ENVIRONMENTAL DETERMINANTS OF THE ECOLOGY AND DISTRIBUTION OF *ACACIA TORTILIS* UNDER ARID CONDITIONS IN QATAR

Thesis submitted for the degree of Doctor of Philosophy (PhD) at Newcastle University

By

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ABSTRACT

Scrub or woodland communities dominated by *Acacia tortilis* form one of the few tree-dominated natural ecosystems in the hyper-arid climate of Qatar, making it a very important tree species that provides an essential habitat both for native animals and domestic livestock. However, the conservation and sustainable management of this tree has so far been neglected and it is now severely impacted by overgrazing and wood fuel collection. This research investigates the main environmental, ecological and management factors affecting the growth and distribution of *Acacia tortilis* in Qatar, including the factors affecting its regeneration. It also aims to guide the implementation of conservation programmes and development of a strategy to forestall deforestation and prevent the extinction of *Acacia tortilis* in Qatar.

Initially, field survey, remote sensing and GIS techniques, together with univariate and multivariate statistical modelling techniques, were used to explore environmental influences on distribution of *A. tortilis* in Qatar at a national scale. Different vegetation indices (VIs), normalized difference vegetation index (NDVI), soil adjusted vegetation index (SAVI), were derived for a time series of Landsat TM/ETM+ images for 1998 and 2010 and tested using ground-truth data to explore the temporal dynamics of Acacia-dominated ecosystems which indicated substantial reduction in vegetation greenness in 2010 than 1998. The initial approach had limited success due to difficulties of identifying *Acacia tortilis* communities accurately on satellite images due to the sparsity of tree cover and indicates the limitations of using remote sensing methods for tracing vegetation dynamics in Qatar and similar arid and hyper arid environments. The multinomial logistic regression model has a superior ability to predict *Acacia* distribution and is a suitable method in the prediction of the occurrence of different vegetation types.

Phytogeographical investigations of the environmental and biotic factors that control the distribution of the *Acacia tortilis* at a local scale, in both areas protected and unprotected from human land use impacts, demonstrate that topographic factors and their control on soil and water conditions are fundamental determinants. The distinctive topography of Qatar has resulted in a heterogeneous soil landscape with extreme contrasts of chemical and physical soil conditions within and between depressions and more elevated positions in soil toposequences. Depressional land forms are more suitable for the *Acacia* tree growth than the surrounding higher ground because depression soils have greater soil water content, soil depth, organic carbon and available phosphorus contents. Conversely, the absence of *Acacia* trees in summit areas is related to severe limitations for tree growth, including negligible soil water content and shallow soil depth caused by impeding bedrock or cemented horizons resulting in drought stress, as well as large contents of gypsum and/or CaCO3 in soils. The slope-controlled movement of eroded soil material, water and plant debris, and the localised leaching of soluble salts, are suggested to be important processes that lead to improved soil quality and better tree growth in depressions.

The regeneration of *Acacia tortilis* through seedling establishment is perhaps surprisingly shown to be greater in the unprotected than in protected areas. This is attributed to the importance of ingestion by large mammals (mainly domestic herbivores) on the germination and recruitment of *Acacia* seedlings. The greater frequency of *Acacia* saplings in depressions within the unprotected areas is, however, also attributed to the presence of greater amounts of soil water, soil depth, available phosphorus, and organic carbon.

Although the action of browsing may be regarded as positive, most anthropogenic impacts were shown to have negative effects on the condition and distribution of *Acacia tortilis*. The results proved that the impacts of cutting and browsing were severe in the unprotected sites, despite the evidence of more active regeneration. It is concluded that there is an urgent need to review the provision and management of protected habitats for *Acacia tortilis* in Qatar. It is suggested that cutting for domestic use should be restricted; that conservation efforts should be concentrated in depressions that favour tree growth; and that the livestock numbers should be limited to enable seedling establishment without excessive browsing.

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GLOSSARY AND LIST OF ABBREVIATIONS

A.tortilis	*Acacia tortilis*
Rawda or *Rawdah*	Arabic term for a depression used by the Qataris
Wadi	Arabic term for a valley, ravine, or channel that is dry except in the rainy season
Sabkha or Sabkhah	Arabic term denoting inland or coastline flat or playa with fine silt and calcareous sands
Hamada	Type of desert landscape consisting of high, largely barren, hard, rocky plateau, with very little sand
Geomorphology	the study of the physical features of the surface of the earth and their relation to its geological structures
Pedology	Is another term for soil science
Petrogypsic	A surface or subsurface soil horizon cemented by gypsum
Petrocalcic	A surface or subsurface soil horizon when secondary calcium carbonate or other carbonates accumulate to the extent that the soil becomes cemented
Karstification	A geological formation of the features of karst topography by the chemical, and sometimes mechanical, action of water in a region of limestone, dolomite, or gypsum bedrock
VI	The vegetation index (VI), defined as the arithmetic combination of two or more bands related to the spectral characteristics of vegetation
NDVI	The Normalized Difference Vegetation Index, which is defined as the difference between the visible (red) and near-infrared (nir) bands, divided by their sum. The NDVI gives a measure of vegetation amount and condition
SAVI	The Soil Adjusted Vegetation Index
EMR	The Electromagnetic Radiation
DOS	The Dark Object Subtraction
DEM	The Digital Elevation Model
TDS	The Total Dissolved Solids
DSB	The Diameter at Stem Base
MLR	Multiple Multinomial Logistic

CHAPTER 1: INTRODUCTION

1.1 Introduction

Acacia tortilis is a 'keystone species' of desert ecosystems found widely in many African and Middle East countries, including the state of Qatar which occupies an arid and hyper-arid peninsula on the Arabia Gulf (Milton and Dean, 1995; Ward and Rohner, 1997; Abulfatih *et al.*, 1999; Dean *et al.*, 1999; Andersen and Krzywinski, 2007a; Abdelrahman and Krzywinski, 2008). The *Acacia tortilis* represents the dominant tree species in several types of Qatari vegetation, and is regarded as one of its most precious natural assets and resources because it provides an essential habitat for native animals and underpins the continued persistence and evolution of natural ecosystems (Abdel-Bari *et al.*, 2007; Norton *et al.*, 2009). Acacia stands also play an important role as wind breaks and in the stabilization of the soil, thereby making it less vulnerable to wind and erosion. As expected of an arid region with unique terrain and harsh climatic conditions including high temperatures and scant unpredictable rainfall, the vegetation is exposed and composed of annuals, ephemerals and short-lived perennials (Batanouny, 1981; Abulfatih *et al.*, 2001; Abdel Bari, 2005). These vegetation life-systems in Qatar comprise more than 60% of the total flora, whereas perennials, including trees, shrubs, undershrubs and perennial herbs, make up about 40% of the total number of species recorded (Abdel Bari, 2005).

The wild flora of Qatar has been found to contain about 400 plant species, of which about 270 are likely to be truly native (Norton *et al.*, 2009). Only 8 native tree species were previously found to exist in the State of Qatar, namely: the mangrove *Avicennia marina*, *Acacia ehrenbergiana*, *Acacia tortilis*, *Ziziphus nummularia*, *Z. spina-christi*, *Prosopis Cineraria,* and the lianas *Cocculus pendulus* and *Ephedra foliata* (a gymnosperm) (Abdel Bari, 2005; Norton *et al.*, 2009). But in recent years other tree species, such as *Prosopis juliflora* have now become naturalized, and the latter occupies deep depressions with relatively finer soils (Abdel Bari, 2005; Norton *et al.*, 2009). In Qatar, the Mimosaceae are represented by two genera: *Acacia* and *Prosopis*. The former is represented by five species, including *Acacia ehrenbergiana* and *Acacia tortilis*, which are both native as emphasized above and the others are introduced species. Meanwhile the latter genus is represented by one local species, *Prosopis cineraria,* and two introduced species, *Prosopis farcta* and *Prosopis juliflora* (Abdel-Bari *et al.*, 2007; Norton *et al.*, 2009). *Acacia tortilis* (Forssk) Hayne is the dominant *Acacia* species in Qatar and usually grows as clumps or solitary scattered trees. It is very common and locally dominant in depressions, wadis and large runnels, and is said to prefer the slightly elevated ground at the edges of such features (Norton *et al.*, 2009). The flora of Qatar can be categorized into five main habitat groups, as described by Norton *et al.*(2009): (i) strongly 'xerophytic' species of rock and gravel deserts where the soil depth is limited and conditions are very dry; (ii) 'halophytic' species tolerant of saline areas, such as saltmarshes, coastal sands, sabkha edges and inland olitic sands; (iii) species that grow in natural silt and sand depressions; (iv) species adapted to grow in deeper sand, where water is available under the surface; and (v) species associated with man-made and man-influenced sites, particularly those receiving artificial irrigation such as roadsides, farms, gardens and sewage ponds.

The need to evaluate *Acacia tortilis* in Qatar

The Qatari population has increased at an unprecedented rate over recent decades. It was about 369,000 in 1986 and has since more than doubled, reaching about 838,000 in 2006. The most recent census indicates that the population has jumped to 2,155,446 (QSA, 2014), indicating that in the last few years the total population has increased by about 250% compared to 2006. The expanding economy and the rapid growth in population has culminated in massive infrastructural development, and expansion of the ownership of livestock and farm land, which in turn has had several types of human impacts on the Qatari environment. With the increasing human population and the rise in standards of living, the Qatari lifestyle has changed considerably, thereby placing a burden on the land (Abulfatih *et al.*, 2001; Sillitoe *et al.*, 2010). For instance, the demands for meat and other farm animals as well as leisure and entertainment are expected to increase. Bradshaw *et al.* (2010) also found that economic prosperity is the most important driver of adverse environmental impacts in developing countries such as Qatar, which is one of the countries with the highest degree of recent adverse impact. Chaudhary and Houérou (2006) also noted that the prosperity of Saudi Arabia after its economic boom from crude oil exportation proved to be unfortunate for the rangelands. They added that, since 1972, two-thirds of the natural vegetation of Saudi Arabia has been destroyed by overgrazing and tree felling for fuel. Likewise, the disturbance of the Qatari natural environment has obviously increased, thereby threatening the existence of keystone species such as *Acacia tortilis* (Batanouny, 1981; Bradshaw *et al.*, 2010). Furthermore, the Qatari government, and particularly the Ministry of Environment and Natural Resources, is not doing much to protect the environment and endangered species. Hence, the local management of natural resources in Qatar has failed to meet international expectations of conservation and local participation (Sillitoe *et al.*, 2010).

1.2 Aims & Objectives

1.2.1 PHASE ONE: Distribution of *Acacia tortilis* in Qatar using field survey, remote sensing and GIS at national scale

There has been no research so far on the evaluation and validation of satellite remotely sensed data to detect changes among natural tree species in Qatar, which is characterized by having sparse vegetation cover. Therefore, this study aims to determine the distribution of *Acacia* tree species and to investigate changes over recent years using remote sensing data acquired from a Landsat satellite to develop vegetation indices. This research addresses the following objectives concerning the usefulness of satellite images:

- Classify study sites into distinct vegetation habitat types.
- Determine to what extent vegetation indices derived from the free Landsat archive enable the detection of *A. tortilis* and other tree species in Qatar.
- Assess the expansion or decrease of *A. tortilis* between 1998 and 2010 in this arid country.

The research also seeks to determine the relationship between a representative range of broad vegetation\habitat types from field sites across Qatar and the environment, to investigate factors affecting *A. tortilis* distribution. Specific aims are:

- To identify the environmental variables associated with different types of vegetation using data collected in the field and from extant GIS databases.
- To use univariate and multivariate statistical modelling techniques to determine the major environmental variables associated with *Acacia* abundance, which could potentially be used to predict its distribution.

1.2.2 PHASE TWO: Multifactorial approach to studying *Acacia tortilis* distribution at local scale

Despite numerous studies undertaken on the genus *Acacia* in arid and semi-arid regions, there is still a paucity of information on *Acacia tortilis* in Qatar. It is therefore important to investigate the environmental and ecological distribution of *Acacia* trees (*Acacia tortilis* Forssk. Hayne) in order to gain an understanding that will inform future initiatives to protect and conserve this important plant. The focus is on the native leguminous desert tree *Acacia tortilis* (Forssk.), because this is the most commonly distributed *Acacia* spp in the Qatari desert and it has considerable importance for the desert ecosystem. In addition, the present work attempts to apply appropriate techniques to shed more light on the relationship between landform and soil and plant distribution, as well as the impact of human activities upon *Acacia spp*. in Qatar. Thus, the specific aims of this research are:

- To determine the environmental and anthropogenic factors affecting the growth, condition and distribution of *Acacia tortilis* in Qatar.
- To compare the condition and distribution of *Acacia* trees in representative protected and unprotected areas in Qatar.
- To analyse the influence of the dominant geomorphological and soil variations of Qatar on the distribution of *Acacia tortilis*.
- To determine the environmental and anthropogenic factors affecting the regeneration of *Acacia tortilis*.

1.3 Thesis Outline

The thesis progresses in two phases to address the above objectives. The present chapter concentrates on a general introduction to the necessity to evaluate *Acacia tortilis* and describes the main objectives. Background information related to the various aspects of Qatar and statements of the relevant problems are highlighted later in this chapter.

The literature related to satellite imaging and vegetation indices that have relevance to detecting changes in vegetation cover and composition as well as the ecology and distribution of *Acacia tortilis* is reviewed in chapter 2. Methods used to investigate various research aspects are mentioned in detail in chapter 3.

Chapter 4 addresses the objectives of phase one of this study concerning the distribution of *Acacia tortilis* in Qatar using an integrated field survey, remote sensing and the extant GIS database at the national scale. Firstly, the tree cover and species composition of desert vegetation in Qatar is estimated using vegetation indices derived from remote sensing. Secondly, approaches are introduced to identify which environmental variables best explain the distribution of vegetation type in space, and which are significantly correlated with environmental variables. Thus, the suitability of multivariate statistical modelling techniques to determine the major vegetation and environmental variables associated with *Acacia* abundance, and that could potentially be used to predict its distribution are discussed.

Chapter 5 introduces of phase two of the research. It addresses a multifactorial approach to studying *Acacia tortilis* distribution at local scale, specifically in the depression ecosystem environment of 3.5 km in radius. The relative impact of protection status, topography and soil properties on *Acacia tortilis* tree and the morphological characteristics of *Acacia tortilis* are quantitatively assessed. Also, details are provided relating to the impact of anthropogenic activities on *A. tortilis*. Finally, an analysis of correlation between the morphological characteristics of *Acacia tortilis* and environmental variables is presented. Then, a multiple regression modelling approach is used to identify which environmental variables among protection status, topographical position, soil properties and depth to water table level best explain the morphological characteristics of *Acacia tortilis*.

The factors influencing regeneration of *A. tortilis* are addressed in chapter 6. The patterns of distribution and recruitment of *A. tortilis* seedlings/saplings in three study areas are presented.

Chapter 7 provides a general discussion and conclusions from the various aspects of the research described in the previous chapters and their relevance in terms of the objectives of the study. It also discusses the limitations of the methods used and suggests future possible research directions in terms of tree distribution and the implications for management in arid conditions.

1.4 Background of the Study Area

1.4.1 Climate of Qatar

The climate is characterised by very hot summers in June, July and August, and a cool winter. Generally, the absolute maximum temperature is 47°C and the absolute minimum temperature is 1°C (Abulfatih *et al.*, 2001). Rainfall is unpredictable, irregular and variable in terms of both time and space, with an average annual rainfall of 73mm in the last 39 years (Figure 1-1). Rain is confined to the period between October and

May. The amount and pattern of rainfall is one of the keys to understanding the dynamic processes of the different terrestrial ground features. From a 5-year moving average of rainfall in Qatar had shown in Figure 1-1, it can be seen that the average rainfall was around 40mm in the mid-1970s and this nearly doubled about ten years later. The highest values were recorded in the late 1990s. The prevailing wind is from the North and North West, resulting in aeolian sand covering much of the South of Qatar with dunes. As a result of the arid climate, the vegetation is open and is composed of a permanent community of perennials and ephemerals that appear after rain (Obeid, 1975).

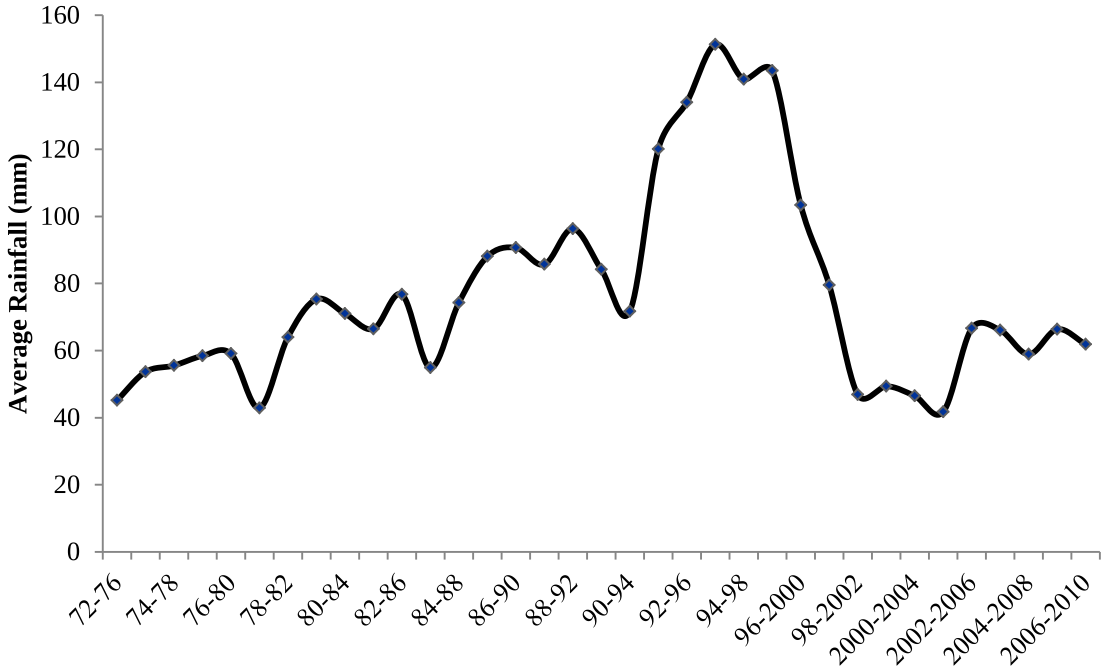


Figure 1-1: 5 Years Moving Average Annual Rainfall of Qatar (1972-2010).

1.4.2 Geology and geomorphology

Several environmental factors can be emphasized which influence the distribution of plants such as *Acacia tortilis.* Among these factors, soil water content is paramount. Hence, consideration should be given to geomorphological features such as geology, topography and pedology that may influence water conditions. This section will evaluate some important relevant factors in Qatar.

The surface soils in Qatar are completely covered with a range of geological formations dating from the Palaeogene to Quaternary ages (Winslow and El Hakim, 2009). The deeper geology of the Qatari landscape is dominated by limestones and this is manifest on the surface mainly through karst-related processes, which are manifest in the form of frequent depressions, sinkholes, caves and solution hollows. The dissolution of the gypsum and anhydrite deposits of the Rus Formation has been linked to the features of karst. Similarly, the dissolution of the carbonate sequences of the Dammam Formation are also associated with these karst features, but to a lesser extent (Winslow and El Hakim, 2009).

Qatar is an elliptically shaped, limestone peninsula with gentle relief caused by the modest tectonic uplift rates along the Qatar arch and comparable erosion rates. It is divided into two basins by the Qatar Dome – the Eastern and Western Basins. Its landscape is dominated by karstic topographies, including widespread depressions which can reach a depth of 25m (Ashghal, 2012). The landscape is remarkably pitted having many (micro) depressions serving as catchments which receive spatially irregular rains. However, the occurrence of torrential showers causes lateral runoff and erosion, particularly on the sloping topography (see Figure 1-2). Both these phenomena play vital roles in shaping the Qatari landscape, hydrology and hydro-geology (Ashghal, 2012). The depressions are formed from the collapse of the subsurface karstic structures. Karstification has significant hydrogeological attributes (Ashghal, 2012), which may be beneficial to plants such as *Acacia tortilis* considering the fact that Qatar lacks perennial surface water. For example, storm events may generate flash floods which usually flush sediments into karst depressions, forming fertile rawda-soils for *Acacia tortilis* (Figure 1-2).

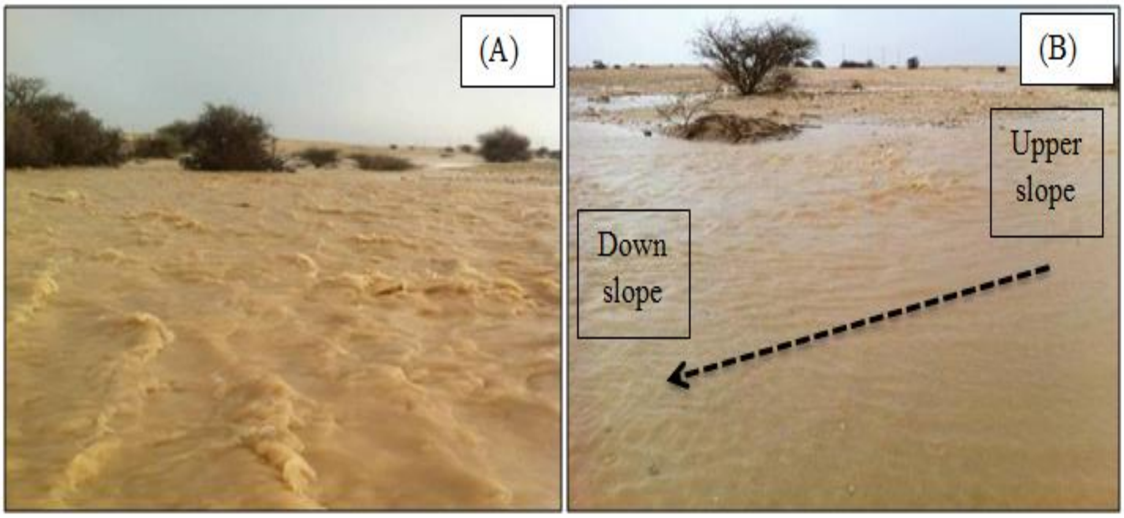


Figure 1-2: (A) Heavy Rainfall, September 28, 2012 and (B) Lateral Runoff and Erosion from Upper Slope to Down Slope in Study Area I.

The land surface is generally of low to moderate relief with a maximum height of 103 meters above sea level (SEL, 1980; Eccleston and Ḥarḥash, 1982) while the lowest part of the peninsula is at a level of 6m below sea level (Yehia *et al.*, 1982). The North-South axis is almost 180 km in length, and the East-West width at its widest point in the central area is 85km (Batanouny, 1981). The major part of the Qatari peninsula is less than 40m above sea level.

The coastline of Qatar is gently emergent and presents a patchy outline with several islands, reefs, caps and extensive areas of marshes (*sabkhas*) (Batanouny, 1981; Yehia *et al.*, 1982). Marshes or *sabkhas* are widespread along the coastal margins of the country, generally close to the water table and covered with salt crust. Rocky hills areas are also common along the coastal areas.

