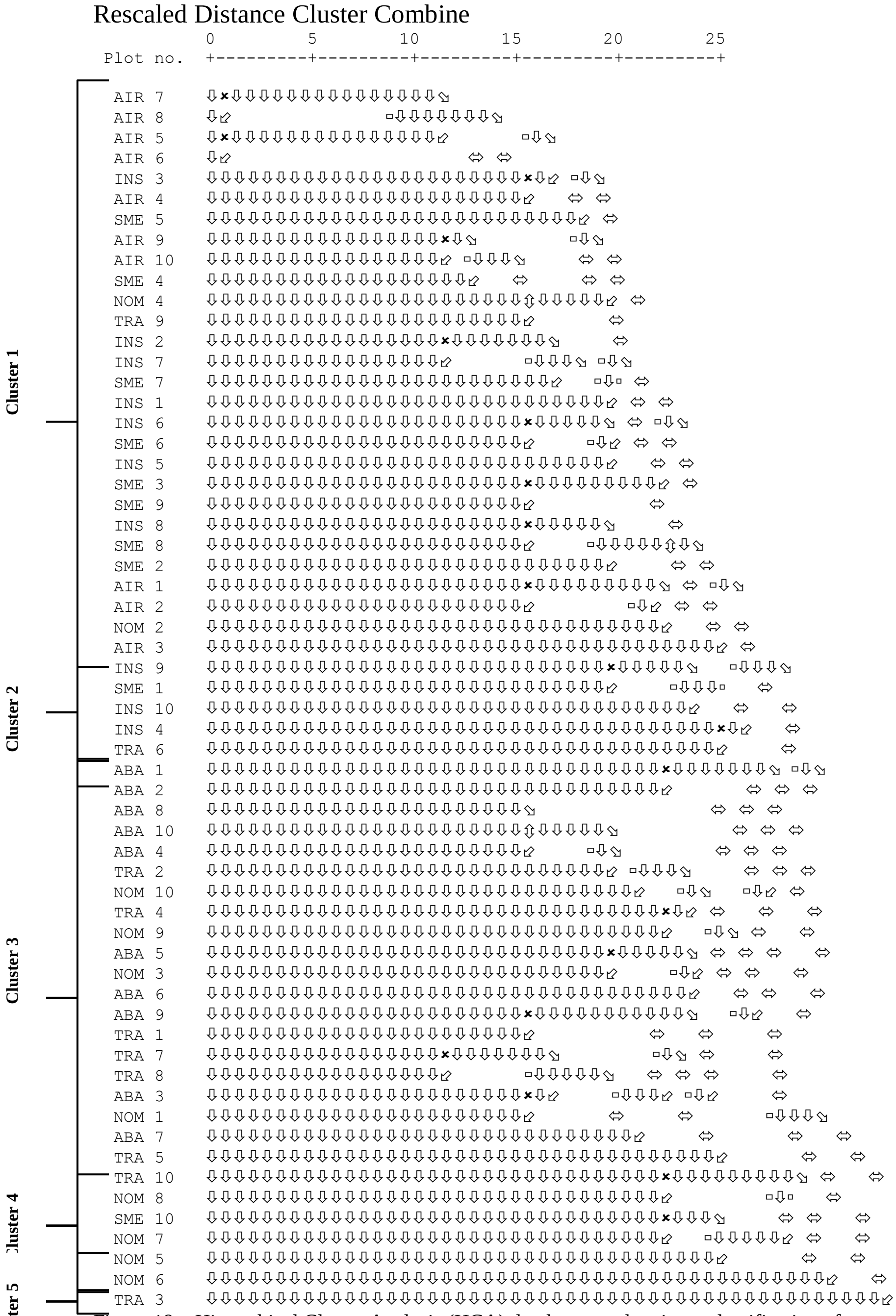

Figure 19. Hierarchical Cluster Analysis (HCA) dendrogram showing a classification of vegetation plots into five clusters based on species presence/absence data. Abattoir Hill Site - ABA, Airport Site - AIR, Inside Smelter Site – INS, Nomstoub Site - NOM, Oustside Smelter Site - SME, Transnamib Site - TRA.

4.5.2 Vegetation-environmental relationships

4.5.2.1 Indirect ordination

The Detrended Correspondence Analysis (DCA) separated the plots into three groups; Groups 1, 2 and 3. Group 1 was associated with plots from the Airport Site which had no pollution but it was mostly disturbed through cutting down of trees.

Group 2 was associated with the plots at the Inside Smelter Site and Outside Smelter Site, which were mostly affected by smelter waste pollution. Group 3 was associated with the plots less affected by pollution but were on a more hilly landscape.

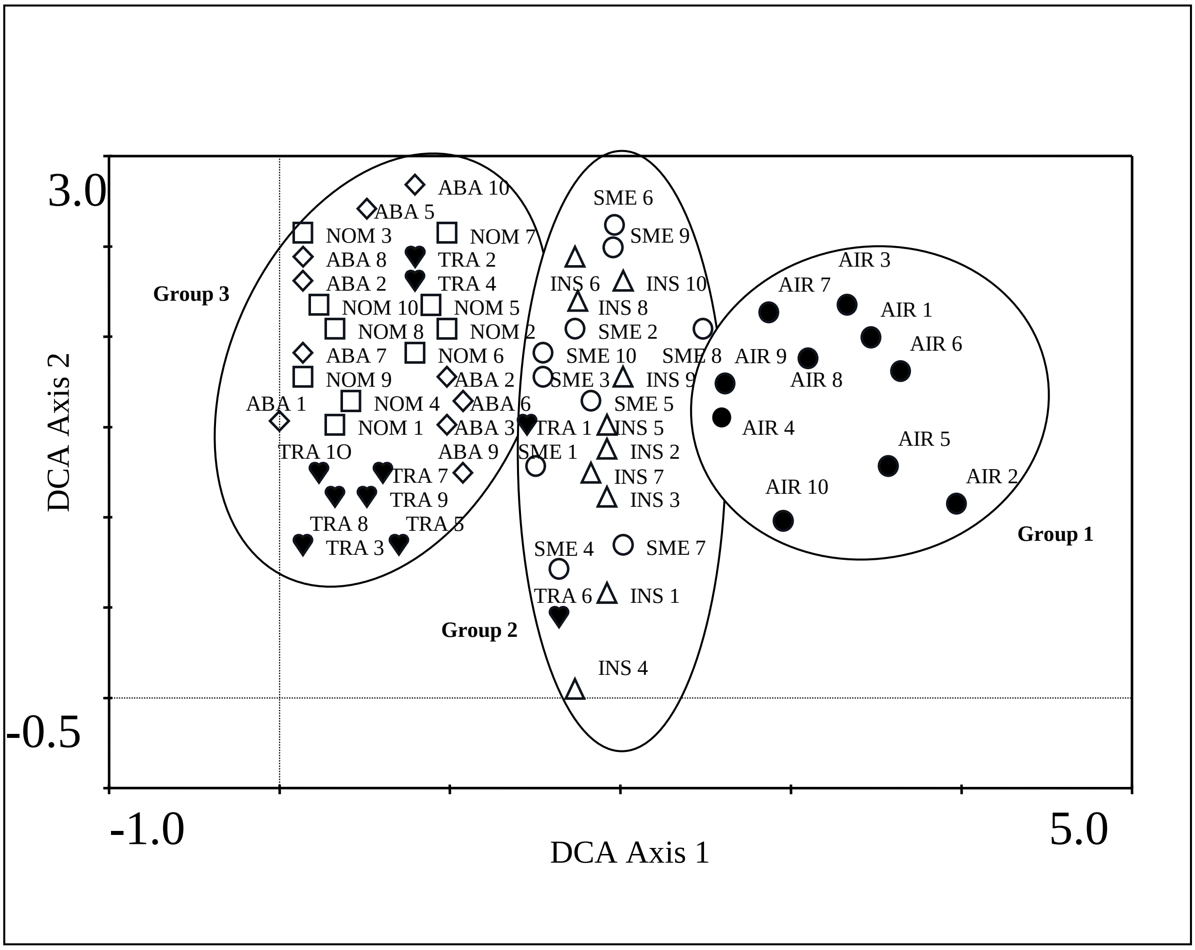

Figure 20. DCA ordination diagram showing the separation of vegetation plots into three groups. Abattoir Hill Site - ◇, Airport Site - ●, Inside Smelter Site - △, Nomstoub Site - □, Outside Smelter Site - ○, Transnamib Site - ♥.

There is evidence of a relatively complex interaction of gradients which may have influenced the pattern. There seems to be no single dominant influence of a specific gradient along either of the DCA axes. The relative importance of each gradient seems to vary along the axes. The variation in species data accounted for along axis 1 was 52.4 %. Axes 2, 3, and 4 accounted for 29.8 %, 22.1 % and 16.1 % of the variation respectively. There is about 100 % species turn-over from the left–most (ABA 1) plot in Group 3 to the right-most (AIR 2) plot in Group 1.

4.5.2.2 Canonical ordination

The explanatory variables which significantly affected species composition were geology ($F = 3.71$, $p < 0.05$), disturbance ($F = 1.52$, $p < 0.05$) and lead concentration in the soil ($F = 1.89$, $p < 0.05$). The influences of arsenic and cadmium on species composition were insignificant. At the 5% level, three of the environmental variables (geology, disturbance and lead) were significantly related to species data. The overall test for all canonical axes was also significant ($F = 1.71$, $p < 0.05$).

The positioning of the environmental variables in Fig. 21 shows that the explainable variation in species composition along axis 1 was positively correlated with geology and disturbance and negatively correlated with heavy metals contamination. The second axis was positively correlated with heavy metal contamination and negatively correlated with geology and disturbance.

Direction and influences of environmental factors clearly indicate that heavy metals influenced species composition in the direction of Inside Smelter Site and Outside Smelter Site (with great influence on plots 1, 5, 7, 8, 4, 9 and 18) while heavy metals slightly influenced species composition at the Abattoir Hill Site. A gradation in vegetation condition mediated by heavy metal is apparent with the direction in lead, arsenic, cadmium increasing from the right to left along axis 1 on the CCA ordination diagram.

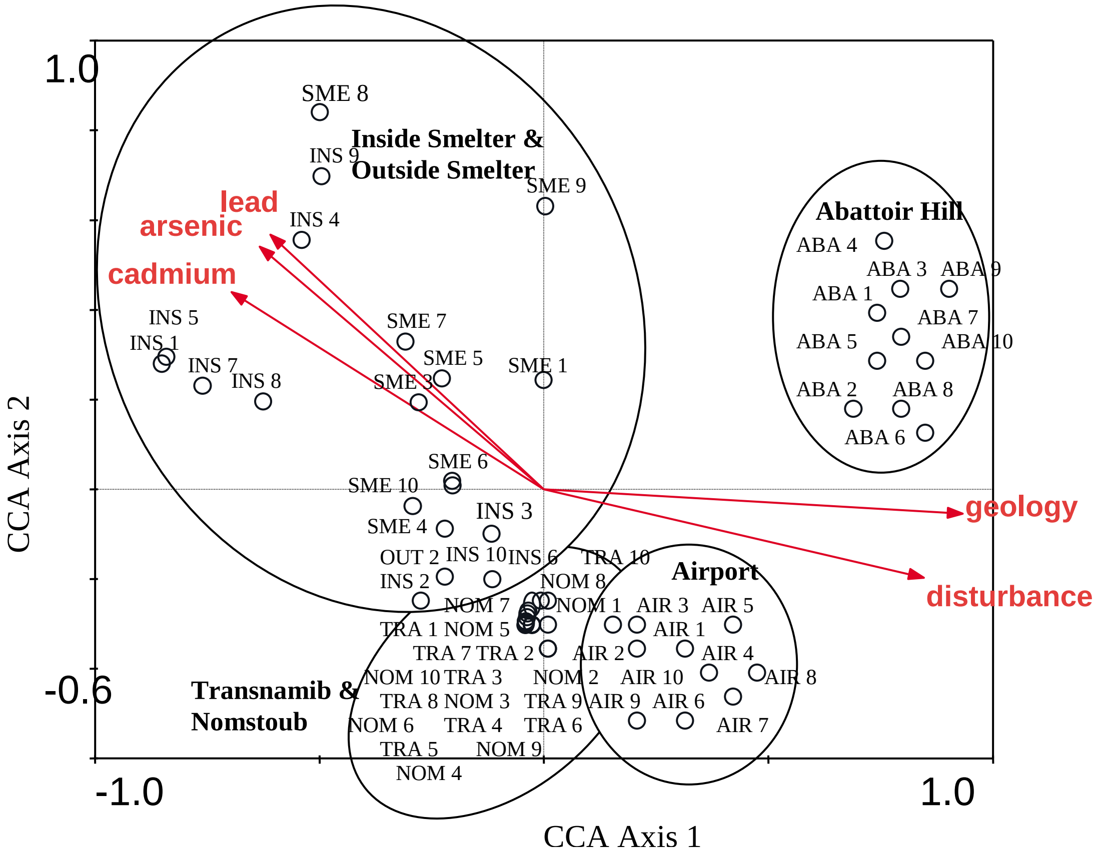

Figure 21. CCA ordination diagram indicating the influence of heavy metals, disturbance and geology on the species abundance of the six study sites. Abattoir Hill Site - ABA, Airport Site - AIR, Inside Smelter Site – INS, Nomstoub Site - NOM, Oustside Smelter Site - SME, Transnamib Site - TRA.

Directions and influences of geology and disturbance clearly indicated the geological influence on species composition was much more important at the Abattoir Hill Site and Airport Site. The species composition at the Nomtsoub Site and Transnamib Site was slightly influenced by disturbances and geology.

CHAPTER 5

DISCUSSION

5.1 Variations in concentrations of heavy metals in the soil

There were significant differences in concentrations of cadmium, lead and arsenic amongst the sites. High heavy metal concentrations were recorded at the Inside Smelter Site and Outside Smelter Site. This was due to the proximity of these sites to the source of pollution, the smelter complex. The Tsumeb Smelter Complex is characterised by industrial particulate emission. Geo-Consult (1996) and Kříbek *et al.* (2005) found that the solid emissions from the copper smelter contained high amounts of toxic metals such as arsenic and lead.