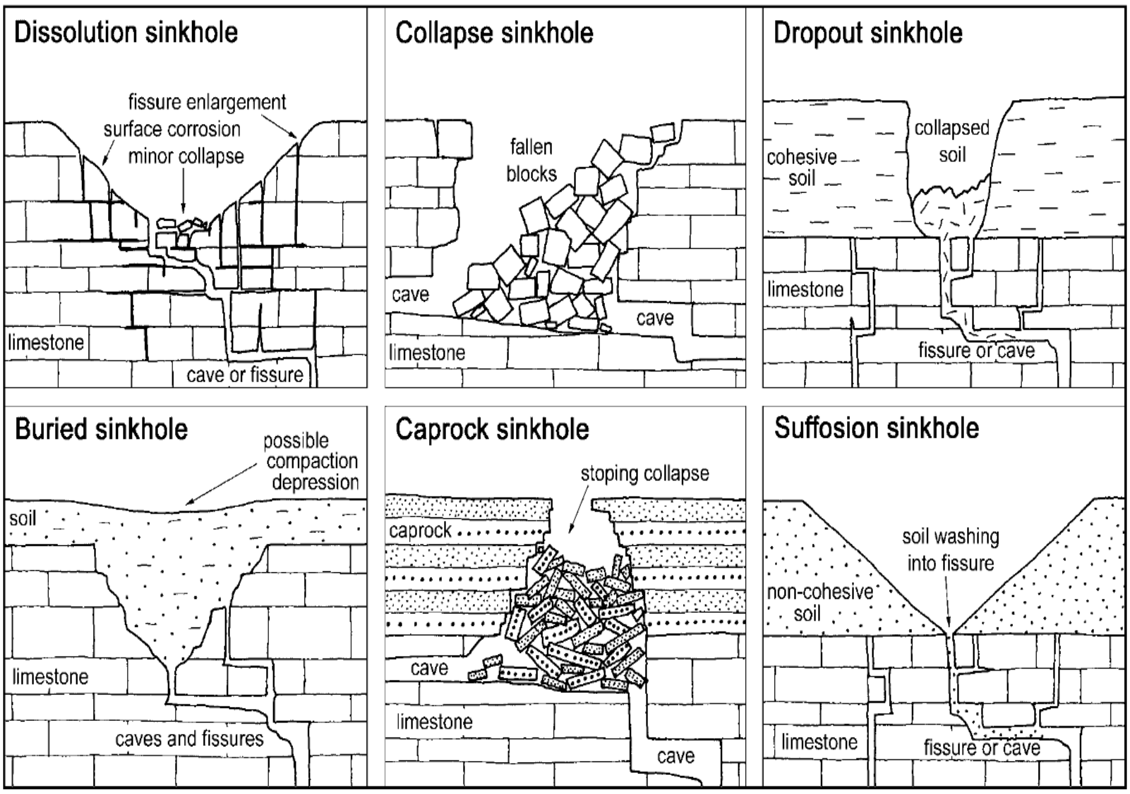


Figure 1-3: Mechanisms of Leading to Creation of Depression Features.

Source: Waltham and Fookes (2003).

Karstification

Karstification is the process whereby the dissolution or tertiary porosity of the non-clastic chemical and organic rocks develops to a noticeable extent. Karst has unique landforms and hydrology that stem from a combination of high rock solubility and well-developed secondary porosity. The solubility of the minerals that form the rock, the degree of saturation of water content contained in the rock and the time of water-rock interaction determine the rate of karstification. Over time, soluble rocks beneath the earth dissolve, culminating in the formation of an underground drainage system which permits the flow of water through the rock. Consequently, the formation of underground karst features is accelerated. Factors that influence the rates of rock dissolution include climate, soil, rock and groundwater quality conditions. Nevertheless, the rate of rock dissolution is extremely slow, in the order of few millimetres per millennium. The three different types of rock porosity correspond to the three types of rock permeability, namely: primary, secondary and tertiary permeability. Primary permeability includes the least movement of water held within the pores between the rock grains. Tertiary permeability has the fastest movement of water flowing through the dissolution cavities of the rock, while secondary permeability is intermediate in rate between primary and tertiary permeability (Ashghal, 2012). Collapse of karstic structures (Figure 1-3) characterise Qatari landscape.

Topography/Landform of Qatar

Topographical features largely reflect the structures of the sedimentary rocks which underlie the whole of the mainland, with a notable feature of numerous widely scattered depressions due to the solution of limestone, or its erosion or collapse (SEL, 1980; Ashghal, 2012). These depressions are the main topographic features of Qatar, numbering about 850 (Yehia *et al.*, 1982). However, a recent project by the Centre for GIS at the Ministry of Municipality and Urban Planning mapped the depressions (Rawda) in 2010 in the whole of Qatar, and it was concluded that the total number of main depressions is about 1982, with a combined area of 279.36 km^2. In general, the Qatari peninsula is dominated by low relief and rarely has areas that could accumulate surface run-off water which could create perennial streams or other water accumulation ponds. The northern and central regions of the country are dominated by shallow ephemeral stream channels. These are difficult to recognize as they are frequently filled with aeolian and colluvial deposits that mainly have their origins from the superficial water sheets that flow after heavy rainfall.

Few attempts have been made to correlate landforms to the vegetation of Qatar. An early study by Babiker (1990) described the effects of landform and soil on the vegetation of the country. Five major landform/soil subdivisions were recognized; depressions, wadis, rocky and conglomerate *hammada* surfaces, sand dunes and *sabkhas*. These five landform/soil subdivisions showed great diversity, and the differences indicate that the physical and chemical properties of soil enhanced by landform variations were probably the major factor involved.

The description of the major Qatari landforms reported by Yehia *et al.* (1982), Babiker (1990) and Norton *et al.*(2009) is summarised below.

a) Lowlands

Depressions (rawda): these subsurface collapse structures are considered to be one of the most important topographic features of Qatar Figure (1-4). They contain moderately compact to very compact soils. These subsurface collapse structures are the result of limestone and gypsum deposits of the Rus and Dammam formation (SEL, 1980). It is assumed that the 'Rawah' geomorphological structures acted as sedimentation basins where storm water runoff and fluvial water were deposited (Scheibert *et al.*, 2005). Frequently become flooded during rainfall and the soils often have a greater organic matter contents than those in other desert areas. They are usually characterized by stands of trees and shrubs, including *Acacia spp*, *Prosopis juliflora*, *Ziziphus nummularia* and *Lycium shawii*; and often rich in annual and perennial herbs and grasses such as *Cymbopogon commutatus*, *Pulicara undulate*, *Andrachne telephioides*, *Astragalus eremophilus*, *Althaea ludwigii* and *Corchorus depessus*.

Figure 1-4: Depression Features in Qatar, with High Vegetation Diversity.

Wadis and runnels (slope): The term wadi is normally used for a stream, channel or valley in a desert regions (Yehia *et al.*, 1982) . In Qatar it can be described as linear patches of accumulated sand and often within otherwise featureless *Hamada* or gravel desert areas and they may flow with water during times of heavy rainfall (Figure 1-5). Many wadi-like channels discharge into shallow 'Rawdas', or pond like depressions that are filled with young alluvial deposits (Scheibert *et al.*, 2005).

They support distinctive types of vegetation composed of certain shrubs, grasses, perennials and annual herbs, for instant *Lycium shawii*, *Acacia tortilis*, *Cymbopogon commutatus* and *Dipcadi erythraeum*.

Figure 1-5: Typical Wadi Features in Qatar, Dominating by *Acacia* Tree.

<u>Sabkhas:</u> this is an Arabic term for low-lying areas generally close to the water table and/or which have been inundated by seawater or rainwater that has dried out leaving a salt crust surface. They occur mainly on or near the coastal areas of Qatar, with the larger ones located at Mesaieed and east of Dukhan.

b) Uplands

<u>Hamada:</u> This landform can be described as a flat or gently undulating desert with stones and rocks on the surface. The major area of the peninsula is covered by this type of landform formed from the limestone bedrock. This type of landform is usually dominated by *Lycium shawii* and *Tetraena qatarenisi* along with the annual grass *Stipa capensis*.

<u>Cliffs and ridges (jabal):</u> these occur in different parts of Qatar, but mainly at the coastal line where marine erosion has taken place with the (solitic limestone) found in the north-east and south-west of Qatar. Old cliffs are more predominant in Al Khor, Dukhan, Abruk and Zekrit.

<u>Sand accumulations:</u> Because Qatar is an arid region the wind plays a central role in shaping the surface. Sand dunes are estimated to cover about 13% of the total area of Qatar (Abulfatih *et al.*, 2001). Sandy landforms and habitats are found in numerous

places in the country, occurring mainly in the south and south-east and with numerous different shapes ranging from Barchans, transverse, longitudinal to compound, and complex dunes. They support distinctive types of vegetation such as *Seidlitzia rosmarinus* and *Cyperus conglomerates*.

1.4.3 Pedology

The soils of Qatar were evaluated by Scheibert *et al.* (2005), who concluded that all of the soils sampled belonged to either the Aridisol or Entisol soil orders, as classified according to the USDA Soil Taxonomy. All the soils sampled in this research belong to the Aridisols order which is characterized by water deficiency and very poor concentrations of organic matter content. In addition the soils have mostly a sandy to loamy texture underlain by either a calcic, gypsic, petrocalcic or petrogypsic horizon (Scheibert *et al.*, 2005; Ashghal, 2012).

Within these orders soils are categorised in nineteen taxonomic soil units or types up to the subgroup level. Soils in this research (area I), which was selected to conduct the multifactorial study of *Acacia tortilis* distribution at local scale, can be classified into four main units or types. These are the haplogypsids and petrogypsids 12 [1] haplocalcids 132[1], haplocalcids 132[2] and lithic haplocalcids 1321[1], which make up more than 60% of all of soils in Qatar (see Figures 1-6 and Table 1-1).

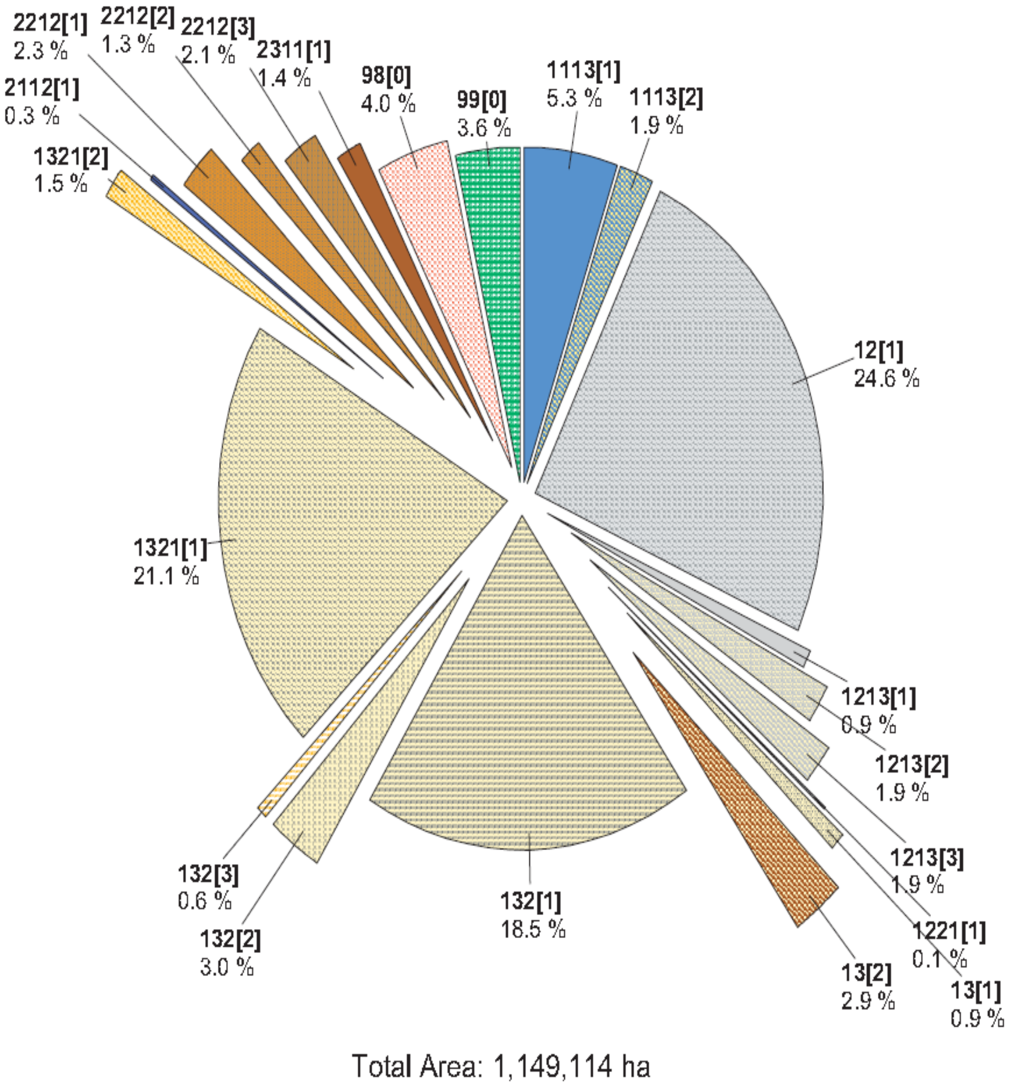


Figure 1-6: Spatial Extent of Soil Units/Types of Qatar. [For legend see Table 1-1]

Source: from (Scheibert et al., 2005).

Table 1-1: Soil Units or Types of Qatar According to US Soil Taxonomy, Highlighted Symbols are Soil Type Found in the Study Area I.

US Soil Taxonomy 8th Edition		Symbol	Legend Name
Order	Aridisols	1113[1]	Typic Aquisalids; sandy and sandy-loamy soils
		1113[2]	Typic Aquisalids & Typic Torripsamments; loamy and clayey soils
		12[1]	Haplogypsids & Petrogypsids; loamy and sandy
		1213[1]	Typic Petrogypsids; sandy
		1213[2]	Typic Petrogypsids; sandy phase: loamy and sandy
		1213[3]	Typic Petrogypsids & Typic Torripsamments; loamy and clayey
		1221[1]	Lithic Calcigypsids; loamy and clayey
		13[1]	Haplocalcids & Petrocalcids; sandy and loamy
		13[2]	Calcids & Torriorthents; sandy skeletal and loamy skeletal
		132[1]	Haplocalcids; loamy
		132[2]	Haplocalcids; loamy and clayey
		132[3]	Haplocalcids & Torriorthents; sandy and loamy
		1321[1]	Lithic Haplocalcids; sandy, loamy and loamy skeletal soils
	Entisols	1321[2]	Lithic Haplocalcids & Typic Torripsamments; sandy, loamy and loamy skeletal
		2112[1]	Typic Psammaquents; sandy
		2212[1]	Typic Torripsamments; sandy
		2212[2]	Typic Torripsamments; sand dunes
		2212[3]	Typic Torripsamments; sandy
		2311[1]	Lithic Torriorthents; rock outcrops, sandy, loamy and loamy skeletal

Source: from (Scheibert et al., 2005).

Haplogypsids and petrogypsids soil unit/type (Symbol: 12[1] in Table 1-1) mainly occur in the North and central parts of Qatar and to a smaller extent in the South, where gypsids are less frequently found (Figure 1-7). These types make up 24.6 per cent of Qatari soil (Scheibert *et al.*, 2005). The soil unit consists of about 23.1 per cent typic petrogypsid (i.e. gypsiferous Aridisoil with a cemented petrogypsic horizon, often at shallow depth), 20.1 per cent lithic haplogypsid (i.e. a shallow calcareous Aridisoil, within 50 cm of the soil surface), 11.6 percent leptic haplogypsid (i.e. a gypsiferous Aridisoil with a gypsic horizon at shallow depth of the soil surface), 3.5 per cent typic haplosalid (i.e. soils that do not have a calcic, gypsic, or petrogypsic horizon), 3.5 per cent lithic haplocalcid, 3.3 per cent typic haplogypsid and 3.1 per cent lithic torriorthent (Generally, Entisols that are neutral or calcareous and are on moderate to very steep slopes; The vegetation on Torriorthents commonly is sparse and consists mostly of xerophytic shrubs and ephemeral grasses). It is worth mentioning that the unit consists mainly of gypsiferous soils dominated by petrogypsids with subsoils cemented by gypsum and non-cemented haplogypsids with bedrock at shallow depths.

The haplocalcid soil types (Symbol: 132[1] and 132[2] in table 1-1) are shallow to moderately deep, well drained sandy loam, loamy sand and loam that formed in colluvium derived from limestone and dolomite (Scheibert *et al.*, 2005). This soil type is Calcids that have a calcic horizon with its upper boundary of the soil surface. Both types make up 21.5 per cent of Qatar and consist of about 18.8 % lithic haplocalcid, 18.5% typic haplocalcid, 6% lithic torriorthent, 5.6% lithic haplocambid, 5.0% lithic haplogypsid and 4.1 % typic petrocalcid. Similarly, as with the previously mentioned soil unit, this haplocalcid type is found to be constrained due to the physical limitations of soil texture and depth as well as to a minor extent by $CaCO_3$ content.

Lithic haplocalcids (Symbol: 1321[1]) make up 21.1 per cent of Qatar soils and are predominantly shallow, well-drained fine sandy loam and loamy sand formed in colluvium and residuum derived from limestone. Within this soil unit there is about 38.6% lithic haplocalcid, 16.1% typic petrocalcid, 9.9% typic haplocalcid, 7.3% lithic torriorthent, 5.1% calcic lithic petrocalcid and 5.1% calcic petrocalcid. This soil unit found to have some constraint due to the physical limitations mainly of soil texture and depth as well as to a minor extent $CaCO_3$ content (Scheibert *et al.*, 2005).

The main physiochemical properties of these four soils are shown in Table 1-2, although the differences between soils found in topographic variations such as wadis and depressions (Rawda) where the *Acacia tortilis* is favoured are not clearly mentioned.

Table 1-2: Main Physiochemical Properties of the Four Soil Types of The Study Area I.

Physiochemical properties	**12[1]**	**132[1]**	**132[2]**	**1321[1]**
Water holding capacity	low	low	low	low
$CaCO_3$ content	high	high	high	high
Gypsum content	Medium to high	Low to medium	Low	low
EC	Strongly saline	Moderately to strongly saline	Slightly to moderately saline	Moderately saline
pH	Moderately alkaline	Moderately alkaline	Moderately alkaline	Moderately alkaline
Organic matter	Very low	Very low	Very low	Very low

Source: (Scheibert et al., 2005).

According to Scheibert *et al.'s* (2005) studies of their physical and chemical properties these soil units are calcareous and their content of gypsum averages 2.58%. The physiochemical properties did not change significantly with depth greater than 40 cm. However, they vary between 0-10 and 10-40 cm. Organic matter content is low at 0.39, 0.46, 0.59 and 0.68% for lithic haplocalcids 1321[1], haplocalcids 132[2], haplogypsids and petrogypsids 12[1] and haplocalcids 132[1] soil units, respectively.

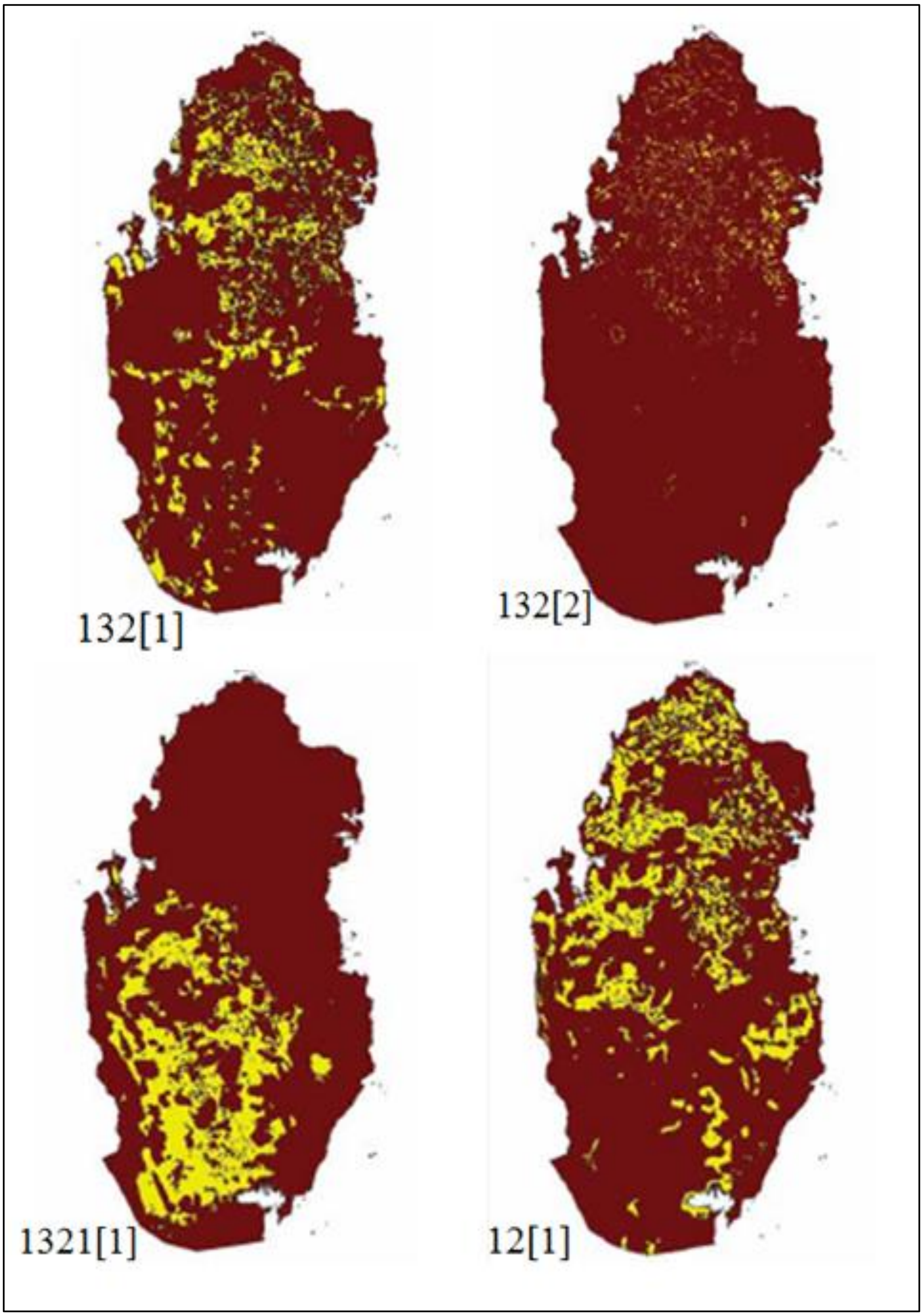


Figure 1-7: Spatial Distribution of the Four Soil Types in Qatar. [Not to scale]

Source: from (Scheibert et al., 2005); Consist of haplogypsids & petrogypsids (12[1]), lithic haplocalcids (1321[1]) & haplocalcids (132[1,2]).