Heavy metal contamination at the Abattoir Hill Site was because this site was located north-west of the smelter complex and according to Kříbek *et al.* (2005) highest heavy metal concentrations were found in the surface soil of the Tsumeb Smelter Complex and downwind, northwest of the smelter complex. The prevailing north-westerly winds carry the smelter emissions directly towards the Abattoir Hill Site, resulting in higher concentrations of sulphur dioxide in the air and heavy metals at ground level. Areas mostly affected by heavy metal pollution are those close to the smelter and in the prevailing wind directions which is north-west.

The heavy metal concentration at the Transnamib Site and Nomtsoub Site was low because these sites were far from the source of pollution. Concentration of heavy metals decreases exponentially with increasing distance from the mine (Jung, 2001; Jordan, 1975). Due to the increasing distance from the smelter and favourable morphology in form of the Tsumeb Hills between the smelter and Airport Site, heavy metal contamination at this site was much lower.

Contents of lead in the surface soils from smelter complex decreased by almost six times at the Abattoir Hill Site and by sixteen times towards the Transnamib Site and Nomstoub Site. Arsenic concentrations in the surface soils decreased by twelve times at the Abattoir Hill Site and by forty times towards the Transnamib Site and Nomstoub Site. The intensity of the impact decreases by varying degrees specific to a given element compound as the distance from the smelter increases (Geo-Consult, 1996).

It was hypothesised (hypothesis a, page 6) that heavy metal contamination will be higher in the soil taken from sites close to the smelter than at sites further away from the smelter. This hypothesises was accepted as the heavy metal contamination was high at the sites close to or within the smelter complex.

With respect to WHO guideline values (Mapani, 2006), the mean arsenic and lead concentrations were above the probable effect limit at the five sites except the Airport Site. The mean cadmium concentrations at the Inside Smelter Site and Outside Smelter Site were more than probable effect values. Guideline values are designed to provide generic guidance on the significance of contaminant concentration in soils. However, the Namibian Government does not have environmental policies with guideline values to asses the contamination of soils. WHO guidelines are applicable to human health, but because Namibia does not have any guidelines for the environment these WHO probable effect values were applied to the general environment. Guideline values are useful as they provide an indication whether the pollution is intensive enough to require an intervention from both the mine management and the government. Guideline values provide an assessment on the impact of pollution on human health. Nonetheless, heavy metal pollution from the smelter should be a cause for concern in the areas within and immediately around the smelter complex.

5.2 Differences in species composition, richness and diversity

There were significant differences amongst the six sites in terms of Shannon-Wiener index of diversity, species composition and richness. The species diversity and richness were lower at the Airport Site than at the Inside Smelter Site, Outside Smelter Site, Transnamib Site and Nomstoub Site. The Airport Site was far from the smelter complex and there was little or no heavy metal contamination (Table 1).

However, the Airport Site was very close to the residential area. The Tsumeb Municipality cuts down the trees around Airport Site to keep the area clean. The low species diversity can be expected because the number of individuals per plot was low (a total of 54 individuals per site) at the Airport Site compared to other sites such as Inside Smelter Site where the number of individuals was 146 per site. Furthermore, the species composition within the Airport Site was similar as all the plots were grouped into one cluster. *Dichrostachys cinerea*, *Combretum apiculatum* and *Terminalia prunioides* trees dominated this site. A high abundance of grass species including *Enneapogon cenchroides* and *Brachiaria marlothii* were found at the

Airport Site. The low abundance and unevenness at the Airport Site is the cause of low species diversity.

According to Molles (1999) high species diversity occurs where there is a combination of more different species and where the numbers of individuals in the total population are more equitable distributed among the species. The difference in Shannon-Wiener diversity (H') for communities reflects the differences in species evenness and abundance (Molles, 1999).

The species diversity and richness at the Abattoir Hill Site were significantly lower than the species diversity and richness at the Transnamib Site. The Abattoir Hill Site had a high abundance of species (a total of 113 individuals per site) and there were on average five different species. The hierarchical cluster analysis (HCA) classified the Abattoir Hill Site into a woodland (Cluster 3) with *T. prunioides* and *C. apiculatum* as the common tree species and also because of the presence of *Acacia tortilis* and *Acacia erioloba*. However, the species were not equitably distributed because *T. prunioides* was the most abundant species and that led to low evenness of species.

This is in agreement with Molles (1999) who stated that if two communities contain the same number of different species, the one with low evenness would be less diverse than the one with high evenness. The high abundance of *T. prunioides* was due to bush encroachment. The Abattoir Hill Site was subjected to wood cutting (*pers. obs.*). De Klerk (2004) indicated that it is important to realise that bush clearing forces invader bushes or their substitutes to re-establish. The clearing of bush at the Abattoir Hill Site led to the high abundance of *T. prunioides*, which according to De Klerk (2004) is an encroacher species in the Karstveld area. Diversity, according to Hill (1973), is of theoretical interest because it can be related to stability, maturity, productivity, evolutionary time, predation pressure and spatial heterogeneity. Diversity is of vital importance for conservation of natural communities, which are increasingly threatened by industrial processes and forest clearing (Naveh & Whittaker, 1979 in El-Ghani, 1998).

The species diversity and richness was not significantly different amongst the Transnamib Site, Nomstoub Site, Inside Smelter Site and Outside Smelter Site. Species richness and diversity can be similar but the species may be different, which leads to differences in species composition. The species composition was different amongst these sites as the HCA classified these sites into different clusters. The cluster analysis classified the species recorded at Inside Smelter Site and the Outside Smelter Site into either cluster 1 or cluster 2; both clusters were dominated by *D. cinerea, T. prunioides* as well as *Combretum* spp.

The species composition at the Transnamib Site was not different from the other five sites as it was scattered amongst the entire five clusters. The Transnamib Site comprised almost all the tree and shrub species with the exception of a few. The species at Nomstoub Site was classified into cluster 1, 3 and 4. The classification of species into different clusters indicates greater differences in species composition amongst the sites. There was no significant difference in species diversity but the species composition was different. Differences in species composition can be attributed to disturbances such as wood clearing and pollution.

Lykke (1998) found changes in species composition and attributed it to fire and disturbances. Pollutant concentrations can be high enough to result in subtle changes in plant physiology, growth and community composition (Barnes *et al*., 1999). Plants absorb heavy metals in many ways; by extracting contaminated soil water, by respiration with contaminated air or by absorbing particulate pollutants on the waxy surfaces of leaves (Aucamp, 2003). Contaminants may undergo transformation through biological, chemical or physical means en route to the receptor, which may affect toxicity, availability and mobility (Aucamp, 2003).

Different species of plants absorb different amounts of heavy metal (Howard-Williams, 1971 in Hamunyela, 2006). Heavy metals may be toxic to some species and not to others. Some species may die off when heavy metal concentrations are high (Ernst, 1972 in Hamunyela, 2006). Some species that cannot tolerate high levels of heavy elements may die completely (Mapani, 2001). The species can disappear from a polluted area as they cannot tolerate the heavy metal in their tissues. A number of species are known to either posses or lack the genetic variability for tolerance to specific toxic chemicals (Dickinson *et al*., 1991). The plant species that grow in polluted environment are those that posses the variability to tolerate heavy metal toxicity. Nevertheless, there is a lack of knowledge of the precise quantitative limits of tolerance, the actual dosage level at which the chemical is toxic and the point beyond which no further adaptation can be achieved by a species (Dickinson *et al.*, 1991).

Plant species that survive in polluted environments have mechanisms that help them survive there. One mechanism may be the production of tolerant pollens (Lepp & Dickinson, 1986 in Dickinson *et al.*, 1991). Heavy metal toxicity varies with season. The timing at which a disturbance such as heavy metal pollution occurs is a crucial determinant of which species will regenerate (Fenner & Kitajima, 1999). When the toxicity is low, some seeds may germinate and grow. Dickinson *et al*. (1991) believe that the adaptation of individual mature plants may be the most significant factor, which determines the ability to survive pollution.

This study investigated the impact of smelter waste on species diversity and thus, it was hypothesised (hypothesis b, page 7) that plant species diversity and richness would be lower closest to the smelter compared to areas further away due to higher pollution in the smelter area. However, it seemed as if pollution has not adversely affected species diversity and richness and hence, the hypothesis is not accepted. It was also hypothesised (hypothesis c, page 7) that species composition would be different amongst the sites. However, this hypothesis will be accepted as there were differences in species composition amongst the sites.

5.3 Differences in vegetation structure

There was a significant difference in tree densities amongst the sites. However, there were no significant differences in shrub densities amongst the sites. The total basal area, woody cover and grass cover were significantly different amongst the sites. There were significant differences in the basal area distribution patterns among the sites. The height distribution patterns were also significantly different amongst the sites.

The tree density at the Inside Smelter Site was significantly lower than at the Outside Smelter Site, Nomtsoub Site and Transnamib Site. The Inside Smelter Site and Outside Smelter Site were highly contaminated by heavy metals. One would expect the tree density not to be significantly different as these sites were close to each other. However, this was not the case. The low tree density at the Inside Smelter Site can be attributed to heavy metal pollution at this site. Heavy metal pollution can influence the development of plants leading to poor recruitment of plants. From her study, Jordan (1975) observed that solution concentration of up to 100 ppm zinc and 10 ppm cadmium did not affect seed germination of oak tree (*Quercus rubra*) but at these metal concentration the radicle fails to elongate. Jordan (1975) observed that zinc or cadmium stunts seedling growth, which may prevent successful seedling establishment in the field.

The mean cadmium concentration at the Inside Smelter Site was 88 ppm. Jordan (1975) indicated that the minimum toxic solution of cadmium concentration for *Quercus rubra* appears to be >1 ppm. Other studies indicated 5.6 ppm cadmium is sand stunted the growth to corn and another found considerable variability in the response of vegetable crops to cadmium with minimum toxic levels in solution varying between 0.2 and 1.0 ppm. The cadmium concentrations at the Inside Smelter

Site are high enough to cause toxicity to the plants developing at the smelter. Different species of plants absorb different amounts of heavy metals (Howard-Williams, 1971 in Hamunyela, 2006) and toxicity of metals differs from one species to the other (Hamunyela, 2006). According to Harper (1977), seedlings will not survive in the presence of toxins such as heavy metals. The few small trees indicate that the plants that manage to establish do not reach maturity, probably because of the effect of heavy metals on plant development.

The difference in basal area distribution pattern at Inside Smelter Site was due to high proportions of trees in the class ≥221 cm^2. The high proportions can be attributed to high abundance of *S. birrea* subsp. *caffra.* The trees at the Inside Smelter Site comprised very few short trees (>2 m), many tall trees (≥5 m). The shrub layer comprised many shrubs with a height between 1.1-1.5

The vertical structure at the Inside Smelter Site was sparsely spaced vegetation with many tall trees with big canopies and huge stems, few short trees and few shrubs as well as a poorly developed grass cover. The big trees may be older than the smelter. Therefore, their germination, establishment and recruitment were not affected since there was no pollution source. Their roots have grown deep enough not to be affected. Only the plants which established after the mine and smelter have suffered the brunt of pollution.

The low grass cover at the polluted Inside Smelter Sites and Outside Smelter Sites were due to high contaminations of heavy metals. The top soil layer was contaminated by heavy metals, which make the grasses more vulnerable to pollution Grasses have a shallow root system, according to De Klerk (2004), the roots of the grasses only occur in the top soil layer. According to Ernst (1972) in Hamunyela (2006), grass species are known to survive better in the mine dumps-polluted area because of their adventitious roots. This was not the case in this study. Pollution have affected the growth of grasses at the polluted sites. This is in agreement with Taylor & Fox (2001) who confirmed that pollution can result in significant changes to canopy cover, understorey vegetation density and ground cover. Hsu *et al.* (2006) observed high concentrations of cadmium in plant species and they revealed the strong influence of industrial pollution to the vegetation, especially the grasses.

The tree density, woody cover as well as the total basal area at the Airport Site were significantly lower than at the other sites. The grass cover at the Airport Site was significantly higher than at the other five sites. The low tree density, woody cover and total basal area at the Airport Site can be expected as the area had few trees as compared to the other sites. The few trees found at the Airport Site contributed to high proportion of trees in the basal area class **≥**221 cm^2 and to high proportion in the height class ≥5 m. The clearing of trees by the municipality seems to have affected the vegetation structure at the Airport Site as this site was far from the source of pollution.

The Airport Site had a well-developed grass layer and sparsely distributed shrubs and trees. The high grass cover at the Airport Site can be attributed to the lower density of trees. According to De Klerk (2004**),** Walter proposed the theory of bush-grass competition in 1971. The theory states that grasses are superior competitors for water in the upper soil layer so that the trees compete successfully by virtue of their exclusive use of subsoil water (De Klerk, 2004). De Klerk (2004) further stated that the effect of clearing tree species shows substantial increases in grass productivity with complete or nearly complete removal of trees. Woody plant density was found to be reduced by woodcutting around settlements (Campbell & Du Toit, 1994 in Sekwela, 2003).

The woody cover at Transnamib Site and Nomtsoub Site was significantly higher than at the Inside Smelter Site, Outside Smelter Site and Airport Site. This would be expected because there was neither cutting nor poisoning at the Transnamib Site and Nomtsoub Site. The Transnamib Site and Nomstoub Site were characterised by a well defined tree layer with a few short trees and a few tall trees – most of the trees were between heights of 2.0 to 3.9 m. The shrub layer was also well defined.