1.4.4 Anthropogenic impacts on the Qatari terrestrial environment

Abiotic factors are often the most important factors influencing the distribution of a species (Kouba *et al.*, 2011). Brown (1988) also noted that abiotic factors can exert significant control over plant distribution. Therefore, it seems possible that anthropogenic impacts will be likely to have a strong impact on the Qatari environment, and especially on its plant ecology and distribution. Four main types of human impact or problems are seen to influence the *Acacia* tree in the desert of Qatar:

❖ **Urban Sprawl:**

Urban sprawl due to the dramatic increase in the population is one of the main factors that influence the loss of *Acacia* habitats. Figure 1-8 illustrates the vast expansion of Doha city, the capital of Qatar, to approximately three fold between 1973 and 2009.

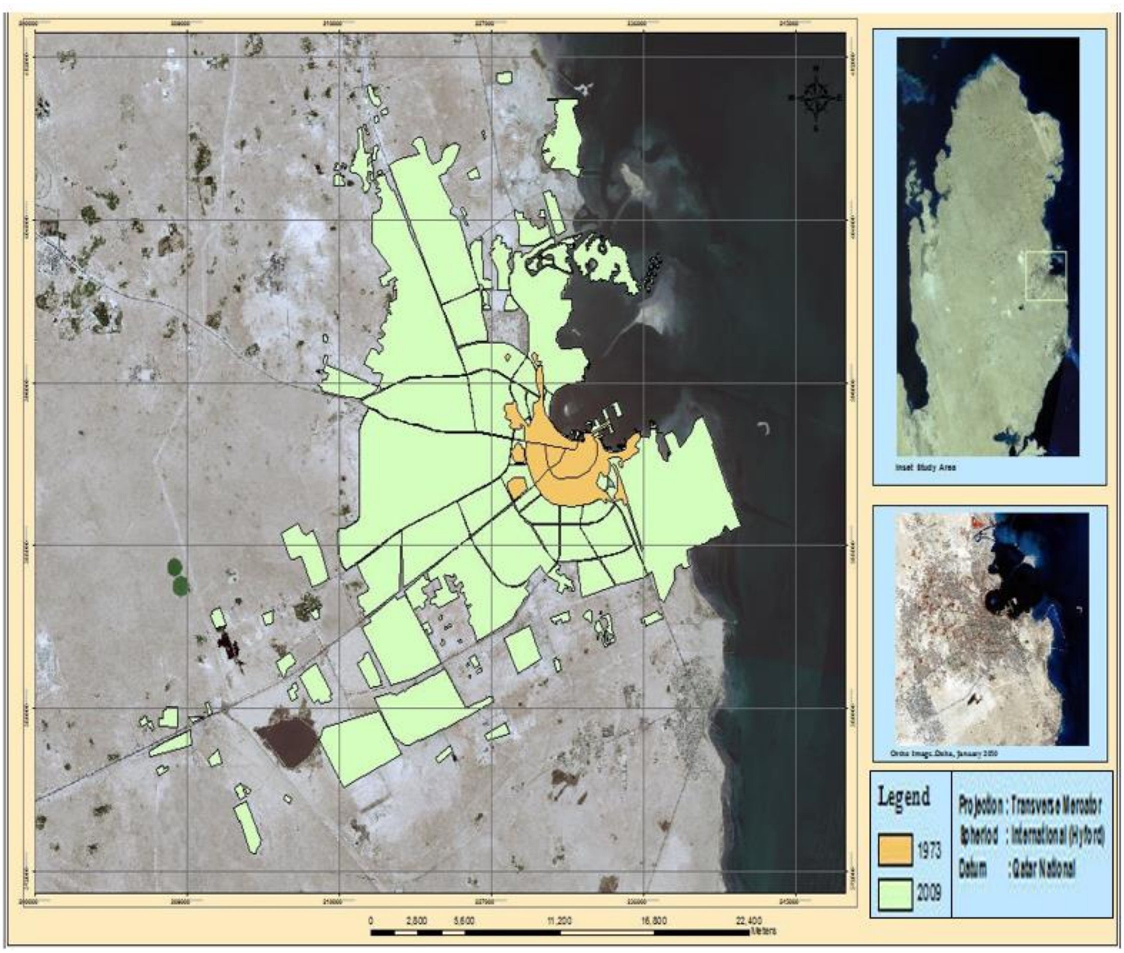


Figure 1-8: Urban Sprawl Change Detection of Doha (orange in 1973- green in 2009).

Map acquired from the GIS department at Qatar University.

- **Land Degradation**

Several studies have reported that the massive infrastructure development due to economic changes has led to degradation of the lands becoming a threat to the natural habitat where most *Acacia tortilis* grows in Qatar (Chaudhary and Houérou, 2006; Bradshaw *et al.*, 2010; Sillitoe *et al.*, 2010), as shown Figure 1-9.

Figure 1-9: Example of Land Degradation on The *Acacia* Tree Habitat in Most of the Developing Areas of Qatar.

- **Agricultural Practices**

In 1993 only 0.7% of the land area in Qatar was cultivated and 4.5% was used as pastureland (Abulfatih *et al.*, 2001). Agriculture was characterized by large numbers of small holdings. These consume more water, give low yields and have high production costs. Recent statistics shown in Figure 1-10 illustrate that there has been a massive increase in the total number of farms, reaching 1245 in 2010 and covering an area of 43730 hectare (3.77 % of the total land), which means that natural habitats were ultimately decreased (data from Department of Animal Resources, Ministry of Environment, 2010). Therefore, a large reduction natural vegetation in in depressions, which are most favourable habitats for the *Acacia* tree (Scheibert *et al.*, 2005).

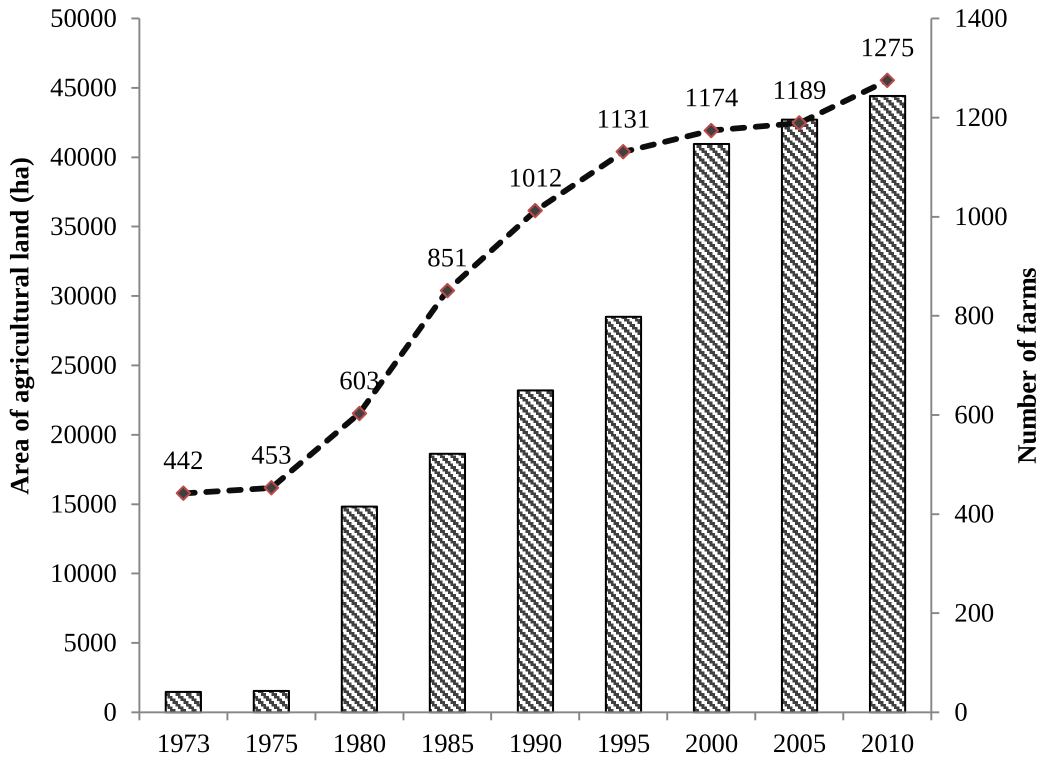


Figure 1-10: Agricultural Land Use in Qatar. [Farm Numbers and the Total Area]

Source: Ministry of Environment (2010).

❖ Overgrazing

With the increase in the local population and the rise in standards of living, a higher demand for meat and other livestock production is expected. Accordingly, the number of imported domestic animals has increased dramatically and this has consequently placed high stress on rangeland (Chaudhary and Houérou, 2006). The high rate of increase in the number of livestock is also placing high stress on pastureland. Grazing in many places is exceeding the carrying capacity and consequently causing land deterioration (Abulfatih *et al.*, 2001; Scheibert *et al.*, 2005).

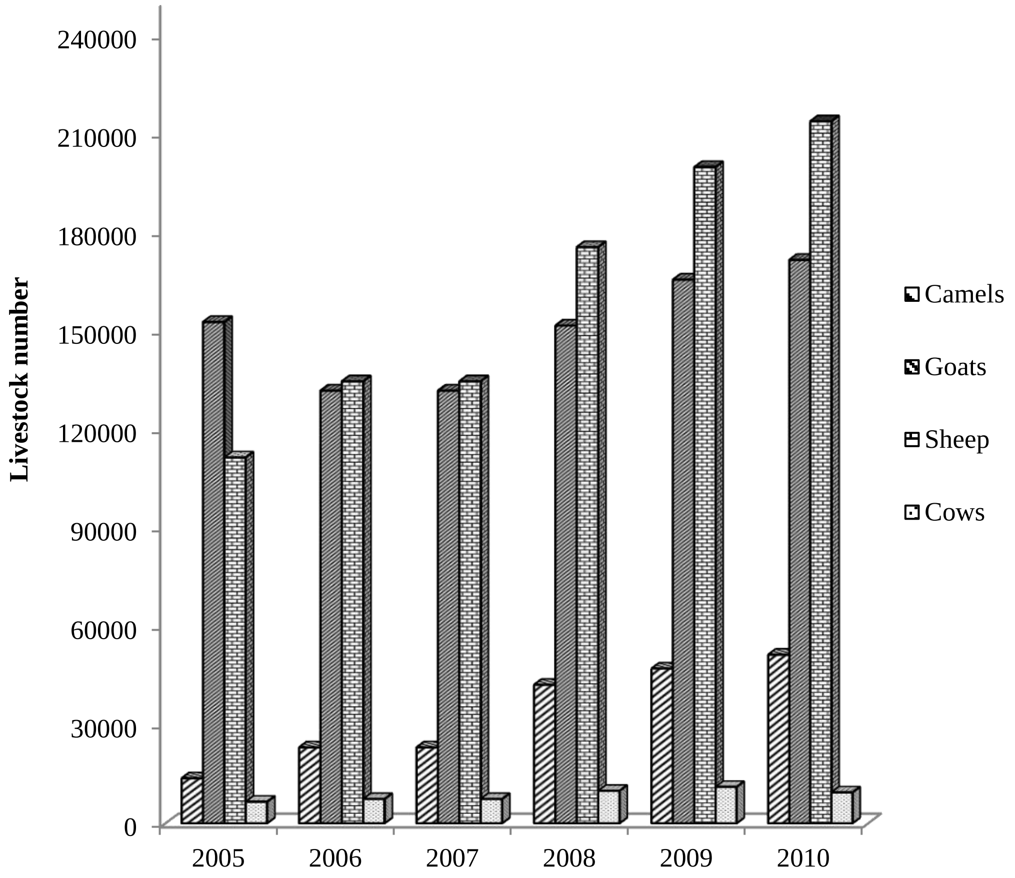


Figure 1-11: Number of Livestock in Qatar 2005-2010.

Source: data from Animal Resources Department, Ministry of Environment.

In spite of previous publications about the number of livestock in Qatar (Abulfatih *et al.*, 2001), accurate statistics only started in 2005 when new labelling systems were introduced by the Department of Animal Resources of the Ministry of Environment (shown in Figure 1-11). In addition, over the last five years the number of camels has increased by more than 350% compared with 2005 (see Figure 1-12). From the last field survey undertaken in April, 2011, probably main reason for the *Acacia* overgrazing in Qatar is due to camel browsing, as shown in Figure 1-13. This is because it is currently very fashionable in Qatar to invest in camel ownership, due to the large potential profits from racing. Consequently, available stock figures and contemporary herding practices suggest that its numbers are exceeded (the carrying capacity) by a large margin (Sillitoe *et al.*, 2010).

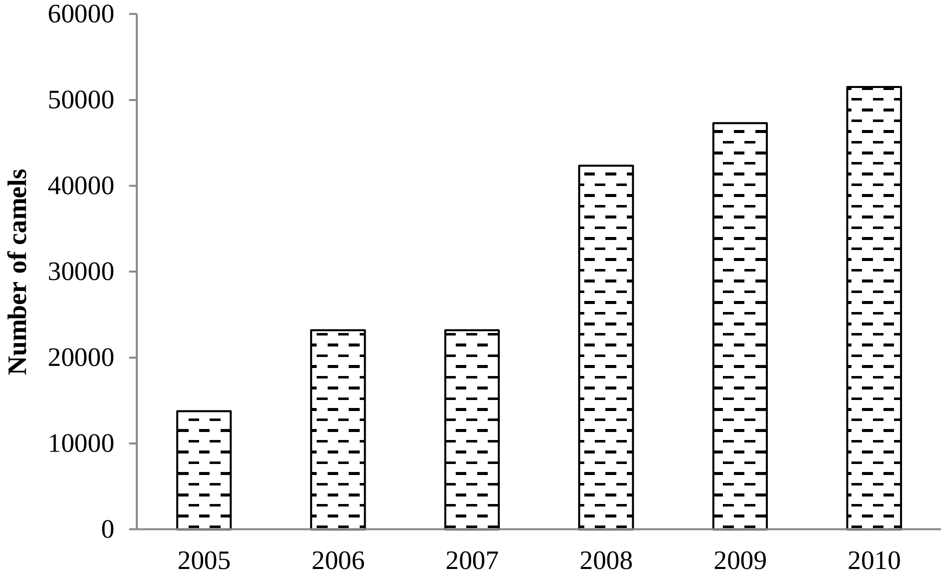


Figure 1-12: Number of Camels in Qatar 2005-2010.

Source: data from Animal Resources Department, Ministry of Environment.

Figure 1-13: Overgrazing on *Acacia* Tree by Camels.

1.5 Environmental Management in Qatar

A. Existing environmental policy of Qatar

The Qatari government has enacted an environmental law (Act Number 32, of the year 1995) to criminalize any action which can damage the botanical environment (vegetation ecosystem) and its natural constituents. It has made the carrying out of any of these actions as a crime punishable by imprisonment as follows:

1. Pasturing in prohibited areas including the following:

   - Pasturing carried out in areas of the botanical environment which need protection or refurbishment.
   - Pasturing carried out in land cultivated for less than 10 years (Article 4, Section 2 of the Act).
   - Pasturing carried out in enclosed areas which are under refurbishment (Article 4, Section 3).
   - Pasturing carried out in areas of the botanical environment where research and studies of botanical cover is being carried out (Article 4, Section 4 of the Act).

2. Crime carrying out actions in areas of the botanical environment without permission:

   - Cutting trees or seedlings in areas of the botanical environment without permission (Article 5, Section 2 of the Act).
   - Cutting, pulling out, burning, removing or transporting leaves or causing damage to trees or seedlings or dry or green grass in areas of the botanical environment without permission (Article 5, Section 4).

3. Prohibited actions in areas of the botanical environment:

   - Burning or the use of fire for anything other than cooking or heating in areas of the botanical environment (Article 7 Section 1 of the Act).
   - Dumping of industrial or agricultural waste, rubbish or broken concrete etc., in areas of the botanical environment (Article 7, section 3 of the Act).

No license for any action in areas of the botanical environment is granted unless deemed beneficial by the Ministry of Environment.

In 2002, the Qatari government has promulgated the law of the environment protection (No. 30 of 2002) to protect the environment against pollution and the following are the summary of relevant articles (Al-Meezan, 2014):

Environment and sustainable development

- Article 2

The present Law aims to achieve the following purposes:

1. Protection and preservation of the quality and natural balance of the Environment.

2. Combat different kinds of pollution; avoid any immediate or long term negative impacts as a result of economical, agricultural, industrial and construction development plans and programs or other developmental programs which aim to improve the standard of living, achieve the Environment integrated protection, and conserve quality and natural balance thereof; and enhance the environmental awareness and principles of controlling pollution.

3. Development of natural resources, conservation of the biodiversity and ensure optimum exploitation thereof for the benefit of the present and future generations.

4. Protection of the community, human heath, other living organisms from all environmentally harmful activities and actions, or that prevent the authorised use of the environmental habitat.

5. Protection of Environment from the harmful impact of activities outside the State.

- Article 9

The Council shall, by coordination with the Competent Authorities, issue the regulations and decisions relating to the conservation of wild life and domesticated living organisms, particularly the endangered species. To enforce such regulations and decisions the Council shall:

1. Prohibit catching rare wild life species.

2. Prohibit cutting and uprooting and removal of wild trees, bushes, and grass.

3. Establish and manage Natural Reserves.

4. Conserve living resources including domesticated animals, local economic plants and their improvement.

The environmental impact of the Projects

- Article 11

The Council shall, by coordination with the competent Administrative Authorities, lay down the necessary criteria, specifications, basics and restrictions for assessing the environmental impact of the Projects and Establishments, which require licensing. In particular the Council shall carry out the following:

1. Determine the categories and sections of the public and private development Projects, which by their nature are harmful to the Environment.

2. Determine the environmentally important areas and location as per the Environment Protection criteria. The Executive Regulation shall determine the procedures for the Environmental Impact Assessment ("EIA") and the conditions for the environmental licensing of the Project or the operating permit, the cases of withholding or cancellation thereof.

- Article 15

'*The Licensing Authority shall ensure that the new Projects and main changes to the existing Projects utilise the state of art economic technology available to control pollution and prevent the environmental Degradation. The Licensing Authority shall also, upon renewal of the licenses of the existing Projects, to ensure that such Projects are using the appropriate technology capable to achieve commitment within the parameters of Environment Protection determined by the Executive Regulation'*.

- Article 18

‘*Whoever designs, implements or operates any Project, shall comply with the systems and measurements of the Environment Protection prescribed under this law, or issued in application thereof. Whoever intends to commit or omit any work potentially harmful to the Environment shall conduct Environmental Impact Evaluation study or any other assessment methods as deemed necessary by this law or the Executive Regulation thereof to identify the Project potential effects, and shall take all the necessary precautions, measures or procedures to counter act such effects, or mitigate the possibility to the minimum level possible’.*

‘Notwithstanding conducting the Environment Impact Assessment study, the owner of the Project shall, in the event of occurrence of any environmental negative effects as a result of committing or omitting an action, be committed to take all the necessary actions to halt such effects or minimise them to the minimum level possible’.

- Article 20

‘*Any natural or corporate person responsible for operating a Project potentially harmful to the Environment shall assign a person to be responsible to ensure achievement of such activities and operations in accordance with the basics and restrictions stated in this law and Executive Regulation thereof’.*

B. The need for better understating of the ecology and what is missing?

Context needs for environmental protection in Qatar. Despite the large body of research studies, legislation and recommendations on the terrestrial environmental protection policy (Al-Meezan, 2014), certain environmental features and habitat types, in particular depression ecosystem, have been much less investigated. The existing environmental policy starts to recognise the need to protect certain environmental features and habitat types. If we going to do that effectively then there is a need to understand the impact of the ecological factors and their interactions. In addition current environmental recommendations and environmental policy needs to put more emphasise on the depression landforms.

CHAPTER 2: A REVIEW OF ACACIA TORTILIS ECOLOGY AND METHODS OF STUDYING VEGETATION CHANGE

Introduction

Desertification is becoming prevalent in arid and semi-arid regions of Northern Africa and Arabian Peninsula following the rapid and pronounced decimation of drought-resistant *Acacia tortilis* Forssk (Hayne), which is one of the most common arboreal plant species with the potential of surviving in the harsh climatic condition of these regions (Kennenni and Maarel, 1990; Ward and Rohner, 1997; Labidi *et al.*, 2007; Abdallah *et al.*, 2008; Abdelrahman and Krzywinski, 2008; Chigani *et al.*, 2012; Traoré *et al.*, 2012). This high mortality of the *Acacia* trees could be caused by a combination of biotic and abiotic factors. The biotic factors may be attributed mainly to anthropogenic disturbances which may include aquifer depletion for agriculture, extensive over-grazing and cutting for various purposes, urbanization and quarrying which may have enormous effects on the survival of the *Acacia* trees (Ward and Rohner, 1997; Labidi *et al.*, 2007; Zaghloul and Hamrick, 2007; Zaghloul *et al.*, 2008; Noumi *et al.*, 2010; Abd el-wahab *et al.*, 2013). Besides anthropogenic factors, the unprecedented infestation of *Acacia* trees and seeds by *bruchid* bettles may culminate not only in the utter destruction of mature *Acacia* trees but also reduces the chances of germination of the seeds and diminishes the natural recruitment / regeneration of this important plant species (Rohner and Ward, 1999; Labidi *et al.*, 2007). In addition, several other abiotic environmental factors such as the drought conditions, soil properties and topography have been shown to affect the abundance and distribution of the dominant species such as *Acacia tortilis* in the arid and semi-arid regions (Traoré *et al.*, 2012).

The socio-economic importance and major role *Acacia tortilis* plays in biodiversity and soil ecology, especially its enormous contributions to the conservation of the ecosystem in these regions, has necessitated a concerted global effort to curb the rapid decline of this invaluable plant (Thomas and Middleton, 1994; Abdallah *et al.*, 2012; Traoré *et al.*, 2012). Many countries have established forest management practices which involve regeneration programme and the development of techniques to protect endangered species like *Acacia tortilis* (Abdelrahman and Krzywinski, 2008; Hatab, 2009). The promulgation of environmental planning and management laws aimed at protecting endangered species is not uncommon in many of these countries that had to deal with endangered species. A typical example is Egypt (Abdelrahman and Krzywinski, 2008); many other countries like Qatar are emulating these initiatives to tackle this problem. Several studies have also been undertaken to provide better understanding of the environmental determinants affecting the distribution of endangered species such as *Acacia tortilis* in arid and semi-arid regions (Anderson *et al.*, 2001; Lahav-Ginott *et al.*, 2001; Abd El-Ghani and Amer, 2003; Noumi *et al.*, 2010; Traoré *et al.*, 2012; Abd el-wahab *et al.*, 2013). Despite these efforts there is still scarcity of reliable detailed historical information and poor understanding of the relationship between the environmental factors and the distribution of *Acacia tortilis* in arid and semi-arid regions (Kennenni and Maarel, 1990; Ward and Rohner, 1997; Eshete and Ståhl, 1998; Wiegand *et al.*, 1999; Wiegand *et al.*, 2000a; Wiegand *et al.*, 2000b; Lahav-Ginott *et al.*, 2001). Hence, it is imperative for more research to be undertaken not only in providing insight on the magnitude of the growing trend of desertification; but also to enable a thorough understanding of those environmental factors that influences the distribution of *Acacia tortilis* in these regions. The findings from such studies would assists in making better policies for managing regeneration programmes to the extinction of plant species like *Acacia tortilis*.

This research aims to address the paucity of information regarding the extent of desertification in Qatar and provide better understanding of the environmental determinants affecting the distribution of *Acacia tortilis* in this small country that is situated in the Arabian Peninsula. Accomplishing the objectives of this research entails the application of several methods for the acquisition of useful data on the soil characteristics and the morphological attributes of *Acacia tortilis* in the study area of Qatar. It also involves the testing of several hypotheses which have been elaborated in previous sections of this thesis. The hypotheses considered in this research were formulated to assess the influence of both the abiotic and biotic environmental factors on the abundance and distribution of *Acacia tortilis* in Qatar. The abiotic environmental factors were based on the variation in topography and soil characteristics in the study area which assert strong influence on the availability of water resources known to be a ‘key factor’ governing the abundance and distribution of *Acacia* communities (Morison *et al.*, 1948; Yair and Danin, 1980; Batanouny and Ismail, 1985; Kennenni, 1991; Patten and Ellis, 1995; Galal, 2011). It also involves scrutinizing the morphological characteristics (e.g. tree height, crown diameter, crown area and basal area) at different topographic positions to ascertain their importance in the production and adaptability of the *Acacia tortilis* (Tietema, 1993; Eshete and Ståhl, 1998; Raebild *et al.*, 2003; Sinsin *et al.*, 2004; Sanon *et al.*, 2007), while the biotic environmental factors such as animal grazing and anthropogenic activities were also assessed to determine their impact on the distribution, establishment and dynamics of *Acacia tortilis* (Kennenni and Maarel, 1990; Rohner and Ward, 1999; Shaltout *et al.*, 2009). Hence, several hypotheses were tested in this research to ascertain if the distribution and regeneration of *Acacia* trees in Qatar was positively correlated with topographic gradient of either slopes or depressions which receives run-off water as water is a limiting factor in arid and hyper-arid regions. Other hypotheses relate the correlation of the distribution and abundance of the *Acacia* trees to either the soil properties or the degree of site disturbance (i.e. site protection). This chapter critically reviews relevant literature that relate to the several hypotheses, soil characteristics and morphological attributes of the *Acacia tortilis* considered in this research with the aim of highlighting important findings on the influence of environmental factors affecting the abundance and distribution of the *Acacia tortilis* in the arid and semi-arid regions.

2.1 Ecology and Distribution of *Acacia tortilis*

The genus *Acacia* was first described by Philip Miller in 1754 and has been shown to be the second largest in the family Leguminosae, with more than 1300 species (Maslin *et al.*, 2003; Steven and Subramanyam, 2009). Moreover, *Acacia* is the largest group of woody trees and shrubs in the subfamily Mimosoideae (Sprent, 1995; Dharani, 2006). Many members of the genus *Acacia* are drought-resistant trees that dominate the regions of arid and semi-arid ecosystems in Northern Africa and Arabian Peninsula due to its ability to tolerate severe climatic conditions (Abdelrahman and Krzywinski, 2008). It is a very important genus because of its numerous uses to man and other organisms within its ecosystem, which include fodder for livestock such as goats and camels; fire wood; charcoal and construction material for the local inhabitants (Kennenni and Maarel, 1990; Wiegand *et al.*, 1999; Kiringe and Okello, 2005; El Ferchichi Ouarda *et al.*, 2009). *Acacia* trees also provide shelter for the local people and their crops under their canopy and have been extensively used for sand stabilization and dune fixation in many countries (Belsky *et al.*, 1989; Kennenni and Maarel, 1990; Dean *et al.*, 1999).

2.1.1 *Acacia* and its environment

Acacia tree functions as `keystone species' in arid and semi-arid regions of Africa and the Middle East and has a significant influences on ecosystem functioning and biodiversity (Milton and Dean, 1995; Ward and Rohner, 1997; Dean *et al.*, 1999; Ba *et al.*, 2002; Stave *et al.*, 2005; Andersen and Krzywinski, 2007a). Deserts, arid and semi-arid regions typical environment of *Acacia* trees, constitute the largest terrestrial biome covering more than 40% of the terrestrial surface (Washington-Allen *et al.*, 2008; Brahim *et al.,* 2011; Sonnenschein *et al.,* 2011). These regions are characterized by droughts, variable rainfall, livestock production and soil erosion (O'Neill, 1996). Vegetation is considered as one of the most essential aspects of such environments because it supports biodiversity, improves air quality, buffers the soil against erosion and is also a major source of human livelihood in terms of food, pasture for livestock, fuel and income (Omuto, 2011). On the other hand, anthropogenic activities profoundly affect such environments, either via habitat destruction and/or biodiversity reduction (FAO, 2005; Pettorelli *et al.*, 2005).

Several studies have demonstrated that wherever *Acacia tortilis* grows, it plays important roles in the biodiversity and composition of the ecosystem (Abdelrahman and Krzywinski, 2008; Abdallah *et al.*, 2012). It has positive effect on the understory vegetation as its canopy provides protection to other vegetation underneath it by significantly reducing the light intensity, air temperature and humidity that increases soil moisture content. *Acacia tortilis* also enhances soil fertility by improving soil nutrient contents and microbial biomass and improves soil structure by adding organic matter to the soil (Wiegand *et al.*, 1999; Ba *et al.*, 2002; Moustafa and Mansour, 2003; Abdallah *et al.*, 2008; Abdallah *et al.*, 2012). It has been suggested that bird droppings which cover the ground under the *Acacia* trees constitute an important source of nutrients to the soil. Again, some ecological conditions such as binding wind-drifted sand play an important role by providing one of the most favourable habitats for plants in the desert for the following reasons: (i) sands readily absorb rainwater without allowing surface run-off; (ii) the upper layers of the sand cover are highly protective against evaporation; (iii) The concentration of injurious salts is at a minimum in sandy soils (Zohary and Orshan, 1956). El-Bana and Al-Mathnani (2009) studied the vegetation-soil relationships in the Libyan Sahara. The results show that *Acacia tortilis* occupied the wadi channels and some plant species in the study area were found to bind wind-drifted sand which accumulates and build up sand mounds and hummocks within or around their canopies.

In an investigation into effect of *A. tortilis* in increasing the organic carbon content in soil, Kahi *et al*., (2010) in Kenya and El Atta *et al.*, (2013) in Saudi Arabia, found that trend of increasing soil organic carbon below the tree canopies of *Acacia tortilis*. In addition, as a leguminous tree *Acacia* is a good colonizer of poor soil (Ben Romdhane *et al.*, 2005). Indeed, by the interactions they have with root nodules, bacteria may be responsible for significant levels of nitrogen fixation (Sprent, 1995; Fterich *et al.*, 2012). The effect of *Acacia* trees on their physical, chemical, and biological environments has been extensively studied in different ecosystems. Nevertheless, the environmental factors affecting plant growth, distribution and dynamics are often complex and difficult to determine (Ben-Shahar, 1991); but are necessary to properly understand the existence, abundance and distribution of this important plant species (Belsky *et al.*, 1993; Belsky, 1994; Ba *et al.*, 2002; Abule *et al.*, 2005; Abdallah *et al.*, 2008; Fterich *et al.*, 2011). Findings from such studies would assists in facilitating ways of dealing with existing threat of the extinction of this important plant species.

2.1.2 Factors determining the distribution of *Acacia tortilis*

Thorough understanding of the environmental factors that affect the growth and ecological distribution of plants such as *Acacia tortilis* is paramount due to the vital role it plays in biodiversity and environmental conservation. These environmental factors common to the arid and semi-arid regions of the world are numerous (Evenari *et al.*, 1985); which may include climate, weather, geomorphology, soils, diseases, hydrology, large and small browsers as well as the human activities. In fact, these unpredictable environmental conditions which randomly fluctuate have been considered to be one of the important stochastic factors that affect survival and reproduction of trees (Boyce, 1992; Menges, 1992). Regardless whether these environmental factors are abiotic (e.g. soil properties) or biotic (e.g. anthropogenic activities; they are often inter-related and affect the survival of *Acacia tortilis* in arid habitats which are usually diverse in terms of climate, soils, vegetation, animals, and the lifestyles and activities of the people. Indeed, it is a daunting task to understand the environmental factors affecting the growth, distribution and dynamics of the *Acacia tortilis* without identifying its unique ability to cope and adapt with the harsh desert conditions. Consequently, there is need to shed more light on the most important environmental factors that may influence the distribution of the *Acacia* tree in the dry-hot environment of Qatar.

2.1.2.1 Abiotic environmental factors

Topography or land heterogeneity

Topography and soil characteristics have strong influences on the availability of water resources and consequently on the distribution of *Acacia* density. This is broadly consistent with the review of literature carried out earlier by Morison *et al.,* (1948); Yair and Danin (1980); Batanouny and Ismail (1985); Kennenni (1991) and Patten and Ellis (1995). Therefore, water has been regarded as the most important single limiting factor in the productivity of desert ecosystems; hence the description of deserts as 'water controlled ecosystems' (Noy-Meir, 1973). The water available for plant uptake is not restricted to the soil water content only, but could also be taken directly from the atmosphere (e.g. dew in the air) or surface water from run-off. Consequently, the availability of water is one of the primary factors controlling the distribution of most plant species in Qatar which is an arid and/or hyper-arid desert that is usually characterized by minimal precipitation and harsh drought environment (Batanouny, 1981; Abulfatih *et al.*, 2001; Abdel Bari, 2005). This has prompted Bendavid-Novak and Schick (1997) to investigate the effect of an abrupt change in the hydrological regime on the patterns of mortality and regeneration of the populations of two species (*Acacia tortilis* and *Acacia raddiana*) in the hyper-arid region of Negev. They reported that the patterns of mortality and regeneration of the *Acacia* tree population were influenced by surface flows and the surface water regime was of a major importance for the distribution of *Acacia* trees in hyper-arid environments. Moreover, the distribution of *Acacia* species in the Negev and Sinai was not in a steady state; the rate of germination and tree establishment was highest in years in which the rains start early. Bendavid-Novak and Schick, (1997) added that such conditions enables the sprouts of the *Acacia* tree to develop relatively deep roots before the onset of their first dry season.

Furthermore, the soil water availability is recognized as a key factor determining tree growth, species composition and distribution as well as ecosystem function in arid and semi-arid areas (Noy-Meir, 1973; Reynolds *et al.*, 2004). Otieno *et al.*, (2001) studied the climatic and edaphic factors prevailing in arid environment which poses challenge to the rehabilitation and planting of *Acacia* trees. Among all studied factors, drought was found to be the single most important factor limiting tree establishment in such environments. Again, Otieno *et al.*, (2001) studied the growth features of *Acacia tortilis* (Forsk), Hyne seedlings and their response to cyclic soil drought stress under controlled conditions. Their results indicated that *A. tortilis* seedlings shifted carbon allocation to the roots, leading to a root: shoot ratio of 1.5 in water-stressed seedlings, compared to 0.5 in the control plants. They concluded that *Acacia tortilis* survive during drought through *dehydration postponement strategy* which involves the reallocation of carbon to the roots away from the shoots and to actually increase root growth.

Edaphic factors

Edaphic (soil) factors are one of the main elements that affect *Acacia tortilis* growth and habitats in areas such as the Middle East (Batanouny, 1981; Babiker, 1990; Abd El-Ghani and Amer, 2003; Norton *et al.*, 2009). Al-Qarawi (2011) assessed the vegetation-soil relationships in Om Al-Khefas, Saudi Arabia, and found that the main soil variables controlling the separation of the vegetation groups are soil texture, pH and $CaCO_3$. According to Al-Qarawi (2011), the tree group represented by *Acacia tortilis* subsp. *tortilis* and *Ziziphus nummularia* is positively correlated with the proportion of silt and clay in the soil. Similarly, Abd El-Ghani and Amer (2003) studied the soil-vegetation relationships and focuses on the environmental factors that control the species distribution in Sinai, Egypt. They found that soil surface sediment, $CaCO_3$, soil saturation, pH and organic matter were the main operating edaphic gradients in the study area and these gradients were related closely and accounted for 67% of the species–environment relationship among the sites. They also added that *Acacia tortilis* occur on the alluvial plains, somewhat fertile with high soil content of sand and gypsum. However, some authors have stated that *A. tortilis* is generally indifferent to soil type and lithology when growing in wadi ecosystems and depends more on the size of the wadi (seasonal water courses) that is receiving run-off (Halevy and Orshan, 1972; Ayyad and Ghabbour, 1986; Kennenni and Maarel, 1990).

Fterich *et al.* (2011) has quantified the effects of the dominant legume *Acacia tortilis* subsp. raddiana on soil properties in arid area of Tunisia. They found that the highest microbial density and activity were recorded in sandy-loam soil. Microbial biomass and activity increased gradually and significantly to a maximum at 20-30cm and subsequently decreased at 30-50cm. They highlighted the considerable effect of *Acacia tortilis* subsp. raddiana on chemical, microbial and biochemical properties of soil and concluded that the improvements in soil properties were dependent on soil texture, with a large increase from gravelly-sand to sandy-loam and loam soils. Based on these findings by Fterich *et al.*, (2011), one is bound to presume that soil texture may be an important factor influencing the *Acacia tortilis* distribution since the different soil textures exhibit different water retention ability. For example, soil water content will be less available for plant uptake in clayey soils compared to sandy-loam soils because clayey soils have greater water retention ability than sandy-loam.

In Qatar, it seems that the degree of retention of soil moisture, level of salinity, soil particle size and degree of soil compaction are the main edaphic factors which are often inter-related and affect plant growth (Norton *et al.*, 2009). While the mineral and nutrient content of soils may be important secondary factors which affects the distribution of the *Acacia tortilis* tree in Qatar (Scheibert *et al.*, 2005). Again, geomorphological or landform has been shown to be one of the major factors affecting the distribution of *Acacia tortilis* in the arid and hot areas (Morison *et al.*, 1948; Yair and Danin, 1980; Babiker, 1990; Kennenni, 1991; Galal, 2011). Abd El-Ghani and Amer (2003) found that plant life in southern Sinai, Egypt was restricted to microenvironments (such as wadis and runnels) where run-off water collects and provides sufficient moisture for plant growth. Also, other authors noted that spatial distribution of plant species and communities over a small geographic area in desert ecosystems is related to heterogeneous topography and landform pattern (Eyre, 1968; Kassas and Batanouny, 1984). Geography and phytosociology of *Acacia tortilis* have been studied by Kennenni (1991) in the Sudan. The results indicate that *Acacia tortilis* is a characteristic species along seasonal water courses (wadis) and in areas receiving run-off. Consequently, its distribution is mainly determined by rainfall, soil and topography.

A detailed study which used phytogeographical methods to analyze the distribution of plant communities in the arid northern Negev was undertaken by Yair and Danin (1980). Their findings indicate that high soil moisture and run-off regime prevail in arid regions that supports high distribution of plant communities. In addition, they found that the best water regime and a high diversity of plant species were associated with massive limestone unit, while the worse water regimes were found where densely jointed and thinly bedded limestones. Consequently, the change along slopes due to the water contributing areas and the soil volume collecting the run-off causes high diversity of micro-habitats, even over short distances. Hence, it is important to consider the following soil chemical properties which influence plant growth and distribution:

- **Soil pH**

The acidity or alkalinity of soil is based on the total hydrogen ion concentration in the soil water solution (expressed on a pH scale). It is an important soil property that reflects the biological processes occurring in the soil and also provides a good indication of its chemical status. In general, soil pH influences nutrient uptake and tree growth. At the extreme values (< 4.0 and > 8.5), it can make some nutrients toxic and others unavailable to plants (Sims, 1986; Rengel, 2003). The concentrations of calcium carbonate and exchangeable cations, which have been found to be very high in most Qatari soils (Scheibert *et al.*, 2005), therefore falls within the expected range for such calcareous soils with pH values above 7 (Dregne, 1976 ; Birkeland, 1999).

- **Electric conductivity (EC)**

Soil salinity is a widespread limitation to plant growth in arid and semi-arid soils worldwide (Janzen, 1993). The concentrations of soluble salts, through their high osmotic pressures affect plant growth by restricting the uptake of water by the roots and can also have a general deleterious effect on plant growth due to the high concentration of salts in the soil solution interfering with the balanced absorption of essential nutritional ions by plants (Tester and Davenport, 2003). In addition, it is one of the most important edaphic factors affecting seed germination and plant growth in the arid regions (Mehari *et al.*, 2005; Abari *et al.*, 2011). *Acacia tortilis* has been shown to dominate soils with moderate salinity (El-Demerdash *et al.*, 1995). The effect of plant species like *Acacia tortilis* on the electrical conductivity of soils in various sites that has been exposed to different extent of livestock grazing was investigated by Abule *et al.,* (2005). In the heavily, medium and lightly grazed sites, they found that the electrical conductivity was significantly higher in soil under the canopies of *Acacia tortilis* compared to the open grasslands in all the sites studied. They also found that the electrical conductivity decreased with an increase in soil depth (Abule *et al.*, 2005). Abdallah *et al.*, (2008) obtained similar results which indicate higher electrical conductivity in the canopied subhabitat in both the lightly and heavy grazed site than in the uncanopied subhabitat. In contrast to the result obtained by Abule *et al.*, (2005), Abdallah *et al.,* (2008) found that the electrical conductivity of the soil from the canopy and uncanopied areas were not significantly different. Other studies indicate that the electrical conductivity in the canopied subhabitat and uncanopied subhabitats were not significantly different (Noumi *et al.*, 2011); which contradicts findings by Abdallah *et al.*, (2012). The contradictory results obtained by various researchers show lack of consensus regarding the effect of *Acacia tortilis* on the electrical conductivity in soil. Again, widely accepted explanation of the mechanism of the effect of *Acacia tortilis* on the electrical conductivity in soil is still elusive (Smit, 2002; Noumi *et al.*, 2011). Nevertheless, it has been deduced that litters of leaves from grazing and the faeces (or waste) of animals indulging in grazing or seeking shelter under the canopies of *Acacia tortilis* may contribute to the higher electrical conductivity within this area (Belsky *et al.*, 1989; Young, 1989). This argument concurs with the findings of Abdallah *et al.*, (2012) that asserted the correlation between the electrical conductivity and the extent of grazing. They found that heavily and medium grazed sites were significantly higher at 99.9%; whereas the lightly grazed site was significant only at 95% level. This suggests that the level of grazing of the *Acacia* trees may have effect on the higher electrical conductivity in soil under its canopies.

- **Available phosphorus (P)**

Phosphorus (P) has been known to be an essential nutrient for a healthy plant growth and like nitrates, anions, cations and other trace elements, it enhances the productivity of plants (Abdallah *et al.*, 2008; Treydte *et al.*, 2008; Cech *et al.*, 2010; Noumi *et al.*, 2011). Although *Acacia tortilis* require available P for its normal physiological functioning; its presence has been linked to soil enrichment in arid ecosystems. For instance, it has been found that available P content was significantly higher in soil under the canopy of *Acacia tortilis* than those in the uncanopied subhabitat (Abdallah *et al.*, 2012; Noumi *et al.*, 2011). In other words, due to enrichment of nutrients such as P; the soil under the canopy area was more fertile than those outside this area. According to Abdallah *et al.*, (2008) the highest mean available P was recorded under the tree canopy and declined towards the open area. In general, they also reported that the topsoil was richer in available P; which decreases with depth in both the canopied and uncanopied areas. The decrease of available P with depth was found to be steeper in the lightly grazed sites (Abdallah *et al.*, 2008). Again, they found that available P was much higher in the lightly grazed site than the heavily grazed site. Furthermore, there was significant difference in the available P under the tree canopy and the uncanopied area in the lightly grazed site. While for all the parameters studied (including available P) were found to be non-significantly different for the canopied and uncanopied subhabitats (Abdallah *et al.*, 2008). Consequently, heavy grazing, especially with long history may have a strong overriding effect on the numerous advantages (e.g. soil enrichment) of *Acacia* trees in the arid regions (Abdallah *et al.*, 2012; Abdallah *et al.*, 2008). The need to derive these benefits offer by *Acacia tortilis* makes it imperative for the implementation of robust environmental management plan to facilitate the protection of this important plant from over-grazing.

- **Organic carbon**

Arid and semi-arid regions are dominated with soils that are highly degraded and generally contain a low level of organic matter which is critical for better soil condition and higher soil productivity (Pascual *et al.*, 2000). Soil organic matter is often described as the percentage of soil organic carbon present in the soil sample. Therefore, organic carbon is part of the soil organic matter which includes other important elements such as calcium, hydrogen, oxygen, and nitrogen. *Acacia tortilis* being a legume tree, organic carbon in soil is an important component for microbial density and activity (Fterich *et al.,* 2011). Furthermore, organic matter possesses important characteristics such as their ability to absorb and release plant nutrients; form water-soluble and water insoluble complexes with metal ions and interact with clay minerals and bind particles together (Schumacher, 2002). Consequently, the determination of soil organic carbon is necessary, as its presence or absence can markedly influence how chemicals will react in the soil (Schumacher, 2002).

The correlation between soil organic matter and vegetation cover of *Acacia tortilis* and its potential of enhancing the nutrient status of soil under its canopy has been severally reported (Gedda, 2003; Abdallah *et al.*, 2008; Kahi *et al.*, 2010; Fterich *et al.*, 2011; Noumi *et al.*, 2011; Abdallah *et al.*, 2012) . Hence, it is no uncommon for higher concentrations of soil nutrients like soil organic matter to be found under the canopies of *Acacia* trees (Belsky *et al.*, 1989; Young, 1989). Similar to other soil nutrients already discussed, Abule *et al.,*(2005) found that soil organic matter was significantly higher under the canopies of *Acacia tortilis* compared to the uncanopied area like open grassland (Abule *et al.*, 2005; Noumi *et al.*, 2011). The soil organic carbon under the canopies of two woody trees namely: *A. tortilis* and *B. aegyptica* has been compared by Abule *et al.,* (2005); their results indicate that there was no significant difference of soil organic carbon (at 95% confidence level) under the canopies both trees in the heavily grazed site. In contrast, the soil organic carbon was found to be significantly higher under the canopies of *A. tortilis* than those of *B. aegyptica* in the medium and lightly grazed sites (Abule *et al.*, 2005). Similar to the trend of other soil nutrients such as phosphorus, Abule *et al.*, (2005) reported that the soil organic carbon significantly decreased with an increase in soil depth for the lightly, medium and heavily grazed sites. This findings on the effect of soil depth on soil organic carbon concurred with other reports (Bernhard-Reversat, 1982; Asferachew *et al.*, 1998; Abdallah *et al.*, 2008).