The basal area distribution of the trees (Fig. 9) from the Transnamib Site and Nomtsoub Site did not followed the inverse J-shape as such – which, according to Dembélé *et al.* (2006) is characterised by a steeper basal area distribution, with more small trees and less large trees. However, high proportions of trees from both sites were from the first basal area classes (17-50.99 cm^2 and 51-84.99 cm^2) which specify that there were more small trees and few big trees. Very few young individuals make it unlikely that species populations can be maintained at the present level because, for a population to remain relatively constant, more individuals are required in the smaller classes than in the larger ones (Lykke, 1998).

The Transnamib Site and Nomstoub Site were less affected by pollution because the smelter is far from these sites. The morphology of the area is dominated by the Tsumeb hills made up of gentle slopes (Ministry of Mines and Energy, 2006b). The Transnamib Site and Nomtsoub Site were located on steeper rocky parts where carbonate bedrocks are exposed. Mendelsohn *et al.* (2002b) believes that there is a diverse assemblage of plants Karstveld Area because of the variety of topography and soils in the landscape.

The tree density and woody cover at the Abattoir Hill Site were significantly lower than at the Outside Smelter Site, Transnamib Site and Nomtsoub Site. The significantly low tree density and woody cover were due to wood cutting in that area (*pers. obs.*). Tree felling reduces the density of mature canopy trees and alters their dominance structure (Mapaure, 2001). The grass cover was significantly higher than at the Inside Smelter Site, Outside Smelter Site, Transnamib Site and Nomtsoub Site. The height distribution follows an inverse-J shape. The tree layer was characterised by few short trees, a few tall trees and most of the tree were between 2.0 to 3.9 m. Most of the shrubs were between 1.6 m and 2.0 m long.

The low densities in some places reflect the impact of harvesting which decreases the actual tree abundance (Kgathi *et al.*, 1994 in Sekwela, 2003). Nichol (1989) in Sekwale (2003) observed an increase in woody species density following previous depletion due to fuelwood exploitation and prolonged droughts. There were twice as many stems as trees, implying that most trees were coppicing, which is a sign of disturbance. The high grass cover can be attributed to tree clearing which according to De Klerk (2004) increases grass productivity.

It was hypothesised (hypothesis d, page 7) that plant density would differ significantly among the sites, with low densities expected at polluted sites and high densities expected at less polluted sites. There was no significant difference in shrub density and in stem density amongst the sites but the tree density was significantly different amongst the sites. The tree density at the Inside Smelter – the most polluted site – was significantly low. It was also hypothesised (hypothesis e, page 7) that vegetation structural attributes (height, basal area, canopy cover) of individual plants would vary significantly among the sites, with higher values expected in less polluted sites.

5.4 Determinants of vegetation structure and composition

Much of the variation in vegetation was explained along the first DCA ordination axis. This variation can be attributed to a complexity of interaction of gradients which influenced the pattern of species composition. The influence of a pollution separated group 2 from group 1 and group 2 from group 3; as group 2 was associated with plots from the polluted sites while group 1 and group 3 were associated with plots from the non-polluted site. Disturbance separated group 1 from the others as group 1 had plots from the Airport Site, which was influenced by wood clearing.

DCA axis 1 also showed an indication of species composition being influenced by the different landscapes as the group 3 was associated with a hilly landscape while groups 2 and 1 were on a more flat landscape. The separation between two extreme plots along the first axis was 4 SD units, indicating that there was no sharing of species between the two. A 100 % species turnover would occur at a minimum distance of 4 SD units (Gauch 1982). The ABA 1 plot - to the extreme left of the DCA axis 1 - consisted of *Acacia erioloba, Commiphora mollis, Terminalia prunioides* and *Ximenia caffra*. The AIR 2 plot - to the extreme right of the DCA axis 1 – consisted of *Aloe littoralis, Combretum apiculatum, Dichrostachys cinerea* and *Helinus integrifolius.* This is an indication of changes in vegetation composition along DCA axis 1.

The CCA indicated a clear influence of disturbance (wood cutting), heavy metal pollution and geology on vegetation composition and structure (Fig. 21). The geology and disturbance were the most important environmental variable that influenced the species composition along the CCA axis 1. The geology at the Abattoir Hill Site was massive light dolomite and that significantly influenced the species composition at that site, heavy metal pollution exerted less relative influence on the species composition at this site. Aplet *et al.* (1998) in Rüdiger *et al.* (2001) reported that the age of the substrate, percolation and evaporation rate of the substrate can strongly influence species composition.

The species composition at Inside Smelter Site and Outside Smelter Site was significantly influenced by heavy metal pollution especially by lead. Heavy metal pollution has been reported to alter communities as plant species that cannot tolerate high levels of heavy metal toxicity die off (Ernst, 1972 in Hamunyela, 2006). The plant species that grow in polluted areas are those that possess the variability to tolerate heavy metals.

With little or no pollution at the Airport Site, the species composition at this site was greatly influenced by disturbance (wood clearing) as well as geology. Clearing of trees, for example, can create new niches where shade-loving species disappear and light loving species come in thus changing the species composition. Lykke (1998) observed changes in species composition and attributed it to disturbances such as wood clearing. The species composition at the Nomstoub Site and Transnamib Site was slightly influenced by geology and disturbance. Wood clearing was not as severe at these sites. Heavy metal contamination was also too low at the Transnamib Site and Nomtsoub Site. It is clear that there were non-measured variables that influenced the species composition at the Transnamib Site and Nomstoub Site.

Variations in the vegetation depicted in fig. 19-21 were not due to disturbance, geology and pollution alone. The measured variables explained some but not all the variation in species composition. There is an indication that other non-measured factors such as topography and soil conditions may be important in determining the variation in species composition.

It was also hypothesised (hypothesis c, page 7) that species composition would be different amongst the sites. However, this hypothesis will be accepted as there were differences in species composition amongst the sites.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The analyses show varying but generally high contaminations of arsenic, cadmium and lead exceeding by far international standards for soils in study area. Sources of the contaminations are solid and gaseous emissions form the smelter and airborne particles from tailings dumps as well as the slag deposits. High heavy metal concentrations recorded at the Inside Smelter Site and Outside Smelter Site were due to the proximity of these sites to the source of pollution, the smelter complex.

There were differences in species diversity and richness amongst the sites. Low species diversity and richness at the Airport Site was attributed to tree clearing. Low species diversity and richness at the Abattoir Hill Site was due to a high abundance of the *Terminalia prunioides* species which is encroaching in that area. Differences in species composition were attributed to pollution and disturbance. Heavy metal contamination contributed to variation in species composition as plant species that grow at the polluted sites can tolerate pollution. Some plant species that were not found on the polluted sites have simply died out or cannot grow there as they do not have the mechanisms to survive in polluted environments.

The vegetation structure was significantly different amongst the sites. The shrub density was not significantly different amongst the sites. However, tree density was significantly different amongst the sites and this can be attributed to low tree density at the Inside Smelter Site. High woody cover at this site can be attributed to the presence of big trees that have very big canopies. The big trees may be older than the smelter. Therefore, their germination, establishment and recruitment were not affected since there was no pollution source. Heavy metal toxicity contributed to poor plant development, poor recruitment and as a result, there were very few small trees at the Inside Smelter Site. These big trees also contributed to the differences in basal area and height distribution patterns. Heavy metal pollution was found to have adverse effects on the grass cover. The tree density and woody cover were significantly low at the Airport Site and Abattoir Hill Site because of tree clearing. However, the grass cover was significantly higher and this can be attributed to the removal of trees as explained by the Walter's two-layer hypothesis.