- **Total gypsum**

There has been growing interest in the study of gypsum contents ($CaSO_4.2H_2O$) in soils, especially, in the semiarid and arid regions of the world where it persists (Porta, 1998). Gypsum is characterized by relatively low solubility in aqueous system. It can also be dissolved and its ions translocate in the soil. The formation lenticular gypsum in the soil could also be due to further precipitation of Ca^{2+} and SO_4^{2-} of gypsum (Porta, 1998). It is not uncommon for gypsum to accumulate in soils due to lack of leaching of the gypsum, especially, in the arid and semi-arid regions with relatively low rainfall. Consequently, the soil physical and chemical properties are affected by the presence gypsum content in the soils and could render the soil infertile (Mashali, 1996). A typical example is Qatar, where plant growth and their productivity are affected by the soil gypsum which acts as a semi-soluble soil constituent where its presence exceeds a given threshold (FAO, 1990). In addition, high gypsum content in soils create imbalances or irregularities that affects water uptake by plants (Mousli, 1981; Schmid and Leuschner, 1998). Poch *et al.*, (1998) noted that water can rarely be used by roots since gypsum crystal prevents root penetration. Therefore, gypsum in layers within the root zone is one of the problems encountered by the roots of most plant, which in turn causes restricted root growth in such soils.

Like many other edaphic factors, the presence of gypsum in soil influences the distribution of vegetation in arid and semi-arid regions (Rubio and Escudero, 2000; Chigani *et al.*, 2012). Although the effect of most edaphic factors such as anions, cations and the various soil nutrients on *Acacia tortilis* and its impact on the soil enrichment of these factors have been extensively investigated; but there is still relative paucity of studies dealing with the effect of gypsum content on *Acacia tortilis*. Nevertheless, studies have shown the effect of gypsum on many other plant species and have emphasized the varied level of resistance to high level of gypsum content in arid and semi-arid soils (Rubio and Escudero, 2000; Chigani *et al.*, 2012). It is typical to find increased gypsum concentrations in the lower soil horizons which often culminate in the formation of hardpan or crust that obstructs the penetration of water and roots into the soil (Chigani *et al.*, 2012). The impenetrable layer of petrogypsic horizon formed due to the secondary gypsum illuviation in the lower soil layer may adversely affect *Acacia tortilis* in arid and semi-arid regions where available soil water content seems to be the key controlling factor governing the abundance and distribution of plant species. It has also been stressed that the chemical and physical properties of gypsiferous soils makes them deficient in soil nutrients such as organic matter which may affect not only the morphological attributes of the plants; but also their diversity, abundance and distribution (Eftekhari and Asadi, 2001). Considering the economic importance of gypsum, its excavation in arid and semi-arid regions that are dominated with plants such as *Acacia tortilis* may affect the distribution of the vegetation cover (Chigani *et al.*, 2012).

Rainfall and climate

Rainfall is an important source of water availability in the soil, which has been found to be a key factor determining the survival and regeneration of the *Acacia* tree in arid and semi-arid areas. Some studies on *Acacia tortilis* showed that only rainfall events higher than 10 mm are beneficial to vegetation in arid areas (Floret and Pontanier, 1982). In addition, *Acacia tortilis* seedlings were able to survive with limited supplies of rainwater only. Thus, it is clearly a facultative phreatophyte that can also extract water from unsaturated soils (Stave *et al.*, 2005). Moreover, Wilson and Witkowski (1998) determined the water requirements for germination and early seedling establishment of four African *Acacia* species, of which *Acacia tortilis* was one of them. They noted that frequent (even small) rainfall events may promote seedling establishment more effectively than fewer large rainfall events. However, a study by Stave *et al.* (2006) assessed the underlying causes of seedling recruitment (establishment) and mortality of the dominant tree species *Acacia tortilis* in Kenya. They argued that seedling recruitment of *Acacia tortilis* was induced by prolonged rainfall. Similarly, Skoglund (1992) stated that recruitment of *A. tortilis* was apparently discontinuous and confined to years with a relatively high precipitation. In addition, Rohner and Ward (1999) reported that several years of high rainfall are necessary for successful establishment of young *Acacia* trees.

Depth to groundwater level and rooting system of Acacia tortilis

It has been argued that rooting depth increases with aridity (Batanouny and Abdel wahab, 1973; Canadell *et al.*, 1996). Several studies have also indicated that *Acacia tortilis* trees had their roots located within both surface soil horizons and the deeper soil horizons with a stable water source reaching more than 25 m (Belsky, 1994; Caldwell *et al.*, 1998; Ludwig *et al.*, 2003; Ludwig *et al.*, 2004; Deans *et al.*, 2005; Do *et al.*, 2008). A field study conducted by Otieno *et al.*, (2005) on *Acacia tortilis* in Kenya showed that the leaf growth and shoot elongation depended on soil water availability and plant tissue water status. Consequently, the success of *Acacia tortilis* in the more xeric regions of the arid environment was due to its deep rooting system and efficient root water uptake and transport (Otieno *et al.*, 2005). They added that root distribution of *Acacia tortilis* seems to determine tree phenology and water use and essential determine species distribution patterns in the arid area. Previous work have shown that *A. tortilis* trees explored the soil profile to depths of up to 35 m to reach water (Ong and Leakey, 1999; Schroth and Lehmann, 2003).

Roots located within the shallow soil layers between 0-40 cm has been shown to be the region of greatest root biomass (Cavender-Bares and Bazzaz, 2000). However, Otieno *et al.*, (2005) found that growth in large *Acacia tortilis* is less affected by soil drying at this depth, therefore, the rapidity and simultaneity with which leaf onset and growth responded to rainfall was an indication that they were able to access water soon after the rainfall. In addition, Do *et al.* (2008) found that due to extensive water use from deep soil layers, the water in the top layers of soil was rapidly depleted soon after the wet season. Also, they added that despite a wide variation of environmental and growth condition reflects on the *Acacia tortilis* regulation of water loss, deep rooting was the most obvious mechanism which provides access to deep water, which in turn strongly regulates canopy conductance. In arid environments, a greater allocation of photosynthates to the roots as compared to shoots is found to be successful mechanism for trees, and sometimes, the absolute root growth is enhanced (Jones, 1992; Scholz *et al.*, 2002). This enables extraction of water from a large volume of soil or from a deep water table when the upper soil horizons are dry (Jones, 1992; Jackson *et al.*, 2000).

Water availability within the top soil is an important factor for the development of adult trees given the seasonal nature of moisture availability. Existence of the fine fibrous and/or woody roots found within this depth has been used as an indicator for such relationship (Otieno *et al.*, 2005). Previous studies have demonstrated that *Acacia* has dense roots close to the soil surface which rapidly utilize any precipitation, and hence rapidly "greens up" in response to even small amounts of rain (Barkham and Rainy, 1976; Otieno *et al.*, 2005). Furthermore, Halevy and Orshan (1973) studied the phenological behaviour of the *Acacia tortilis* in the Negev and Sinai and found that partial defoliation took place in July and the flush of growth of new leaves in August, a long time before the first rain. They also added that *Acacia tortilis* reached their maximal leaf cover in December and the leaves lasted until the next summer. Moreover, the growth of new leaves took place in autumn (Oct and Nov). From the field observation, *Acacia* trees in Qatar follow the same trend of flushing new leaves by the end of September before the commencement of the rainy season. Since plants require water for the important physiological phase of leaf onset (i.e. producing new leaves); therefore, it can be deduced that in severe hyper-arid areas the *Acacia* trees could have possibly depend on the underground water for leaf onset.

2.1.2.2 Biotic environmental factors

Predators and human impacts

A considerable amount of literature has been published on the abiotic factors that are often the most important factors influencing the distribution of a species (Kouba *et al.*, 2011). Brown (1988) emphasized that abiotic factors can exert significant control over plant distribution. Many studies have also focused on the biotic factors that affect the *Acacia* trees. For instance, Bruchid beetles (Bruchidae) have been found to constitute the major pests of *Acacia* seeds that can seriously hamper the tree regeneration. The process of infestation involves the Bruchids initially attacking the fresh green *Acacia* pods on the tree; re-infestation following emergence may then occur on mature dry pods on the tree or ground (Miller and Coe, 1993). Rohner and Ward (1999) studied the effects of large mammalian herbivores on the establishment of young *Acacia raddiana* and *Acacia tortilis* in the Arava Valley between the Red Sea and the Dead Sea. Large herbivores were found to impact on the *Acacia* species because when excluded the seed accumulation under trees were high and direct observations revealed that ungulates were the main seed dispersers of these *Acacia* species. Seed germination was facilitated by gut passage through ungulates. Herbivores such as goats and camels facilitate the dispersal of *Acacia* seedlings and improve its germination by scarification of the seed coat and killing of bruchid beetles (Hauser, 1994; Rohner and Ward, 1999; Or and Ward, 2003). Over 95% of seeds not consumed by ungulates were destroyed by insects such as bruchid beetles. Whereas, seedlings survival was determined largely by water availability and was independent of herbivore density. Consequently, they concluded that large mammalian herbivores are important components of arid *Acacia* savannas and that wild and domestic ungulates should be included in future conservation plans.

Other studies attempted to assess the mortality rate of the *Acacia* tree in arid and semi-arid regions. The population ecology of *Acacia tortilis* in the semi-arid region of the Sudan has been investigated (Kennenni and Maarel, 1990). This study indicates that the population of this plant species in the arid region of Sudan is rapidly declining and that drought and lethal cutting were the main mortality factors. Shaltout *et al.*, (2009) analysed the structure of the populations of eight common shrubs and trees in South-East Egypt, of which *Acacia tortilis* subsp. *tortilis* was among those studied species. They concluded that overgrazing, especially by camel stock, as the obvious cause of degradation that affects the life of mother trees of *Acacia tortilis* in Wadi Allaqi Biosphere Reserve (South-East Egypt). Similarly, anthropogenic activities such as overgrazing, overcutting, off-road driving and out-door activities (e.g. picnics by locals and tourists) were also found to contribute to the vegetation dynamics in Saudi Arabia (Al-Qarawi, 2011). It is also worthwhile to mention that *Acacia* species (*A. ehrenbergiana*, *A. tortilis* subsp. *tortilis* and *A. tortilis* subsp. *raddiana*) are considered the most grazed plants in the region (Shaltout *et al.*, 2009).

2.1.3 Morphology and performance of *Acacia tortilis*

Morphological and physiological properties of *Acacia tortilis* are affected by different abiotic factors (El Ferchichi Ouarda *et al.*, 2009), and its morphological characteristics are controlled by its growing conditions. Raddad and Luukkanen (2006) noticed that dendrometric parameters such as height, basal diameter, and crown area reflect adaptation to the environment. Biomass is the most important indicator of the production and adaptability of trees including *Acacia* to the environment (Tietema, 1993; Raebild *et al.*, 2003). In general, the dendrometric parameters of a given species depend on the local environmental conditions which may include the following: weather conditions, soil properties, vegetation type, age and wellbeing of the trees. Hence, there are distinct variations of dendrometric parameters of trees (e.g. *Acacia tortilis*) in different ecological regions (Tanka, 2006).

Generally, the tree height, canopy and diameter area, diameter at breast height and number of branches are the most commonly used measurements in the *Acacia* tree morphological characteristics (Eshete and Ståhl, 1998; Noumi *et al.*, 2010). The canopy area of *Acacia* tree is a significant parameter that determines the total amount of light the tree intercepts for photosynthesis (Tanka, 2006). The size of the shade area which blocks light from the understorey is also determined by the canopy area. Furthermore, the crown is the centre of physiological activity such as gas exchange which drives growth and development. It also plays dominant roles in the fire susceptibility, physical stability and microclimate of plants (Aaron, 2003). The total height of *Acacia* trees also play important role in the interception of light for photosynthesis and forming shade for the protection of understorey. It is needed for estimation of other parameters such as crown ratio, timber volume, site index and in forest growth and yield models (Tanka, 2006).

2.2 Techniques for Investigating Vegetation Distribution

It is becoming increasingly important for ecologists to understand the response of vegetation to environmental changes such as climate variability and global changes (Pettorelli *et al.*, 2005; Karnieli *et al.*, 2008; Boelman *et al.*, 2011; Omuto, 2011; Zhou *et al.*, 2011). Monitoring of the long-term changes of biophysical characteristics such as tree canopy cover of arid and semi-arid ecosystem over vast spatial ranges is imperative for unravelling the composition, dynamics and distribution of vegetation cover (Yang *et al.*, 2012). In most cases, the monitoring of vegetation over large areas by ground observations is impractical (O'Neill, 1996), which raises a strong need for the application of other sophisticated and flexible methods (Turner Ii *et al.*, 2007). Techniques widely used for the investigation of vegetation distribution include: Remote Sensing (RS) and Geographical Information System (GIS). These techniques makes it possible to estimate these changes in vegetation spatially and temporally in less time, at lower cost, with better accuracy and over large areas (Pickup *et al.*, 1993; Rasuly *et al.*, 2010). Recently, the increasing availability of digital imagery in the Landsat archive is enabling us to study and detect changes in vegetation from space using satellite-derived data.

2.2.1 Remote sensing of vegetation in arid regions

Remote sensing is one of the most effective tools for the assessment of desertification due to its cost and time effectiveness (Dawelbait and Morari, 2012). Since the 1970s (Figure 2-1), satellite remotely sensed data has provided a potentially beneficial tool with a continuous record of global terrestrial vegetation change (Carreiras *et al.*, 2006; Sonnenschein *et al.*, 2011). The analysis of such data may help to identify problems in the environment that would otherwise be difficult to identify such as sparsely vegetated remote areas (Stein and van der Meer, 2001). Moreover, with environmental concern over the loss of forest and habitat, the analysis of fine spatial resolution satellite imagery has become an important tool for forest cover mapping, identification of tree species and assessment of forest growth at landscape and regional scales (Coops and Waring, 2001; Wulder *et al.*, 2004; Hyde *et al.*, 2006).

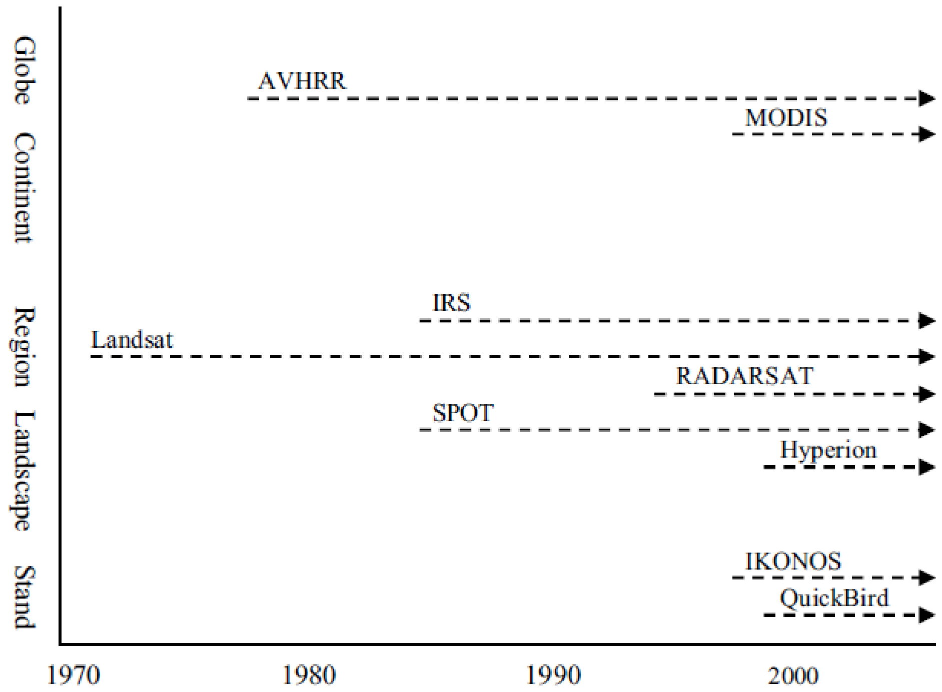


Figure 2-1: Time Line and Scale of Application of Major Satellite Remote Sensors Useful for Vegetation Mapping.

Source; Shao and Reynolds (2006)

The most commonly applied sensors in the field of vegetation mapping include Landsat, SPOT, MODIS, NOAA–AVHRR, IKONOS and QuickBird (Xie *et al.*, 2008). According to Wulder *et al.*, (2008), the Landsat sensors provide the longest continuous space-based record of Earth's land in existence. Landsat TM provides imagery at medium to coarse spatial resolution with multispectral data (120 m resolution for thermal infrared band and 30 m for multispectral bands) with each scene covering an area of 185 × 185 km; with temporal resolution of 16 days. Landsat ETM+ (Landsat 7) has been functioning since 1999 to present and it is characterized as a medium to coarse spatial resolution with multispectral data (15 m resolution for panchromatic band, 60m for thermal infrared and 30m for multispectral bands). Each scene covers an area of 185 km × 185 km; the temporal resolution is 16 days.

The above mentioned Landsat satellite data are suitable for regional scale mapping that could be used in the mapping of vegetation at community level or some dominant species can be possibly discriminated (Xie *et al.*, 2008). This is exemplified by the application of remote sensing (e.g. using Landsat Thematic Mapper data) and Geographical Information System (GIS) in the mapping and monitoring of vegetation cover in arid ecosystem to ascertain the extent of desertification and possible environmental determinants that impact these changes (Ringrose, 1996; Ringrose *et al.*, 1998). For example, Henshaw *et al.*, (2013) used Landsat TM scenes to assess the spatio-temporal variations in vegetation cover and channel positions at various sites with different environmental attributes. Their findings highlight the importance of Landsat TM data in revealing useful biogeomorphological information that could be needed for further investigation of related sites. They also mentioned some limitations associated with the application of Landsat TM data caused by its relatively low spatial resolution. While Smith *et al.*, (2007) investigated the tendency of producing a more accurate Landsat Enhanced Thematic Mapper (ETM+)-derived reference imagery using spectrally informed methods. This will facilitate the efficacy of spectral index methods to discriminate between the intended target (e.g. vegetation cover) and any undesired interference (e.g. soil surface and litter) over a series of spatial scales. Studies like this are aimed at minimizing the overestimation of the intended target such as vegetation cover. Nevertheless, reliable information derived from the application of these sophisticated techniques has the potential to immensely contribute to biodiversity conservation (Boyd and Foody, 2011).

In arid regions, the focus is mainly on optical remote sensing techniques which utilize data from sensors that collect radiation in the reflected solar spectrum to either (i) calculate the vegetation indices or (ii) for image classification. The latter is beyond the scope of this research and it is of limited application; hence will not be elaborated upon in this thesis. Nevertheless, vegetation indices (VIs) which is the arithmetic combination of two or more bands relating to the spectral characteristics of vegetation has been widely used by ecologists for quantitative estimation of feasible vegetation parameters (Levin *et al.*, 2007; Amiri and Shariff, 2010). Other uses of vegetation indices include: "the phenologic monitoring, vegetation classification, and biophysical derivation of radiometric and structural vegetation parameters" (Huete and Justice, 1999), vegetation parameters such as leaf-area-index (LAI), canopy moisture content, chlorophyll content, percentage green cover and green biomass (Cohen *et al.*, 2003; Lhermitte *et al.*, 2011; Stuckens *et al.*, 2011).

Tucker, (1979) established a relationship between plant biomass and a standardized vegetation index. Several other researchers have reviewed vegetation indices based on ratios of the radiance in the red and infrared spectral bands, selected to optimize the reflectance contrast between vegetation and other materials (Jackson *et al.*, 1983; Tueller and Oleson, 1989). Consequently, a number of vegetation (photosynthetic materials) and brightness indices (non-photosynthetic materials) have been developed over the years to facilitate the monitoring of desertification. They include: Normalized Difference Vegetation Index (NDVI) (Rouse *et al.*, 1974), Ratio Vegetation Index (RVI) (Jordan, 1969), Enhanced Vegetation Index (EVI) (Huete *et al.*, 2002), Soil Adjusted Vegetation Index (SAVI) (Huete, 1988), Stress Related Vegetation Index (STVI-1, 2 and 3) (Ridao *et al.*, 1998) and red band reflectance (Yang and Prince, 1997). Several of these vegetation indices (or brightness indices) are preferred more than others due to their unique attributes; nevertheless, they are also not without limitations.

With reference to spectral vegetation indices it is vital to exploit the spectral signatures of healthy green flora compared to vegetation that has been observed to be in a poor condition. Nowadays, the NDVI has achieved positive approval due to the fact that it is easy to use, employs only two wavelengths and because of the important plant characteristics the ratio reflects. If the theory of normalization is employed, the comparison of absorbed incident light reflected can be positioned in a simple ratio which is present on a scale of between -1.0 and 1.0. As a consequence, this makes an evaluation of environmental responses comparable (Crippen, 1990). It can also be noted that the NDVI is able to identify vegetation vigour, which means that it is able to distinguish the deterioration in pigments due to the existence of subsurface materials (Lasaponara and Masini, 2012). However, in this study, only the normalized difference vegetation index (NDVI), soil adjusted vegetation index (SAVI) and brightness index are discussed.

Normalized difference vegetation index (NDVI)

Among the existing vegetation indices, a combination of the spectral bands ratio response between visible (red) and near infrared (nir) wavelengths is the most operational, global-based and often used vegetation index (Huete and Justice, 1999; Karnieli *et al.*, 2002). A typical example is the NDVI which is the most widely applied vegetation index for the mapping of spatial and temporal variation of biophysical condition and vegetation cover (Tucker, 1979; Burgheimer *et al.*, 2006). It is sensitive to changes in greenness and photosynthetically active radiation since the pigment in plant leaves, chlorophyll, tends to absorb strongly the red wavelengths of sunlight (0.4 to 0.7 µm) for use in photosynthesis and also largely reflects in the near-infrared wavelengths (0.7 to 1.1 µm) as a result of the cells structure of the leaves (Figure 2-2). The basis of using these two bands is to describe much physiological and biophysical information of plant structure and growth (e.g. spatial and/or temporal changes) (Morales *et al.*, 2012).

The NDVI operates by contrasting intense chlorophyll pigment absorptions in the red wavelength against the high reflectivity of plant materials in the near infrared (Tucker, 1979). Moreover, NDVI was demonstrated to be an effective index to quantify the concentrations of green leaf vegetation (Jensen, 2000), and is preferred as simple index for vegetation monitoring because of the compensation for changing illumination conditions, surface slope, aspect, and other extraneous factors (Lillesand *et al.*, 2004). Again, it is widely accepted due to its robustness and simplicity, particularly, its ratio properties which enable the NDVI to cancel out a large proportion of noise caused by changing sun angles, clouds, shadow and topography (Huete and Justice, 1999). Additionally, it has been shown to be related to a number of plant physiological and biophysical parameters such as detection of phenological changes (Huete *et al.*, 2002; Volcani *et al.*, 2005), leaf area index, biomass assessment (Baugh and Groeneveld, 2006; Pfeifer *et al.*, 2012) and identification of tree species (Carleer and Wolff, 2004; Komura and Muramoto, 2007; Xing and Chang, 2009).