The indirect gradient analysis indicated a rather complex interaction of gradients, which accounted for differences in species composition. The influence of a pollution gradient and disturbance gradient contributed to the differences in species composition among the sites. The direct gradient analysis indicated that geology and disturbance (wood cutting) influenced species composition especially at the Abattoir Hill Site and Airport Site. The species composition at Inside Smelter Site and Outside Smelter Site were significantly influenced by heavy metal pollution especially by lead. Geology and disturbance slightly influenced the species composition at the Transnamib Site and Nomtsoub Site. It can, therefore, be concluded that heavy metal pollution does have an influence on species composition and vegetation structure.

6.2 Recommendations

a. The mine should continue with their monitoring efforts as well as the implementation of their short and long term environmental management plan. Monitoring of vegetation, soil and fauna (especially the monitoring of invertebrates as they are good indicators of detecting changes in the environment) should be incorporated in the current environmental plan of the mine. This can be done by doing species inventories seasonally.

b. It is evident that the main source of soil contamination by heavy metals and sulphur is the dust fall-out from the Tsumeb Smelter. The smelter complex is recommended to implement measures such as fixing their baghouses, which will reduce dust fall-out.

c. The Republic of Namibia drafted the Environmental Management Bill as well as Pollution Control and Waste Management Bill and both bills await Cabinet approval. Both bills will give general principles for the management of the environment and natural resources as well as proper waste management. In the absence of these bills, the industries and mines are not enforced to control pollution. The Cabinet is kindly requested to expedite the passing of these bills into laws.

d. The current study did not focus on long-term influence of heavy metals, for example lead or copper, on various plant species found in the area. In order to understand long-term influence of such metals on specific plants, long-term vegetation monitoring is recommended. The outcome of such research would point to specific plants that tolerate low and high levels of metals. Those that can tolerate high levels may be used for mine rehabilitation, for example vegetating the tailing dams.

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APPENDICES

Appendix 1. The GPS readings of all the plots.

Inside Smelter Site

INS 01	S 19º 13' 16.1"	E 17º 43' 17.9"
INS 02	S 19º 13' 15.8"	E 17º 43' 17.7"
INS 03	S 19º 13' 15.5"	E 17º 43' 17.4"
INS 04	S 19º 13' 15.2"	E 17º 43' 17.1"
INS 05	S 19º 13' 10.2"	E 17º 43' 10.3"
INS 06	S 19º 13' 10.9"	E 17º 43' 10.7"
INS 07	S 19º 13' 11.5"	E 17º 43' 11.0"
INS 08	S 19º 13' 12.0"	E 17º 43' 10.2"
INS 09	S 19º 13' 11.7"	E 17º 43' 10.6"
INS 10	S 19º 13' 11.2"	E 17º 43' 10.3"

Outside Smelter Site

SME 01	S 19º 13' 07.4"	E 17º 43' 06.7"
SME 02	S 19º 13' 07.1"	E 17º 43' 06.0"
SME 03	S 19º 13' 06.5"	E 17º 43' 07.0"
SME 04	S 19º 13' 06.3"	E 17º 43' 06.7"
SME 05	S 19º 13' 05.8"	E 17º 43' 06.1"
SME 06	S 19º 13' 05.5"	E 17º 43' 06.2"
SME 07	S 19º 13' 05.2"	E 17º 43' 06.3"
SME 08	S 19º 13' 04.9"	E 17º 43' 06.3"
SME 09	S 19º 13' 04.6"	E 17º 43' 06.5"
SME 10	S 19º 13' 04.3"	E 17º 43' 06.0"

Abattoir Hill Site

ABA 1	S 19º 13' 09.8"	E 17º 42' 08.6"
ABA 2	S 19º 13' 09.6"	E 17º 42' 08.2"
ABA 3	S 19º 13' 09.6"	E 17º 42' 07.9"
ABA 4	S 19º 13' 09.5"	E 17º 42' 07.6"
ABA 5	S 19º 13' 09.9"	E 17º 42' 07.5"
ABA 6	S 19º 13' 10.1"	E 17º 42' 06.0"
ABA 7	S 19º 13' 09.9"	E 17º 42' 06.1"
ABA 8	S 19º 13' 09.8"	E 17º 42' 05.7"
ABA 9	S 19º 13' 09.7"	E 17º 42' 05.3"
ABA 10	S 19º 13' 09.5"	E 17º 42' 05.0"

Transnamib Site

TRA 1	S 19º 14' 16.2"	E 17º 41' 49.9"
TRA 2	S 19º 14' 16.1"	E 17º 41' 50.2"
TRA 3	S 19º 14' 15.6"	E 17º 41' 50.5"
TRA 4	S 19º 14' 15.5"	E 17º 41' 50.8"
TRA 5	S 19º 14' 15.4"	E 17º 41' 51.1"
TRA 6	S 19º 14' 15.5"	E 17º 41' 51.5"
TRA 7	S 19º 14' 15.4"	E 17º 41' 51.9"
TRA 8	S 19º 14' 15.6"	E 17º 41' 52.2"
TRA 9	S 19º 14' 15.3"	E 17º 41' 52.5"
TRA 10	S 19º 14' 15.3"	E 17º 41' 52.8"

Nomtsoub Site

NOM 1	S 19º 14' 28.2"	E 17º 41' 29.8"
NOM 2	S 19º 14' 28.6"	E 17º 41' 28.5"
NOM 3	S 19º 14' 28.7"	E 17º 41' 28.3"
NOM 4	S 19º 14' 28.8"	E 17º 41' 27.9"
NOM 5	S 19º 14' 28.8"	E 17º 41' 28.2"
NOM 6	S 19º 14' 28.9"	E 17º 41' 27.6"
NOM 7	S 19º 14' 28.8"	E 17º 41' 27.4"
NOM 8	S 19º 14' 28.6"	E 17º 41' 27.2"
NOM 9	S 19º 14' 29.1"	E 17º 41' 27.1"
NOM 10	S 19º 14' 29.4"	E 17º 41' 26.5"

Airport Site

AIR 1	S 19º 15' 25.7"	E 17º 43' 27.6"
AIR 2	S 19º 15' 25.6"	E 17º 43' 27.3"
AIR 3	S 19º 15' 25.5"	E 17º 43' 27.1"
AIR 4	S 19º 15' 25.3"	E 17º 43' 26.7"
AIR 5	S 19º 15' 25.4"	E 17º 43' 26.4"
AIR 6	S 19º 15' 25.2"	E 17º 43' 26.1"
AIR 7	S 19º 15' 25.1"	E 17º 43' 25.7"
AIR 8	S 19º 15' 25.0"	E 17º 43' 25.3"
AIR 9	S 19º 15' 24.8"	E 17º 43' 25.0"
AIR 10	S 19º 15' 24.6"	E 17º 43' 24.6"

Appendix 2. The list of recorded plant species in the study area**.**

Acacia erioloba E.Mey.

Acacia mellifera (Vahl.) Benth.

Acacia tortilis (Forssk.) Hayne.

Aloe littoralis Baker.

Aristida effuse Henrard.

Boscia albitrunca (Burch.) Gilg & Benedict.

Brachiaria marlothii (Hack.) Stent.

Catophractes alexandri D.Don.

Cenchrus ciliaris L.

Combretum apiculatum Sond.

Combretum hereroense Schinz

Combretum imberbe Wawra

Commiphora angolensis Engl.

Commiphora glandulosa Schinz

Commiphora mollis (Oliv.) Engl.

Croton gratissimus Burch.

Dichrostachys cinerea (L.) Wight & Arn.

Diospyros lycioides Desf.

Enneapogon cenchroides (Roem. & Schult.) C.E.Hubb.

Eragrostis lehmanniana Nees.

Eragrostis trichophora Coss. & Durieu

Euphorbia guerichiana Pax

Grewia bicolour Juss.

Grewia flava DC.

Grewia flavescens Juss.

Helinus integrifolius (Lam.) Kuntze

Leucaena leucocephala (Lam.) de Wit

Ozoroa paniculosa (Sond.) R.&A.Fern

Sclerocarya birrea subsp. *caffra* (A.Rich.) Hochst.

Terminalia prunioides M.A. Lawson

Terminalia sericea Burch. ex DC.

Urochloa brachyuran (Hack.) Stapf.

Ximenia caffra Sond.

Appendix 3. The species matrix based presence/absences of woody plants.

A: Inside Smelter Site

	PLOTS									
SPECIES	**INS 1**	**INS 2**	**INS 3**	**INS 4**	**INS 5**	**INS 6**	**INS 7**	**INS 8**	**INS 9**	**INS 10**
Acacia erioloba	0	0	0	0	0	0	0	0	0	0
Acacia mellifera	1	0	0	1	0	0	0	0	0	0
Acacia tortilis	0	0	0	0	0	0	0	0	0	0
Aloe littoralis	0	0	0	0	0	0	0	0	0	0
Boscia albitrunca	0	0	0	0	0	0	0	0	0	0
Catophractes alexandri	0	0	0	0	0	0	0	0	0	0
Combretum apiculatum	1	1	0	0	1	1	1	1	0	1
Combretum hereroense	0	0	0	0	0	0	0	1	1	0
Combretum imberbe	1	1	1	1	0	0	1	0	1	0
Commiphora angolensis	0	0	0	0	0	0	0	0	0	0
Commiphora glandulosa	0	0	0	0	1	0	0	0	1	1
Commiphora mollis	0	0	0	0	0	0	0	0	0	0
Croton gratissimus	0	0	0	0	0	0	0	0	0	0
Dichrostachys cinerea	1	1	1	1	1	1	1	1	1	1
Diospyros lycioides	0	0	0	0	0	0	0	0	0	0
Euphorbia guerichiana	0	0	0	0	0	0	0	0	0	0
Grewia bicolor	0	0	0	0	0	0	0	0	0	0
Grewia flava	0	0	0	0	0	0	0	0	1	1
Grewia flavescens	0	0	0	0	0	0	0	0	0	0
Leucaena leucocephala	0	0	0	1	0	0	0	0	0	0
Ozoroa paniculosa	1	0	0	0	1	1	0	1	1	0
Sclerocarya birrea subsp. *caffra*	0	1	0	0	1	1	0	1	1	1
Terminalia prunioides	1	1	0	1	0	1	1	1	1	1
Terminalia sericea	0	0	0	0	0	0	0	1	0	1
Ximenia caffra	0	0	0	0	0	0	0	0	0	0

B: Outside Smelter Site

	PLOTS									
SPECIES	**SME 1**	**SME 2**	**SME 3**	**SME 4**	**SME 5**	**SME 6**	**SME 7**	**SME 8**	**SME 9**	**SME 10**
Acacia erioloba	0	0	0	0	0	0	0	0	0	0
Acacia mellifera	0	0	0	0	0	0	0	0	0	0
Acacia tortilis	0	0	0	0	0	0	0	0	0	0
Aloe littoralis	0	0	0	0	0	0	0	0	0	0
Boscia albitrunca	0	0	0	1	0	0	1	0	0	1
Catophractes alexandri	0	0	1	0	0	0	0	0	1	0
Combretum apiculatum	0	1	1	1	0	1	1	1	1	1
Combretum hereroense	0	1	1	0	1	0	1	1	1	0
Combretum imberbe	1	0	0	0	0	0	1	1	0	1
Commiphora angolensis	0	0	0	0	0	1	0	0	0	0
Commiphora glandulosa	1	0	1	0	0	0	0	0	0	0
Commiphora mollis	0	0	0	0	0	0	0	0	0	0
Croton gratissimus	0	0	0	0	0	0	0	0	0	0
Dichrostachys cinerea	1	0	1	1	1	1	1	1	1	0
Diospyros lycioides	0	0	0	0	0	0	0	0	0	0
Euphorbia guerichiana	0	0	0	0	0	0	0	0	0	0
Grewia bicolor	0	0	0	0	0	0	0	0	0	0
Grewia flava	1	0	0	0	0	0	0	0	1	1
Grewia flavescens	0	0	0	0	0	0	0	0	0	1
Leucaena leucocephala	0	0	0	0	0	0	0	0	0	0
Ozoroa paniculosa	0	1	0	0	0	0	0	1	0	0
Sclerocarya birrea subsp. *caffra*	0	0	0	0	0	1	0	0	0	1
Terminalia prunioides	1	1	1	1	1	1	1	1	1	1
Terminalia sericea	0	0	0	0	0	0	0	1	0	0
Ximenia caffra	0	0	0	0	0	0	0	0	0	0

C. Abattoir Hill Site

	PLOTS									
SPECIES	**ABA**	**ABA 2**	**ABA 3**	**ABA 4**	**ABA 5**	**ABA 6**	**ABA 7**	**ABA 8**	**ABA 9**	**ABA 10**
Acacia erioloba	1	0	0	0	0	0	0	0	0	0
Acacia mellifera	0	0	0	0	0	0	0	0	0	0
Acacia tortilis	0	0	0	0	0	0	0	0	1	0
Aloe littoralis	0	0	0	0	0	0	0	0	0	0
Boscia albitrunca	0	0	0	0	0	0	0	0	0	0
Catophractes alexandri	0	0	0	0	1	1	0	0	0	0
Combretum apiculatum	0	0	1	1	0	0	0	0	1	1
Combretum hereroense	0	0	0	1	1	1	0	1	0	1
Combretum imberbe	0	0	0	0	0	1	0	0	0	0
Commiphora angolensis	0	0	0	0	0	0	0	0	0	0
Commiphora glandulosa	0	0	0	0	0	0	0	0	0	0
Commiphora mollis	1	0	1	1	0	1	0	1	1	0
Croton gratissimus	0	0	0	0	1	1	1	0	1	0
Dichrostachys cinerea	0	0	0	0	0	0	0	0	1	0
Diospyros lycioides	0	0	0	0	0	0	0	0	0	0
Euphorbia guerichiana	0	0	0	0	0	0	0	0	0	0
Grewia bicolor	0	0	0	1	1	1	0	0	0	0
Grewia flava	0	1	0	1	1	0	0	1	0	1
Grewia flavescens	0	0	0	0	0	0	0	0	0	0
Leucaena leucocephala	0	0	0	0	0	0	0	0	0	0
Ozoroa paniculosa	0	0	0	0	0	0	0	0	1	0
Sclerocarya birrea subsp. *caffra*	0	1	0	0	0	0	0	0	0	0
Terminalia prunioides	1	1	1	1	1	1	1	1	1	1
Terminalia sericea	0	0	0	0	0	0	0	0	0	0
Ximenia caffra	1	1	0	0	0	0	0	0	0	0