Conversely, in arid environments most investigators perceive desert landscapes as areas with sparse tree cover and this is equated with sparseness of all vegetation (Karnieli *et al.*, 2002). The wide range of tree cover types and density make it difficult to quantify a biophysical attribute in estimation of tree cover using remote sensing data (Carreiras *et al.*, 2006), due to low tree cover and density, short tree stature and canopy background (i.e. dead branches, shadows and soil) at fine spatial scales (Ko *et al.*, 2009). Also, NDVI cannot differentially detect changes in vegetation cover and vegetation conditions (Dawelbait and Morari, 2012). In other words, NDVI cannot discriminate between the radiance signals given by the alteration of vegetation cover and condition of the cover caused by the spectral variability of background materials like scattered litter and soil which may result to the non-linearity of the relationship between NDVI and vegetation characteristics (Huete *et al.*, 1992; Asner, 2004; Ding *et al.*, 2014). This could be a potential source of error, thereby, limiting the application of NDVI in estimating the vegetation cover in an arid ecosystem (Dawelbait and Morari, 2012).

It has been reported that NDVI is sensitive to signals from soil background and gives a non-linear relationship with greenness culminating to saturated signals for high biomass conditions (Huete and Jackson, 1988). Again, NDVI and several other vegetation indices have been reported to overestimate the extent of desertification in sparsely vegetated areas caused by several factors including the unpredictability of seasonal vegetation changes and the harsh impact of the climate (Dawelbait and Morari, 2008; Wessels *et al.*, 2012). Despite these limitations, NDVI has the advantage over most other vegetation indices for being more sensitive to signals emanating from sparsely vegetated areas (i.e. low biomass conditions); consequently, magnifying the disparities of the signals in those areas (Yang, 2012). In fact, many authors demonstrated the usefulness of NDVI time series to extract and track seasonal changes and phenological behaviour of arid and semi-arid vegetation (Weiss *et al.*, 2004; Buyantuyev *et al.*, 2007; Baghzouz *et al.*, 2010; Vicente-Serrano *et al.*, 2010; Shoshany and Karnibad, 2011). For example, Symeonakis and Drake, (2004) developed desertification monitoring system based on four indicators (vegetation cover, rain use efficiency, surface run-off and soil erosion) which were subsequently combined to highlight those areas that are more susceptible to degradation. It is worthwhile to mention that this study highlights the importance of NDVI in estimating desertification monitoring indicators like vegetation cover and rain use efficiency. The system developed by Symeonakis and Drake, (2004) exhibits the potential for real time monitoring and emphasized the relevance of remote sensing data achieves in evaluating both spatial and temporal variations in degradation.

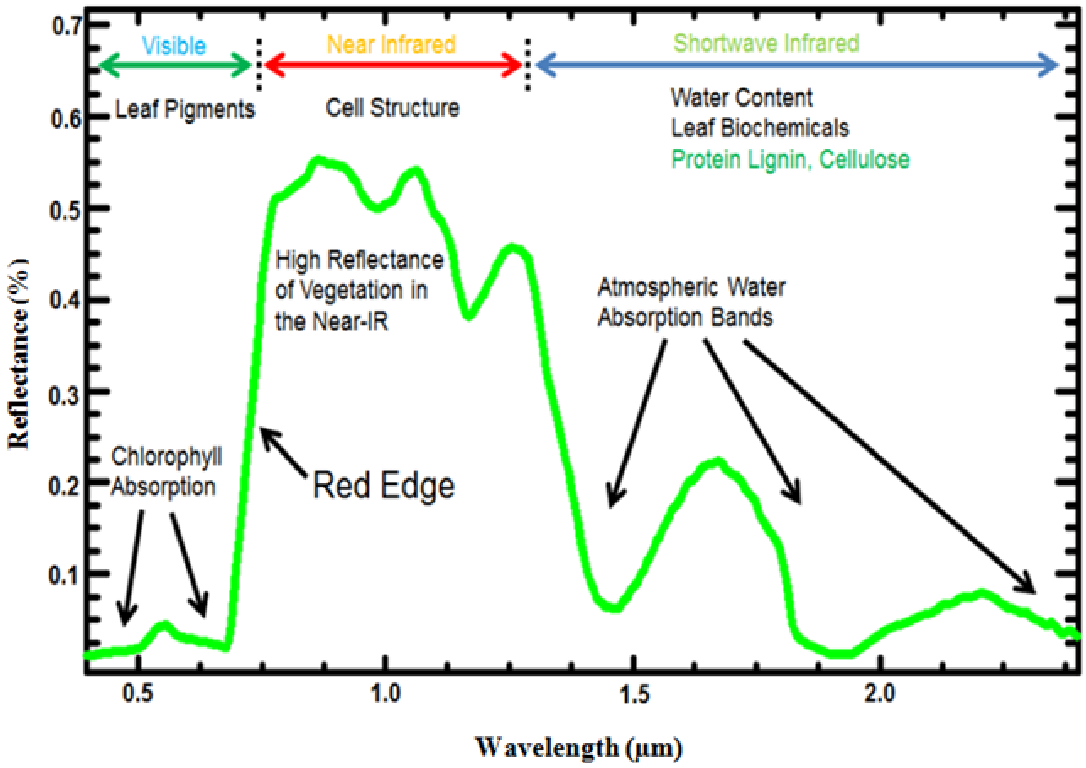


Figure 2-2: Spectral Reflectance Patterns or Spectral Signatures of Vegetation.

Source: Elowitz, Mark R. "What is Imaging Spectroscopy (Hyperspectral Imaging). Retrieved April 7, 2014, from http://www.markelowitz.com/Hyperspectral.html

Soil adjusted vegetation index (SAVI)

Soil background is one of the main causes of variation in the vegetation index values (Gilabert *et al.*, 2002). Hence, overcoming this limitation of the NDVI requires an alternative. The Soil-Adjusted Vegetation Index (SAVI) was proposed by Huete, (1988) to minimizing the effect of soil background conditions. The SAVI involves an addition of a constant, L to the denominator of the NDVI equation to indicate soil brightness dependent correction factor. The optimal L values differ with vegetation density, L= 1 with low vegetation density, L=0.5 with intermediate vegetation densities and L=0.25

for higher densities (Huete, 1988). In this report we considered vegetation correction factor at the study area as sparse so employed the L= 0.75.

The vegetation canopy reflectance rises as the soil reflectance increases (Huete, 1988). Thus, the effect of soil is crucial for sparse canopies where a large amount of the background is visible (Huete, 1988; Danson, 1998). In this respect, many of the vegetation indices can be limited due to the contribution of the background reflectance (Gong *et al.*, 2003; Meza Díaz and Blackburn, 2003). Variations in the spectral properties of the soils background brightness can create noise in the detection of vegetation attributes (Meza Díaz and Blackburn, 2003). It has been established that the variations in the spectral properties caused by background brightness could considerably affect the detection of sparse vegetation in heterogeneous environments using remotely sensed data (Bannari *et al.*, 1996). Hence, as Qatar is characterised by arid desert, it would be expected to have sparse vegetation with more reflectance from the surface of the soil, as well as soil vegetation interaction. Therefore, the use of the soil adjusted vegetation index (SAVI) helps to reduce the effect of the background-brightness (Van Leeuwen and Huete, 1996).

Brightness index

As previously mentioned, the most common spectral index of vegetation canopy “greenness” is the NDVI, which detects changes in chlorophyll content and is well correlated to vegetation biomass (Tucker, 1979; Choudhury, 1987). Conversely, there is evidence to suggest that brightness indices are more able to identify woody canopy cover in semi-arid savannahs (Yang and Prince, 1997). Additionally, using a brightness index such as red reflectance or albedo is not new, as it has been used to detect changes in land cover (Otterman, 1977; Brad Musick, 1986; Yang and Prince, 1997).

In their study, Yang and Prince, (1997) demonstrated the potential of red band reflectance “brightness index” from satellite sensors to estimate vegetation canopy cover. They determined that the red band was the band with the highest correlation to the vegetation canopy cover and biomass and explained the relationship between changes in background reflectance, canopy reflectance and shadow reflectance. In general, the sensitivity of the spectral data to the forest variables is highest when the contrast between the background reflectance and canopy reflectance is greatest (Yang and Prince, 1997). In a follow-up study in eastern Zambia, Yang and Prince, (2000) established a higher correlation between savannah vegetation cover percentage and the red band of Landsat Multi-Spectral Scanner (MSS) (R^2=0.88) with a relatively small sample set (n=22). However, they reported that this relationship between canopy cover and red reflectance may not be used for Landsat (MSS) images acquired in a different season or different region. Furthermore, in a simulation and sensitivity analysis by Yang and Prince (1997) they predicted that the relationship between red reflectance and canopy cover is near linear only when canopy cover in the region is below 80% and satellite data were acquired at a solar zenith angle of less than 30% over relatively flat land.

An up to date review of the Scopus database for Yang and Princes' (1997) methods established that fourteen articles were cited (Bégué *et al.*, 1997; Goetz *et al.*, 1999a; Goetz *et al.*, 1999b; Goetz *et al.*, 2000; Demattê *et al.*, 2003; Gerard, 2003; Xu *et al.*, 2003; Zhu and Waller, 2003; Tao *et al.*, 2005; Heiskanen, 2006; Lloyd *et al.*, 2008; Pintea *et al.*, 2011; Zhan *et al.*, 2012; Adjorlolo and Mutanga, 2013) and noted that all of them had been conducted in a non-arid environment. Amongst these articles only five referred to Yang and Princes' (1997) methods, in order to:

(i) Study the NPP (the net fixed carbon from the atmosphere into plant per unit time) as the explained indicator of changes in carbon bio-sequestration in China (Zhan *et al*., 2012),

(ii) Estimate crop net primary production (NPP) and forecast crop yields in China, with maize (Tao *et al.*, 2005),

(iii) Analyse the interannual changes in NPP (interannual variation in terrestrial net primary production (NPP) which was modelled using the global production efficiency model (GLO-PEM), a semimechanistic plant photosynthesis and respiration model driven entirely with satellite advanced very high resolution radiometer (AVHRR) observations) globally (Goetz et al., 2000),

(iv) Study the NPP in Central Canada (Goetz et al., 1999b),

(v) Model the loss of assimilated carbon via autorophic respiration (Goetz et al., 1999a).

Recently, Lawley *et al.*, (2014) developed and demonstrated a method for quantifying land cover across several arid regions in South Australia using albedo from Advanced Land Observing Satellite Panchromatic Remote-sensing Instrument Stereo Mapping (ALOS PRISM) images (2.5 m spatial resolution). They revealed that soil exposure or vegetation cover can be detected in high resolution satellite imagery where individual trees and shrubs can be distinguished, which allows relatively bare soil and cover estimates to be made. The study concludes that using MODIS satellite images characterised by lower resolutions are unsuited for monitoring sparsely vegetated arid landscapes.

A key study was performed by Xu *et al.*, (2003) comparing single band vegetation indices, multi-band regressions and multi-spectral transformation for crown closure estimation using Landsat TM imagery in oak savannah. In their study, a correlation analysis between vegetation index NDVI (the combined use of NIR and red bands) and the red band (redness) were completed. The NDVI illustrated a minor improvement over the red band, which indicated that the NDVI analysis provides better estimation results for the oak crown closure.

Hence, it is not feasible to apply single band analysis with lower resolution imagery because it demonstrated that better results are obtained from the high spatial resolution images. Moreover, no single study exists from Yang and Prince (1997), which has the same arid environment as Qatar. For example, the harsh environment with sparse vegetation is characterised by a spiny canopy that is able to cope with higher evapotranspiration, whereas most of the reviewed papers were conducted in semi-arid or tropical areas characterised by dense vegetation. The soil in Qatar is calcareous, therefore, it has a higher albedo, which would simply swamp the image reflectance, whilst the areas identified in the studies were characterised by a low albedo (the surface reflectivity to solar radiation). An ideal white body has an albedo of 100% and an ideal black body of 0% (Mohanakumar, 2008). Therefore, the brightness index method proposed by Yang and Prince (1997) is considered to be inappropriate for adoption in this research in Qatar.

2.2.2 Statistical modelling in plant ecology (spatial prediction of species distribution)

Predictive modelling of the relationships between the vegetation cover and its environmental variables are imperative in ecological conservationism (Guisan and Zimmermann, 2000; Austin, 2002). Hence, there has been an extensive application of a variety of statistical modelling techniques in ecological studies to effectively deal with the massive data frequently obtained from sophisticated methods such as geographical information system (GIS) and remote sensing (Aspinall and Veitch, 1993; Franklin *et al.*, 2000). In most ecological studies, statistical modelling is restricted to its primary purpose of prediction of species distribution (Austin, 2002), which often involves the characterization of vegetation (Kelly *et al.*, 2004a); while the testing of ecological hypothesis and unravelling of the functional relationships between plant species and environmental variables are given secondary considerations (Guisan and Zimmermann, 2000). Although the causation of functional relationships between plant distribution and environmental variables cannot be ascertained by statistical modelling, but can only be pursued by varying experimental conditions and rigorous hypothesis testing (Austin, 2002). However, the effectiveness and success of statistical modelling in ecological studies and environmental conservation should be considered on a wider context transcending the primary purpose of mere prediction of species distribution. It also depends on three components which include adequate consideration of ecological theory to be tested, the appropriate collection and measurement of ecological data and choosing the right statistical methods based on the statistical theory, restrictive assumptions and significance tests (Austin, 2002). These components are indispensable in the spatial modelling of vegetation in ecological studies. For instance, the prediction of vegetation cover without adequate consideration of ecological theory (or knowledge) will definitely not be robust. In other words, the more ecological knowledge is incorporated in the spatial modelling process, the more robust the outcome is likely be (Kelly *et al.*, 2004b). Similarly, the accuracy, scale of resolution and types of errors associated with the data acquisition process such as remote sensing are likely to have impact on the robustness of the vegetation prediction(Austin, 2002). Furthermore, the appropriate statistical model has to be applied to yield robust prediction. However, certain ecological assumptions have to be made to allow the application of current statistical methods which are static and inflexible to take into consideration the dynamic attributes of the ecosystem (Guisan and Theurillat, 2000; Guisan and Zimmermann, 2000; Austin, 2002). For example, the vegetation is assumed to be in a state of equilibrium with their environment or the changes of the biota in relationship to the environment are very slow and insignificant (Austin, 2002).

This central ecological assumption may be invalid and misleading when considering sites in which the vegetation has undergone intense animal/anthropogenic disturbance. Hence, the prediction of vegetation cover of intensely disturbed sites is likely to be less robust using the current statistical models that are static. In other words, the degree of success of current statistical models in ecological studies depends on the impact of history and disturbance the site has undergone (Austin, 2002). Consequently, there need for the re-evaluation of statistical methods to incorporate the dynamic attribute of ecological systems which will maximize the functional relationships between plants and environment culminating to a more robust spatial prediction of species distribution. In fact, there is growing consensus that the ecological concept of continuum relationships between plant species and environment gives a more robust spatial prediction of vegetation cover (Austin and Smith, 1989; Franklin, 1995; Guisan and Zimmermann, 2000).

There are several ecological assumptions of lesser consensus that needs to be considered in predictive modelling of vegetation cover. Foremost among these assumptions is the environmental gradient which refers to the shape of the response of vegetation to environmental variables. Many ecologists have proposed a unimodal, symmetric bell-shaped response (Giller, 1984; Begon *et al.*, 1990; Krebs, 1994; McCune, 2004); but there is no substantial evidence to support this assumption (Austin, 1999b). Hence, there is no general consensus on this issue. It has also been argued that the species response shape may not necessarily conform to the unimodal, symmetric bell-curve, but may vary depending on the impact of the environmental variables on the plant. Environmental variables have been classified as either idealized or distal/proximal gradients (Austin, 2002). Variables that have no physiological effect on plant growth or competition are regarded as indirect gradients (e.g. altitude, latitude or longitude). While those inconsumable variables that have direct physiological influence on plant growth are termed direct gradients (e.g. temperature, pH and electrical conductivity). Resource gradients are consumable variables such as light, water and nutrients. It is important to emphasize that some of the variables such as water can be a resource gradient or an indirect gradient depending on the conditions (Austin, 2002).

The classification could also be based on the nearness of the environmental predictors to the plants. Those variables that are close to the plants are referred to as proximal; while those that are distant from the plants are said to be distal. Most proximal gradients are causal variables which may be resource or direct that influence the plant response. In contrast, indirect gradients are obviously distal variables (Austin, 2002). Consequently, the robustness of statistical models depends on the environmental predictors considered based on the above classification. Spatial prediction of species distribution based on proximal resource and direct gradients are the most robust and widely applicable in ecological studies (Austin, 2002). Although predictive mapping of species distribution based proximal variables is almost unrealistic due to the difficulty in determining proximal variables using sophisticated technology such as GIS (Austin, 2002). Nevertheless, it has been emphasized that the nature of correlations between the indirect variables and the causal gradients will determine the shape of the species response (Guisan *et al.*, 1999; Franklin *et al.*, 2000; Guisan and Zimmermann, 2000; Meentemeyer *et al.*, 2001). It has also been argued that in numerous occasions indirect variables such as topographic position typically replace a combination of different causal gradients which definitely impact on the species response shape (Guisan and Zimmermann, 2000). In this instance, the predictive models will be robust only if the causal gradients are linearly correlated and are also linearly correlated with the indirect variables (Austin, 2002).

Despite the curvilinear relationships between plant response and environmental variables may be ecologically reasonable, many researchers have used regression models fitting straight-line to explain this relationship without valid justification. However, the application of regression models with polynomial or quadratic equation to fit the curvilinear or hyperbolic relationships between plants response and environmental variables have been advanced by some researchers (Austin, 1999a; Pausas and Austin, 2001; McCune, 2004). Regression models hardly incorporate ecological theory, with the exception of canonical correspondence analysis (CCA) which incorporate several ecological assumptions and has been shown to robustly deal with unimodal species responses especially with the relaxation of the assumptions compared to other statistical models (Austin, 2002). However, the suitability of the generalized linear models (GLM) and canonical correspondence analysis (CCA) in the spatial prediction of plant distribution has been assessed by Guisan *et al.* (1999). They found GLM to be superior in predicting the distribution of individual species; while

CCA had some advantages and seems to be more promising in the spatial prediction of rare plant species. Furthermore, they found that all the studies reviewed showed that symmetric unimodal responses are uncommon; while skewed curves predominate (Austin, 2002). However, it was impractical to undertake a more detailed comparison as no two studies have the same experimental approach or used similar vegetation data. However, the restrictive assumptions and limitations of myriad statistical methods currently existing makes it difficult for the selection of the appropriate methods for most ecological studies.

At present, the preferred statistical models employed in ecological studies are generalized additive models (GAM); classification and regression tree (CART) and GLM. It is not uncommon to combine these statistical models to achieve the best results. This is usually exemplified by the use of GAM and CART to define the functions to be included in a parametric GLM (Austin, 2002). The complex function that may arise from the use of GAM may be resolved by GLM which have the potential of capturing most of the same variation in the data and also providing a more rational ecological justification. CART which is characterized with producing discontinuities cannot handle continuous functions sometimes encounter in ecological studies. Hence, Guisan and Harrell (2000) has advocated for better statistical models like GLM explicitly explained by McCullagh and Nelder (1989) to deal with the deficiencies of GAM and CART in analysing ecological data. In particular, the logistic regression (e.g. ordinal or multinomial) which is a type of GLM based on probabilistic statistical classification that is gaining prominence in ecological studies due to its advantage of robustly dealing with dichotomous (i.e. presence or absence of criteria) and categorical data with different error structures that are often associated with vegetation distributions (Rushton *et al.*, 2004; Zare Chahoukia and Zare Chahoukia, 2010). Logistic regression also has a function of sigmoid curve that is suitable in explaining the non-linear relationship between plant species and environmental variables (McCune, 2004). In addition, the incorporation of spatial autocorrelation usually through an autologistic regression is becoming necessary to make robust spatial prediction of plant distribution (Austin, 2002). Moreover, the spatial prediction of plant distribution may require a combination of these predictive modelling techniques for better and robust results.

2.3 Research Questions

2.3.1 Environmental influences

Variation in topography and soil characteristics are believed to have strong influences on the availability of water resources and consequently on the distribution of *Acacia*. Such a trend is broadly consistent with the literature. Morison *et al.,* (1948); Yair and Danin (1980); Batanouny and Ismail (1985); Kennenni (1991); Patten and Ellis (1995) and Galal (2011) have suggested that presence of natural vegetation in wadis and depressions in arid areas is restricted by micro-environmental factors, intercepting the collection of run-off water or near-surface groundwater table which provides the needed moisture for plant growth. The following are the proposed research questions that have been raised as a consequence of evident gaps in the literature:

❖ **Presence of mature *Acacia tortilis***

(i) As water is a limiting factor in arid and hyper-arid regions it is logical to hypothesize that the type, density and performance of *Acacia tortilis* in Qatar probably depends upon the availability of water in the specific habitats. Distribution of *Acacia tortilis* trees in Qatar is assumed to be linked with moist sites on slopes or depressions that receive run-off water. Previous research has shown that an intimate relationship exists between the landform relief, soils, water availability and *Acacia tortilis* growth (Batanouny and Ismail, 1985; Abd El-Ghani and Amer, 2003).

(ii) Study of the topographic positions and dendrometric parameters (tree performance e.g. tree height, crown diameter, crown area and basal area) has been used as indicators of the distribution and abundance of the *Acacia tortilis* (Coughenour *et al.,* 1990; Sanon *et al.,* 2007; Noumi *et al.,* 2010). Accordingly, topographic positions (summit, slope and depression) have been hypothesized as one of the main features controlling the production and adaptability of *Acacia* in the Qatari desert.

❖ **The establishment and regeneration of *Acacia tortilis***

(i) The regeneration rates of *Acacia tortilis* has been found higher in the unprotected areas due to the feeding of large mammalian herbivores contributing positively to the seed germination due to the breakage of seed dormancy (through feeding, digestion and excretion) as well as increased dispersion, off-setting the negative affect of the bruchid beetles which feed on the *Acacia* seeds and used them for egg-laying purposes (Miller, 1994; Rohner and Ward, 1999; Rodríguez-Pérez et al. 2011). How regeneration of Acacia in protected areas compares with plant-animal mediated rates in unprotected areas needs further investigation.

(ii) *Acacia tortilis* modifies soil fertility by increasing soil organic matter, organic carbon, total nitrogen and exchangeable Phosphorus as its canopies attract mammals which deposit dung under the trees (Bernhard-Reversat, 1982; Argaw et al., 1999; Fterich et al., 2012; Noumi et al., 2012). Positive change in the soil fertility is also aided by the litter dynamics of *Acacia*. How such increases in soil fertility affect the germination and new seedling establishment will also be studied in the present research.

❖ **Effect of water regime**

(i) The adaptation and distribution of *Acacia tortilis* within the environment rests upon its access to ground water table and the depth of underground water within the soil. As a result, the depth of ground water is an important factor (Caldwell *et al.*, 1998; Ludwig *et al.*, 2003; Do *et al.*, 2005; Otieno *et al.*, 2005).

(ii) Water availability within the top 50 cm soil is an important factor for the development of adult trees given the seasonal nature of moisture availability. Existence of the fine fibrous and/or woody roots found within this depth has been used as an indicator for such relationship (Otieno *et al.*, 2005). The present research has employed the same to indicate the differences in lateral roots across both sites (protected and unprotected).

(iii) Time and frequency of rainfall is an essential factor controlling germination and seedling establishment of the *Acacia tortilis* tree (Floret and Pontanier, 1982; Wilson and Witkowski, 1998; Rohner and Ward, 1999; Stave *et al.*, 2006). It is worth mentioning that during September- October 2012, just before the field work, Qatar witnessed excessive rainfall at the studied sites which helped to collect the data related to regenerative responses between the two sites.

- **Effect of soil properties**

Understanding the association between soils and vegetation is essential for most investigations of plant habitats. Thus, the relationship between the *Acacia tortilis* and the many soil properties is presumed to regulate its distribution in different topographic positions.

Soils in Qatar are calcareous (Scheibert *et al.*, 2005). Due to very low rainfall, there is insufficient leaching to remove Ca^{2+} from the soil profile and soil accumulates more $CaCO_3$. The calcareous nature of soils affects the soil properties related to plant growth such as fertility and the availability of plant nutrients (FAO, 1973). Excessive calcium carbonate poses serious problems to plants by raising soil pH to levels where plant nutrients become unavailable (Çelik *et al.*, 2010). In order to survive, *Acacia tortilis* has become well adapted to the high $CaCO_3$ content of Qatari soils. However, the effect of the presence or absence of major nutrient on *Acacia* needs a systematic evaluation. As such, the following indicators have been selected for the present study:

(i) Gypsum content is known for negative impact on the tree survival and growth (Poch *et al.*, 1998; Singh *et al.*, 2001) through causing an imbalance in the water uptake by the plant (Mousli, 1981; Schmid and Leuschner, 1998). From preliminary field observations no trees existed when the gypsum crystals were found in slope and summit landforms. As such it could be one of the edaphic factors controlling the distribution of *Acacia tortilis*.

(ii) Phosphorus is an important plant macronutrient (Schachtman *et al.*, 1998) which has strong influence on tree growth (Cech *et al.*, 2010). Hence, the availability of P is likely to be a key factor for the *Acacia tortilis* as well.

(iii) Organic carbon is an important edaphic variable that is associated with *Acacia tortilis* tree and its seeds (Moleele *et al.*, 2005). It's presence or absence can markedly influence the way chemicals may react in the soil (Schumacher, 2002).

(iv) Electric conductivity (Salinity) is one of the most important factors affecting the *Acacia tortilis* growth and germination (Rehman *et al.*, 1997; Mehari *et al.*, 2005). The adverse effect is attributed to ionic toxicity and the decline in osmotic pressure (Levitt, 1980).

(v) Soil pH (the negative log of the hydrogen ion activity in solution) is an important chemical soil parameter influencing the nutrient uptake and tree growth (Rengel, 2003). It also affects the soil functions as well as quantity, activity, and types of microorganisms.

(vi) Physical properties (condition) of the soil could also affect the distribution of *Acacia tortilis*, especially at the high point of topographic position (summit); as such, soil permeability or depth to the cemented or rocky layer has been known as a major factor controlling the tree distribution (Scheibert *et al.*, 2005; Norton *et al.*, 2009).

(vii) The developments of surface soil crust in the depression position soils at the protected sites due to there being fewer disturbances by large herbivores could lower and inhibit the penetration of seeds and reduce water infiltration (Van Bremen and Kinyanjui, 1992; Deines *et al.*, 2007). Therefore, this factor has also been included in the present research.

2.3.2 Anthropogenic impact

Biotic factors such as grazing and human interference through cutting and development affect the distribution, establishment and dynamics of *Acacia* (Kennenni and Maarel, 1990; Rohner and Ward, 1999; Shaltout *et al.*, 2009). These have been included in the present study for comparative purposes i.e. in comparison with environmental factors as well as across protected and unprotected sites. The reviewed literature has pointed out the relevance and need for such comparisons as follows:

(i) The density and population of *Acacia tortilis* in Qatar has been influenced by the rate of human disturbance such as cutting, grazing and habitat destruction (Batanouny, 1981; Bradshaw *et al.*, 2010). Consequently, decline in the number of *Acacia tortilis* tree as well as its natural habitats is occurring mainly due to increased human activity.

(ii) The cumulative effect of continuous browsing over many years is apparent in the reduced height, branches numbers and crown diameter of *Acacia tortilis* in the anthropogenic site.

(iii) Despite the positive effects that the large mammals or ungulates may have on the trees, herbivore may also exert negative effects, especially by restricting the growth and survival of young trees of the *Acacia tortilis* (Mwalyosi, 1990). Hence, protecting site has lower anthropogenic impact on the *Acacia tortilis* condition and morphological features compared with the unprotected site.

CHAPTER 3: METHODOLOGY

Introduction

The purpose of this chapter is to present the philosophical assumptions underpinning this research, as well as to introduce the research strategy and the empirical techniques applied. The assumptions underlying this research come from the ecological and environmental perspective. The research strategy adopted was to conduct multiple studies in two phases (phase 1 and 2). Phase one looking at the distribution of *Acacia tortilis* at national scale, whilst phase two is to studying *A. tortilis* distribution at local scale (I) with two nested regeneration study areas (II and III). The main data collection techniques used in this research study were satellite image analysis, plant/soil sampling and laboratory analysis.

This chapter is divided into two sections. In the first, the interpretive stance in the field of remote sensing is examined. The next section is about the multifactorial approach (i.e. phytogeographical approach). The phytogeographical method is a widely accepted research strategy in the field of geographical distribution of plants, more particularly distribution of individual plant taxa. The second section will also describe the research approach followed in fieldwork research. This fieldwork will enable us to increase our understanding of environmental factors related to the growth and condition of the *A. tortilis*. Finally, techniques applied for the regeneration study will be under the phase two study section.

3.1 Phase I: Distribution of *Acacia tortilis* in Qatar Using Field Survey, Remote Sensing and GIS at a National Scale

3.1.1 Study area

The present study was carried out in Qatar, which is situated in the middle of the western coast of the Arabian Gulf and covers 11,606.8 square kilometres. The country stretches from latitude 26° 40`N and longitude 50° 45’-51° 40’E, as shown in Figure 3-1. It is almost flat and the surface of Qatar is in low to moderate relief, with the highest elevation at 103m above sea level about 20 km north of Sauda Nathil. The lowest part of the peninsula is at a level of 6m below sea level in an area 15 km south-east of Dukhan (Yehia *et al.*, 1982). The climate is characterised by very hot summers in June, July and August, and cool winters. Generally, the absolute maximum temperature is 47°C and the absolute minimum temperature is 1°C (Abulfatih *et al.*, 2001).

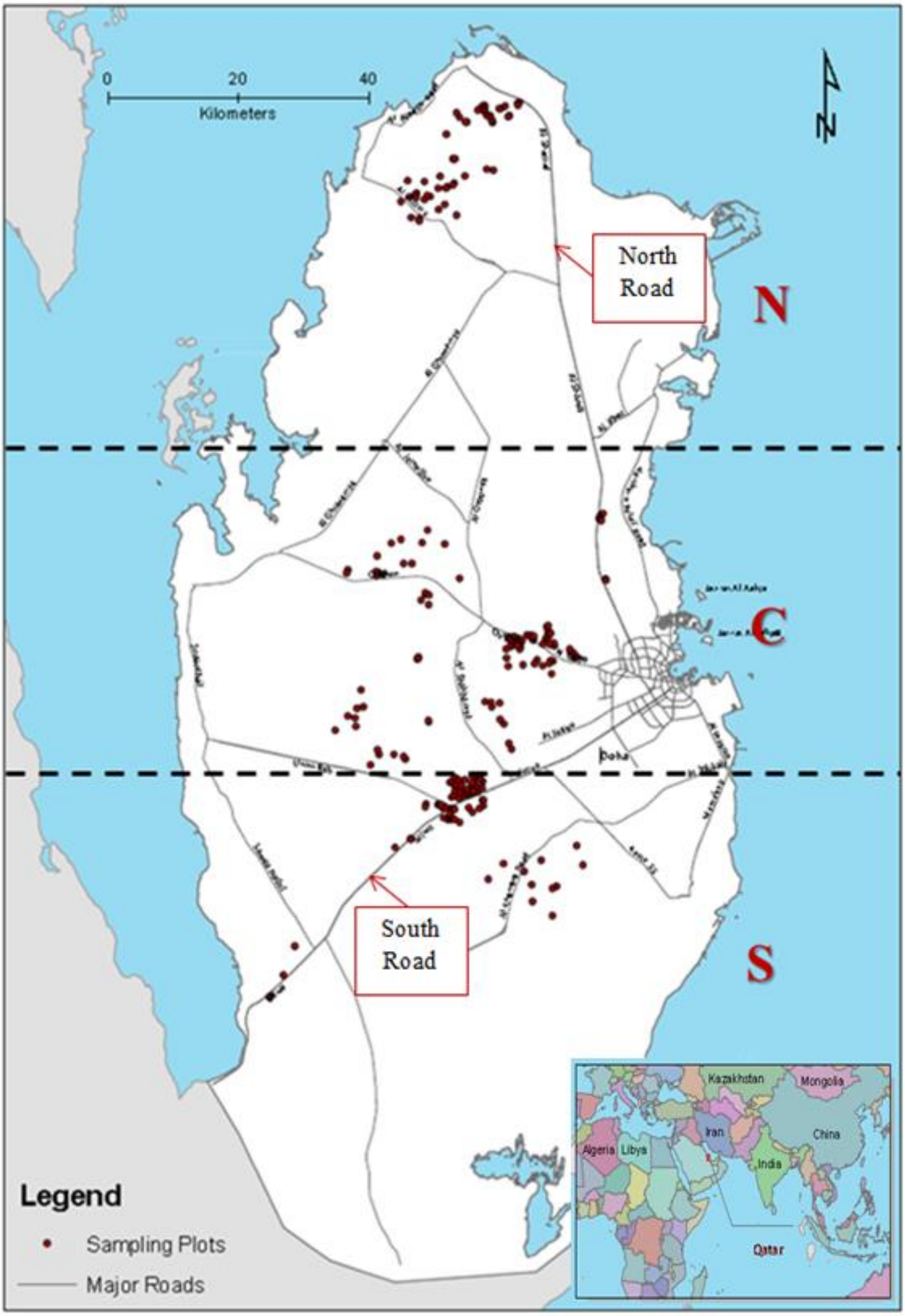


Figure 3-1: Location of the Study Area and Specific Sampling Plots.

Source: The GIS Centre, State of Qatar.

3.1.2 An overview of sampling strategy

In order to study the *Acacia* tree distribution of Qatar at a national scale, different data sets were exploited (using series of satellite images acquired by Landsat-5/TM and Landsat-7/ETM+ as well as aerial photograph with high resolution). NDVI and SAVI data were obtained from the satellite images while vegetation, percent cover and bare soil data were acquired from the aerial photographs. Remote sensing and GIS were also used to gather environmental gradients such as elevation, distance to coast line, depth of water table, disturbance index, TDS and topographic positions which may affect patterns of *Acacia* distribution.

276 sampling plots were employed for this study. In an attempt to spatially cover the entire country, it was divided into three regions north, central and south, Figure 3-1. Then, a field survey was conducted in August 2011 to locate and geo-reference sample quadrats to be used as training sites to evaluate the satellite remotely sensed data in detecting changes and or classifying sites in to distinct vegetation types. Three major roads covering most of Qatar starting from Doha, the capital, to the north, to the west and to the south were used for this purpose using an off-road vehicle. Existing minor car tracks or tyre marks widely distributed over each area were used as transects. Heavily used tracks, asphalt roads, areas close to large settlements, farms and sand dunes or sabkahs were avoided. Areas with trees were then thoroughly observed and the number/type of trees recorded using form sheets. Coordinates of ground samples were determined using Garmin Gpsmap 62s (GPS) and latitude and longitude values were imported into a GIS with ArcMap 9.3 (ESRI, copyright 2008). Distance between GPS points were always more than 50m to avoid satellite image pixels (30m resolution) overlapping .Then, square buffers were created for each quadrat of 50×50 metres in size. These areas with native trees were delineated as shown in Figure 3-1 with a total of 138 plots. Gaps between one area and the next indicate the presence of either farms, buildings, sand dunes or Sabkhas.

Data of the natural vegetation distribution, canopy cover percentage and bare soil plots were generated using a 60 cm colour ortho image of the year 2010 for Qatar (Source: GIS centre, The Environmental Studies Centre, Qatar University) and was used as base map in GIS. Image information are summarised in Table 3-1. Detailed species identification was conducted at each plot by categorising tree presence into three classes in all plots as Acacia, Mixed, No Acacia. The bare soil plots were generated using

ArcMap 10 software. From the 60cm spatial resolution ortho-rectified digital aerial photography (January, 2010), adjacent 50 * 50 meters bare soil plots (total number = 138) were subsequently identified for comparative analysis. Hence, the total tested plots are 276 plots (138 vegetated + 138 adjacent bare soils). Vegetation types consisted of the following native species: *Acacia tortilis*, *Acacia ehrenbergiana*, *Ziziphus nummularia*, *Prosopis juliflora*, *Prosopis cineraria* and *Lycium shawii*. Tree percentage cover was determined using high resolution aerial photography, at 60cm spatial resolution (Jan, 2010), which facilitated mapping of the natural vegetation distribution in Qatar.

Table 3-1: Summary of Ortho Image information.

Information	**Discription**
Date of capture	January 2010
Product Type:	Orthorectified Imagery
Imaging Bands	Natural Color
Bit Depth	8
File Format	TIFF
Spatial resolution	60 CM
Datum:	QND
Ortho Images are produced from aerial photos taken by UCX large format digital camera at 27500 feet MSL.	

Since the desert vegetation is scattered, heterogeneous and variable, quadrats were selected to represent the species type at the different topographic positions that influence the appearance and distribution of these tree species. The targeted tree species in Qatar mainly occurs within the depression and slope areas.

3.1.3 Estimating tree cover and species composition of desert vegetation in Qatar using vegetation indices derived from remote sensing

Several methods based on vegetation indices have been designed and used to extract vegetation reflection using the satellite image data. A commonly vegetation indices includes Normalized Difference Vegetation Index (NDVI) and Soil Adjusted Vegetation Index (SAVI) are used for monitoring purposes and multi-temporal images to study change detection, temporal vegetation dynamics and agricultural applications. These indices are calculated based on the spectral profile of the available data and they able to classify different pixels based on the received response.

Satellite imagery and data collection

The image datasets used in this study came from two distinct sources: 60cm spatial resolution ortho-rectified digital aerial photography from January 2010 (acquired from the Remote Sensing Unit, Environmental Studies Centre at Qatar University) and 30-m Landsat 5 TM and Landsat 7 ETM+ imagery (World Reference System, Path/Row 163/42, 163/43) acquired from the United States Geological Survey (USGS) http://earthexplorer.usgs.gov/. On the date of data acquisition a clear atmospheric conditions prevailed (according to USGS condition criteria); also the USGS centre has corrected radiometric and geometrical distortions in the images to a quality level of 1G before delivery. Image selection was based on phenological periods during the intra-annual growth season and rainfall. A time sequence of multi-spectral Landsat 5 TM and Landsat 7 ETM+ images was used to identify spatial and temporal changes in the vegetative cover of Qatar (Table 3-2). The dates selected represent 2010, at the beginning of the study, and 1998, allowing the changes during this 12-year period to be assessed.

Table 3-2: Acquisition Dates of Satellite Images Processed.

Acquisition date	Sensor	Satellite
11/05/1998	TM	Landsat 5
28/06/1998	TM	Landsat 5
31/08/1998	TM	Landsat 5
03/11/1998	TM	Landsat 5
21/12/1998	TM	Landsat 5
02/04/2010	ETM+	Landsat 7
20/05/2010	ETM+	Landsat 7
21/06/2010	ETM+	Landsat 7
07/07/2010	ETM+	Landsat 7
30/12/2010	ETM+	Landsat 7

It is worth noting that the Landsat ETM+ imagery for 2010 was subject to data gaps owing to the failure of Scan Line Corrector (SLC) of the ETM+ instrument in 2003.

Calibration and atmospheric correction (image pre-processing)

In order to monitor terrestrial surfaces and extract information from remote measurements over time, corrections to data are required (Hadjimitsis *et al.*, 2010). The aim of this operation is to remove noise and increase the interpretability of image data. This is necessary because the electromagnetic radiation (EMR) signals collected by satellites in the solar spectrum are modified by scattering and absorption by gases and aerosols through the atmosphere from the earth's surface to the sensor (Song *et al.*, 2001). Radiometric calibration and atmospheric corrections were applied according to the recommendations of Chander *et al*. (2009) and Song *et al*., (2001).

Radiometric calibration is the fundamental step in image data calculation to convert 8-bit (Landsat 5) and 9-bit (Landsat 7) digital number (DN) to at-satellite reflectance. Landsat 5 and Landsat 7 images were first converted to at-satellite radiance as in Eq. A:

$$L_{\lambda}= ((LMAX_{\lambda}-LMIN_{\lambda})/(Q_{calmax}-Q_{calmin}))\ (Q_{cal}-Q_{calmin})+LMIN_{\lambda} \qquad (A)$$

Where,

$L\lambda$= Spectral radiance at the sensor's [W/(m^2 sr μ m)]
Q_{cal}= Quantized calibrated pixel value [DN]
Q_{calmin}= Minimum quantized calibrated pixel value corresponding to $LMIN_{\lambda}$ [DN]
Q_{calmax}= Maximum quantized calibrated pixel value corresponding to $LMAX_{\lambda}$ [DN]
$LMIN\lambda$= Spectral at-sensor radiance that is scaled to Q_{calmin} [W/(m^2 sr μ m)]
$LMAX\lambda$= Spectral at-sensor radiance that is scaled to Q_{calmax} [W/(m^2 sr μ m)]

A number of methods have been developed to remove or reduce atmospheric effects. The dark object subtraction (DOS) method was used for atmospheric correction. This method is selected because of the lack of concurrent atmospheric data or field spectral measurements of archive data as well as it is considered to be the simplest and most widely used image-based approach to absolute atmospheric correction (Huguenin *et al.*, 1997; Song *et al.*, 2001). The lowest pixel value from a histogram of an image band needs to be determined, and then that value is subtracted from all of the pixels in that band. This process is repeated for all image bands. DOS was estimated using Eq. B (Song *et al.*, 2001):

The path radiance is estimated as:

$$L_p=G \cdot DN_{min}+B-0.01[E_0 \cos(\theta_0)T_z+E_{down}]T_v/\pi, \qquad (B)$$

where:

L_p= is the path radiance, T_v is the atmospheric transmittance, ρ is the surface reflectance, E_{down} is the downwelling diffuse irradiance, E_0 is the exoatmospheric solar constant, T_z the atmospheric transmittance and θ_0 the solar zenith angle. G is the sensor gain, B is the bias used for converting the sensor signals (DN) to at-satellite radiance, and DN_{min} is the minimum DN value.

Satellite image analysis

Satellite images were processed using Erdas Imagine 2011 software. Spectral measures relating to the presence of vegetation were calculated based on the Landsat TM/ETM+ individual channels; namely the NDVI (Rouse *et al.*, 1974) and the Soil Adjusted vegetation Index (SAVI) (Huete, 1988). The equations for these indices are shown in Table 3-3.

Table 3-3: Vegetation (Spectral) Indices Calculated for the Landsat Data.

Spectral indices	Equation
NDVI	$(\rho_{NIR}-\rho_{RED})/(\rho_{NIR}+\rho_{RED})$
SAVI	$[(\rho_{NIR}-\rho_{RED})/(\rho_{NIR}+\rho_{RED}+L)] \times (1+L)$

Note: NDVI and SAVI are spectral vegetation indices, NIR is the reflectance value of the near infrared band, RED is reflectance of the red band, and L is the soil brightness correction factor. The optimal adjustment was found at L = 0.75.

3.1.4 Patterns of *Acacia tortilis* distribution related to environmental gradients in Qatar on a national scale

In order to determine the main environmental factors that may affect the distribution of the *Acacia tortilis* tree at the national level, each of the 138 vegetation type plots (Acacia, mixed and No Acacia) and 138 bare soil plots were examined, and the following parameters were recorded:

- Elevation (derived from the Digital Elevation Model (DEM)): In order to measure surface altitude, a digital elevation model (DEM) was used. The DEM acquired from Centre for GIS (CGIS) - Ministry of Municipality and Urban Planning (MMUP). The data (DEM) are from mass points, breaklines (high and low) of a project done in 1996. The spatial resolution was 10 meters and the pixel depth was 8 bit. The ESRI's ArcInfo Workstation version 9.3 software was used to create elevation model.

- Distance to coastline (measured using ArcGIS (ArcMap10) software).

- Depth to water table level (see section 3.2.1.6)

- Soil type (acquired from *The Atlas of Soils for The State of Qatar* by Scheibert *et al* . (2005).
- Disturbance index (distance between human activities such as farms or roads from the plots studied) as an indicator of expected distance, was derived from the Electronic Place Finder 2010, the Ministry of Municipality and Urban Planning, using ArcMap 10 software. In general, the Electronic Place Finder 3.1. is a product of the Centre for GIS for easy display and locating the addresses and landmarks in Qatar. It also, enables to search through, display and relate information on various geographic features of Qatar, like Municipality, Zone, District, City, Place, Street, Plot and important Landmark. In addition, the Center for Geographic Information Systems, under the patronage of Ministry of Municipality & Urban Planning, coordinates a systematic implementation of GIS in Qatar, which facilitates data transfer and sharing.

- Data of the total dissolved solids (TDS) was obtained from a project report by Winslow and El Hakim (2009). In this report 8509 wells were inventoried all over Qatar and 80 wells from them were sampled in the laboratory. A map of the TDS that generated from this study (Figure 3-2) was used and georeferenced using ArcMap 10 software in order to extracted TDS of groundwater. Knowing the sampling plots coordinates of this study; it was possible to find out their corresponding TDS values and recorded them in a spread sheet for further calculation and analysis (data was derived from a project report by Winslow and El Hakim, (2009).

- A topographic position (depressions, slopes and summits) was determined from the 60cm spatial resolution ortho-rectified digital aerial photography map (January, 2010). The summit position is the highest point/part and most stable whilst the backslope (slope) is zone of deposition (see Figure 3-7).