D. Transnamib Site

	PLOTS									
SPECIES	**TRA 1**	**TRA 2**	**TRA 3**	**TRA 4**	**TRA 5**	**TRA 6**	**TRA 7**	**TRA 8**	**TRA 9**	**TRA 10**
Acacia erioloba	0	0	0	0	0	0	0	0	0	0
Acacia mellifera	0	0	0	0	1	1	0	0	0	0
Acacia tortilis	0	0	0	0	0	0	0	0	0	0
Aloe littoralis	0	0	0	0	0	0	0	0	0	0
Boscia albitrunca	0	0	1	0	1	0	0	0	0	0
Catophractes alexandri	0		0	0	0	0	0	0	0	0
Combretum apiculatum	1	1	1	1	1	1	1	1	1	0
Combretum hereroense	0	1	0	1	1	0	0	0	0	0
Combretum imberbe	0	0	1	0	0	1	0	0	0	0
Commiphora angolensis	0	0	0	0	0	0	0	0	0	0
Commiphora glandulosa	0	0	1	0	1	1	1	1	1	0
Commiphora mollis	1	1	0	1	1	0	1	1	0	0
Croton gratissimus	1	1	1	1	1	0	1	1	0	1
Dichrostachys cinerea	1	0	0	1	0	1	0	0	1	1
Diospyros lycioides	0	0	1	0	0	1	0	0	0	0
Euphorbia guerichiana	0	0	0	0	0	0	0	0	0	1
Grewia bicolor	0	0	1	1	0	0	0	0	1	1
Grewia flava	0	1	0	0	0	0	0	0	0	0
Grewia flavescens	0	0	0	0	0	0	0	0	0	1
Leucaena leucocephala	0	0	0	0	0	0	0	0	0	0
Ozoroa paniculosa	1	0	1	0	1	0	1	0	0	1
Sclerocarya birrea subsp. *caffra*	1	1	0	0	0	1	0	0	0	0
Terminalia prunioides	1	1	1	1	1	1	1	1	1	1
Terminalia sericea	0	0	0	0	0	0	0	0	0	0
Ximenia caffra	0	0	1	0	0	0	0	0	0	0

E. Nomtsoub Site

SPECIES	PLOTS **NOM 1**	**NOM 2**	**NOM 3**	**NOM 4**	**NOM 5**	**NOM 6**	**NOM 7**	**NOM 8**	**NOM 9**	**NOM 10**
Acacia erioloba	0	0	0	0	0	0	0	0	0	0
Acacia mellifera	0	0	0	0	0	0	0	0	0	0
Acacia tortilis	0	0	0	0	0	0	0	0	0	0
Aloe littoralis	0	0	0	0	0	0	0	0	0	0
Boscia albitrunca	0	1	0	0	1	0	0	0	1	1
Catophractes alexandri	0	0	1	0	0	0	1	0	0	0
Combretum apiculatum	1	1	1	1	1	1	1	0	1	1
Combretum hereroense	0	0	1	0	0	1	0	0	0	1
Combretum imberbe	0	0	0	0	0	0	0	1	0	0
Commiphora angolensis	0	0	0	0	0	0	0	0	0	0
Commiphora glandulosa	1	0	1	1	0	1	0	0	0	0
Commiphora mollis	1	0	0	0	0	1	0	0	1	0
Croton gratissimus	0	0	1	0	0	0	1	1	1	0
Dichrostachys cinerea	0	0	0	1	0	1	0	0	0	0
Diospyros lycioides	0	0	0	0	0	0	0	0	0	0
Euphorbia guerichiana	0	0	0	0	0	0	0	0	0	0
Grewia bicolor	1	0	1	0	1	1	0	1	1	1
Grewia flava	0	0	1	0	0	1	1	1	1	1
Grewia flavescens	0	1	0	1	1	1	1	1	0	0
Leucaena leucocephala	0	0	0	0	0	0	0	0	0	0
Ozoroa paniculosa	0	0	0	0	1	1	0	1	0	0
Sclerocarya birrea subsp. *caffra*	0	0	1	0	1	1	1	0	0	1
Terminalia prunioides	1	0	1	1	1	1	1	1	1	1
Terminalia sericea	0	0	0	0	0	0	0	0	0	0
Ximenia caffra	0	0	0	0	0	0	0	0	0	0

F. Airport Site

SPECIES	PLOTS AIR 1	AIR 2	AIR 3	AIR 4	AIR 5	AIR 6	AIR 7	AIR 8	AIR 9	AIR 10
Acacia erioloba	0	0	0	0	0	0	0	0	0	0
Acacia mellifera	0	0	0	0	0	0	0	0	0	0
Acacia tortilis	0	0	0	0	0	0	0	0	0	0
Aloe littoralis	0	1	0	0	0	0	0	0	0	0
Boscia albitrunca	0	0	0	0	0	0	0	0	0	0
Catophractes alexandri	0	0	0	0	0	0	0	0	0	0
Combretum apiculatum	1	1	0	0	1	1	1	1	1	1
Combretum hereroense	0	0	1	0	0	0	1	1	0	0
Combretum imberbe	0	0	0	0	0	0	0	0	0	0
Commiphora angolensis	0	0	0	0	0	0	0	0	0	0
Commiphora glandulosa	0	0	0	0	0	0	0	0	0	1
Commiphora mollis	0	0	0	0	0	0	0	0	0	0
Croton gratissimus	0	0	0	0	0	0	0	0	0	0
Dichrostachys cinerea	0	1	1	1	1	1	1	1	1	1
Diospyros lycioides	0	0	0	0	0	0	0	0	0	0
Euphorbia guerichiana	0	0	0	0	0	0	0	0	0	0
Grewia bicolor	0	0	0	0	0	0	0	0	0	0
Grewia flava	0	0	0	0	0	0	0	0	0	0
Grewia flavescens	0	0	0	0	0	0	0	0	0	0
Leucaena leucocephala	0	0	0	0	0	0	0	0	0	0
Ozoroa paniculosa	0	0	0	1	0	0	0	0	0	0
Sclerocarya birrea subsp. *caffra*	0	0	1	0	0	0	0	0	0	0
Terminalia prunioides	0	0	0	0	0	0	0	0	1	1
Terminalia sericea	0	0	0	0	0	0	0	0	0	0