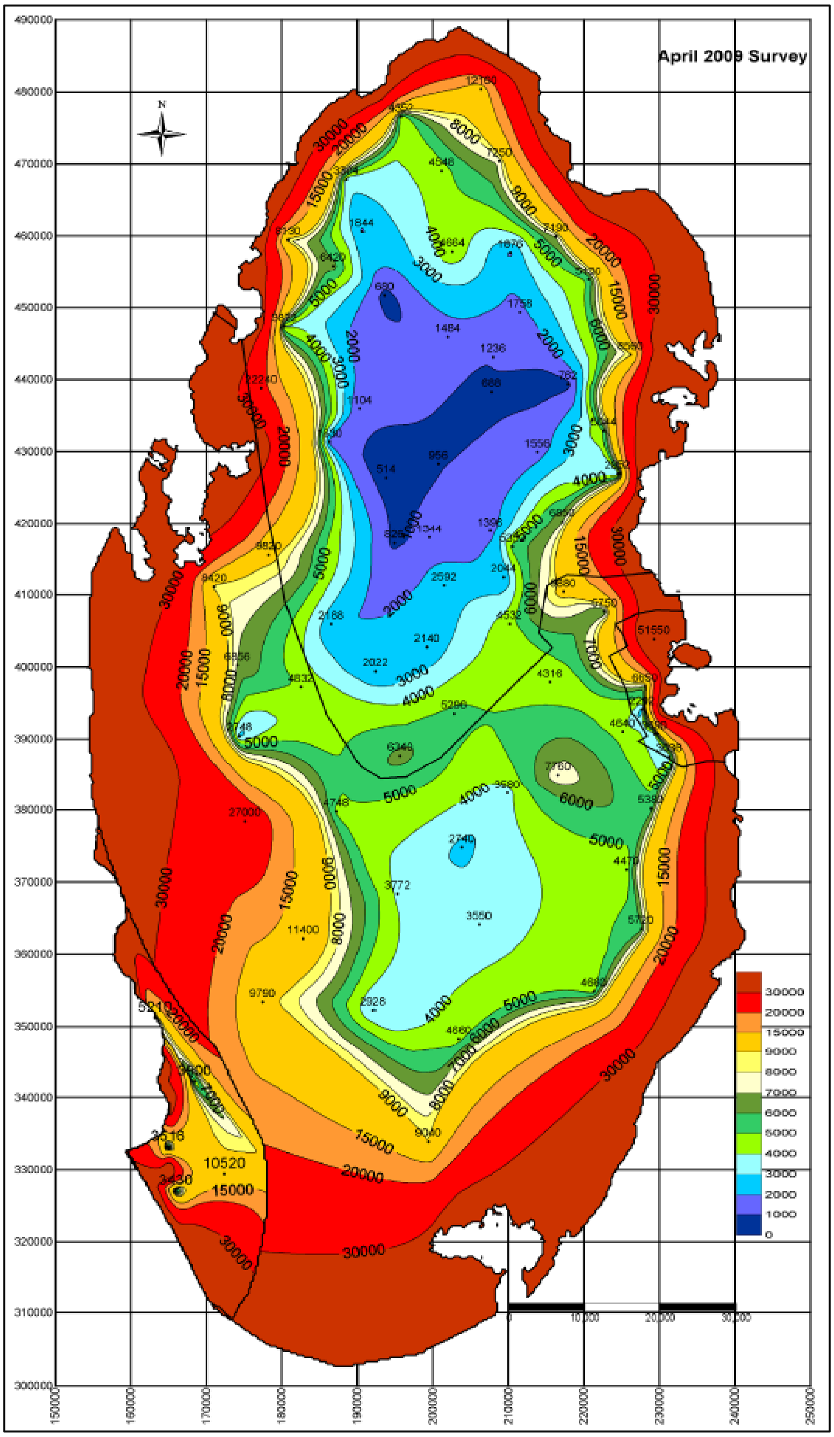


Figure 3-2: Map of Total Dissolved Solid (TDS) Isoconcentration in ppm.

Source: Ministry of Environment, Project Report by (Winslow and El Hakim, 2009)

3.1.5 Statistical analyses

The flowchart summarizes the statistical methods that are used to interpret studied variables on a national scale, Figure 3-3. Values of plots of the vegetation indices for the ground data were extracted from images (averages for plot area) for the selected years. Data were tested for normality using Anderson Darlington test. Data acquired from NDVI and SAVI were transformed using reciprocal if the data were not normally distributed. One-way ANOVA was used to analyse the NDVI and SAVI data within measurement date using Minitab 16. Mean comparisons were made using the Tukey's HSD $p<0.05$.

Relationships between vegetation types and different environmental variables, elevation, distance to coastline, depth to water table level, soil type, disturbance and total dissolved solids (TDS) were evaluated and significant bivariate relationships were determined with significance defined as a p-value of < 0.05 using SPSS 21 for Windows (SPSS Inc., Chicago. IL, USA). In addition, differences and relationships between the following factors: elevation, distance to coastline and depth to water table and vegetation type were evaluated using the non-parametric Kruskal–Wallis test. Meanwhile, the link between disturbance and vegetation type was analysed with GLM, ANOVA in Minitab 16.

Chi-square tests were used to assess the statistical significance of associations between independent categorical variables of topographic position (1=depression, 2=slope and 3=summit) and vegetation type as well as between soil type and vegetation type.

Principal component analysis (PCA) was performed in order to identify groups of highly inter-related environmental variables. A Varimax rotated PCA was performed in order to reduce 7 natural environmental and contaminant variables to a subset of non-correlated composite variables. This method was chosen because it is considered to be robust and uses knowledge of the existing variables.

SPSS offers three methods for computing factor scales, one of which is regression. The other two are the Bartlett and Anderson-Rubin methods. The regression method was used.

It is plausible to assumed the ordering of the categories within the response variable is meaningful as it goes from 1=Acacia, 2=Mixed, 3=No Acacia and 4=Bare soil. There seems to be an inherent order in the categories so far as acacia is concerned. Looking at this it is clear that the first category contains only acacia, the second contains acacia and other vegetation type, the third category contains no acacia and the forth category is bare soil containing no acacia as well. There is a natural decreasing amount of acacia within the categories therefore ordinal logistic regression will be used to examine the relationship between the dependent variable and the independent variables.

Multiple multinomial logistic regression (MLR) and ordinal regression (Hosmer and Lemeshow, 2000) were used to model the probability of occurrence of each vegetation type as a function of each environmental variable. MLR is an extension of binary logistic regression that may be applied when the response variable has more than two categories (here, vegetation type classes). The response variable has *k* categories of vegetation types. Thus, MLR allows for the estimation of the probability of occurrence of each category as a function of the environmental variables in question. The Wald statistic (Hosmer and Lemeshow, 2000) was used to evaluate the significance of independent variables, and Akaike's Information Criterion AIC (Akaike, 1974), was used to select the best model from a set of candidate models.

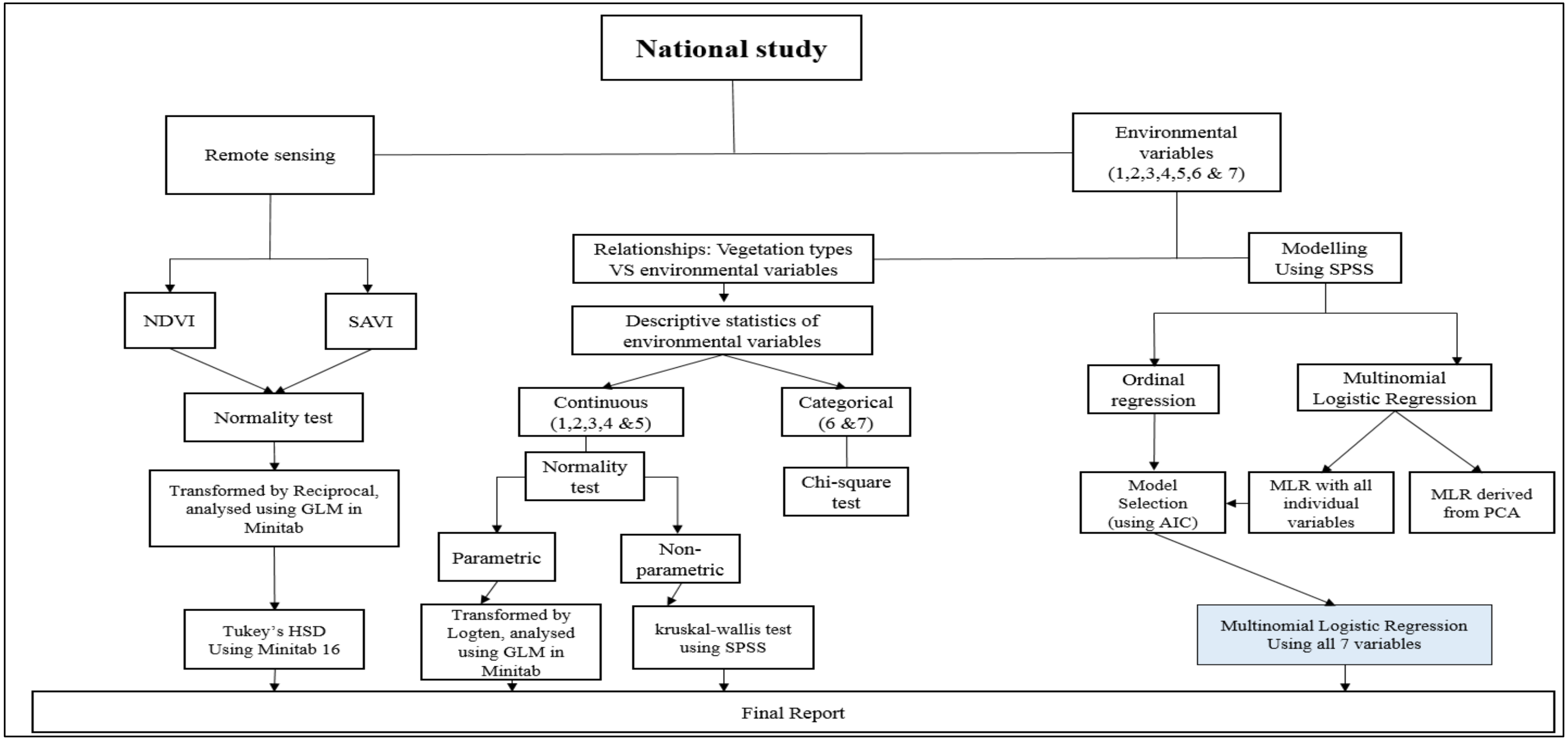


Figure 3-3: Flow Chart for the statistical analysis for a National scale study.

Note: The environmental variables are 1= elevation; 2= distance to coastline; 3= depth to water table level; 4= disturbance index; 5= total dissolved solids (TDS); 6= soil type and 7= topographic position.

3.2 Phase II: Multifactorial Approach to Studying *A. tortilis* Distribution at Local Scale.

3.2.1 Area I description

The study area I situated in the arid-desert region of Qatar at the Latitude 25° 18´; Longitude 51° 12´ which is a mostly flat and barren plain covered with sandy soils (Figure 3-4). Since the climatic and topographical features exhibit little variation across the country, the study area was carefully chosen to represent those geographical attributes which mainly influence the distribution of *Acacia tortilis*. Area I is located in central Qatar, which has been naturally dominated by *Acacia tortilis.* A protected area with a long known history of about forty years with an adjacent unprotected area exposed to anthropogenic activities was selected to enable the assessment of the impact of environmental determinants of *Acacia tortilis* on both of these areas.

Study area I, contains the three main topographic positions of depression, slope and summit. The depression is the most favourable environment that supports the growth of *Acacia tortilis,* and this constituted the main landform in the sampling. Consequently, more useful information on the impact of environmental variables on *Acacia tortilis* in study area I could be obtained. Study area I was mainly chosen because it constituted a protected area and represent about 60% of the main soil units of Qatar (see chapter 1). Therefore, study area I is characterised by all the necessary conditions, which include soil type, high population of *Acacia* species, and the main geomorphological characteristics of Qatar. They represent the most common natural habitat of *Acacia* trees as well as the dominant soil type of Qatar.

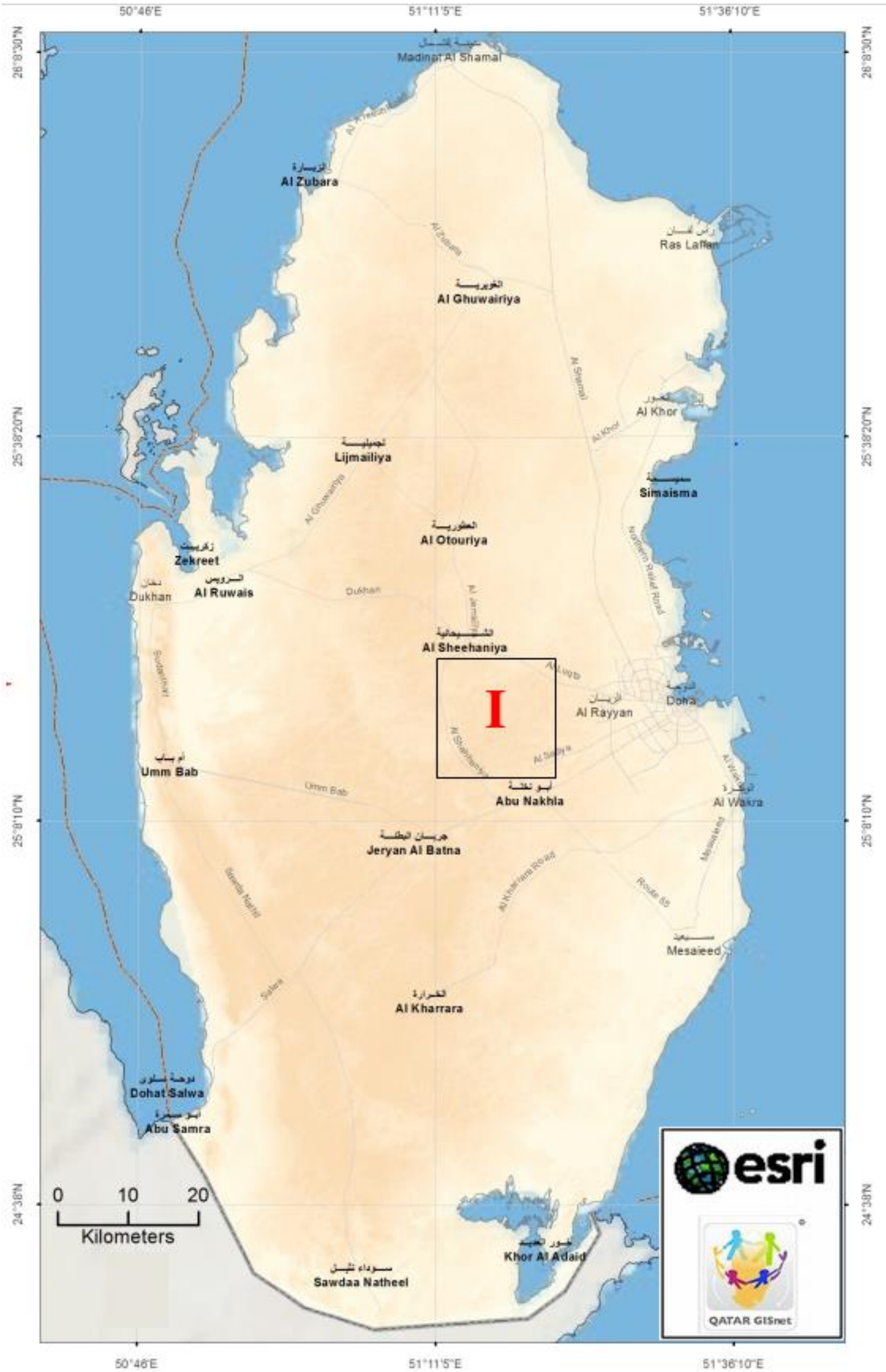


Figure 3-4: Location of the Study Areas in Qatar. Area I Was the Main Study Area Including Protected and Unprotected Sites.

3.2.1.1 Experimental design and sampling strategy

The study area I was first divided into protected and unprotected zones. The protected zone was at the centre of the study area with a radius of 1.5 km. the unprotected zone was surrounding this with its perimeter 3.5 km from the centre. The study area I was further divided into three replicates by defining sectors each with an internal angle of 120° as shown in Figure 3-5. Each sector contained a various number of depressions, some of which contained dense tree cover (less than 20 m between trees) while others contained sparse tree cover (more than 40 m), using a classification adapted from Hackett *et al.* (2013).

As shown in Figure 3-5, a label of 12 depressions were identified for sampling. They were located by using ArcMap 10 software to randomly allocate a sampling point within each zone/sector. In the field the depression nearest to the sampling point was selected. The actual locations of sampling points are shown in Figure 3-6 and coordinates for each are provided in Appendix 1.

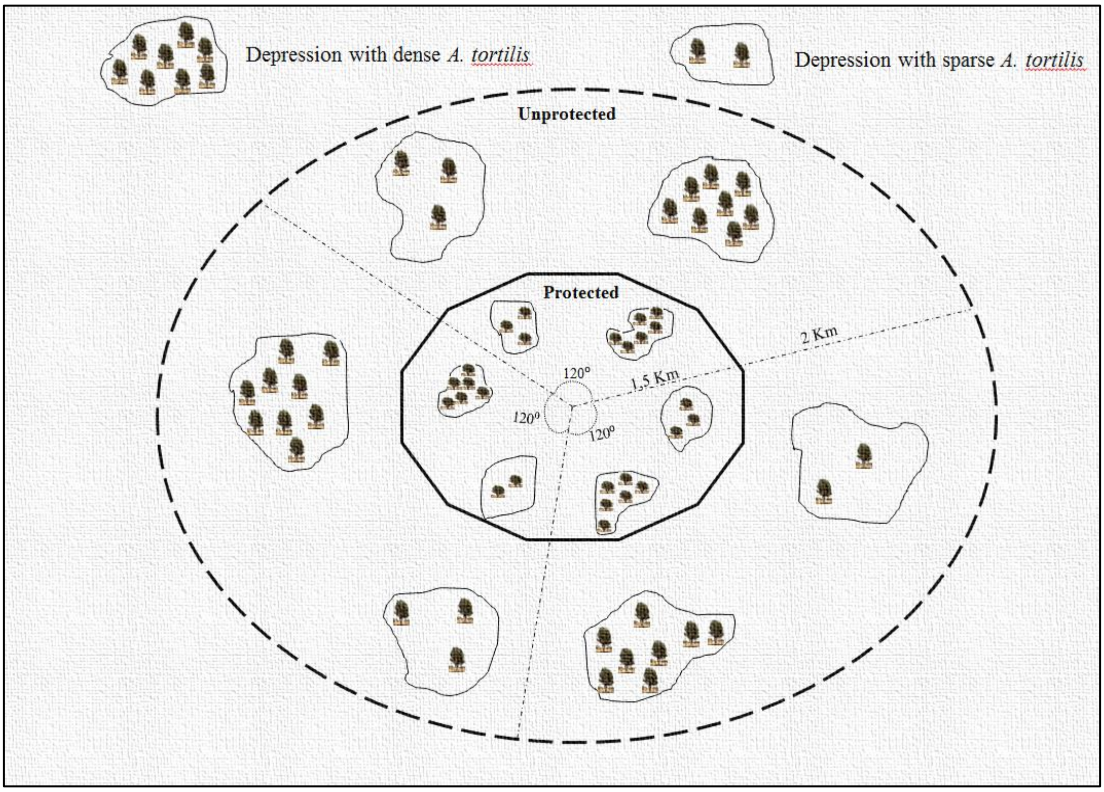


Figure 3-5: Study Area I Showing Sampling Areas with Dense and Sparse Tree Cover in the Protected and Unprotected Depressions. (Not to scale)

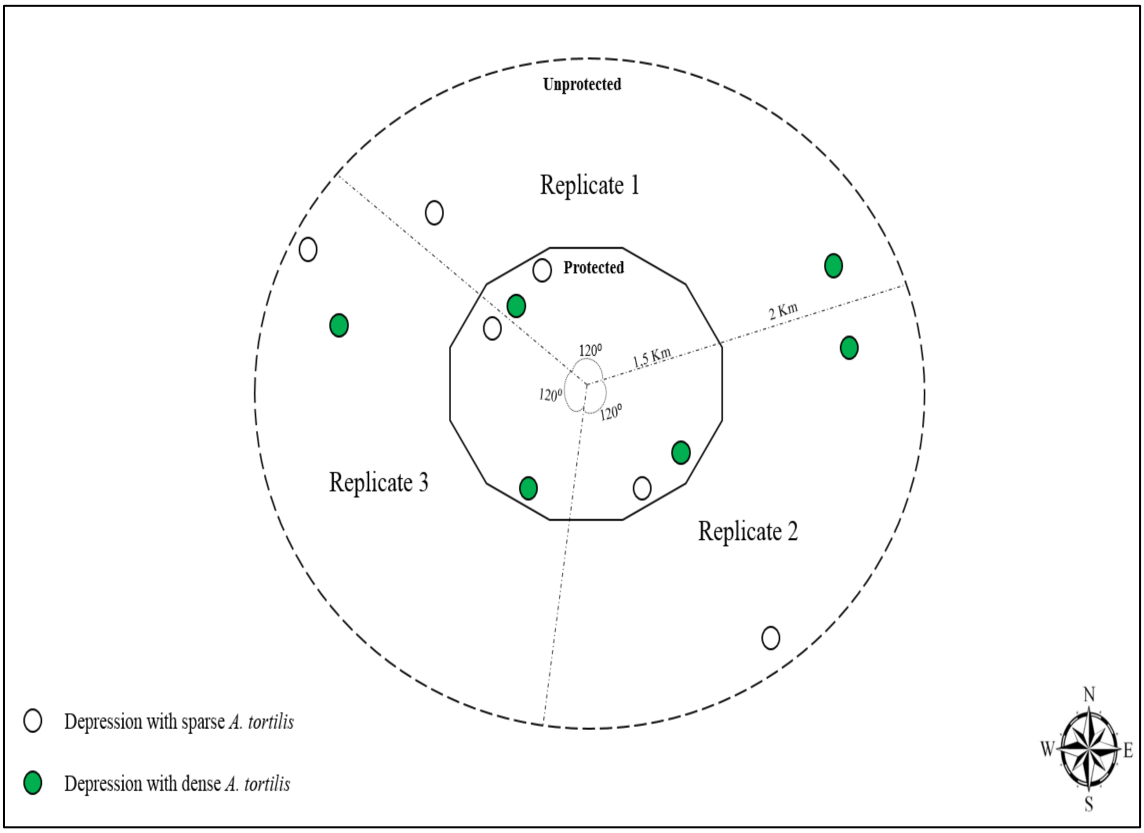


Figure 3-6: Random Sampling Points of Study Area I.

The sampling points for each depression (either dense or sparse) were identified by drawing two transect lines (with 20 m width) inclined to each other at a given degree, starting from the centre of the depression and subsequently passing through the topographic positions on the slope and the summit (Figure 3-7 and 3-8). Each transect line direction was identified by a random orientation table (expressed in degrees from the north) using Excel software (Appendix 1, Table 1). The lengths of each transect line varied depending on the topographic positions.

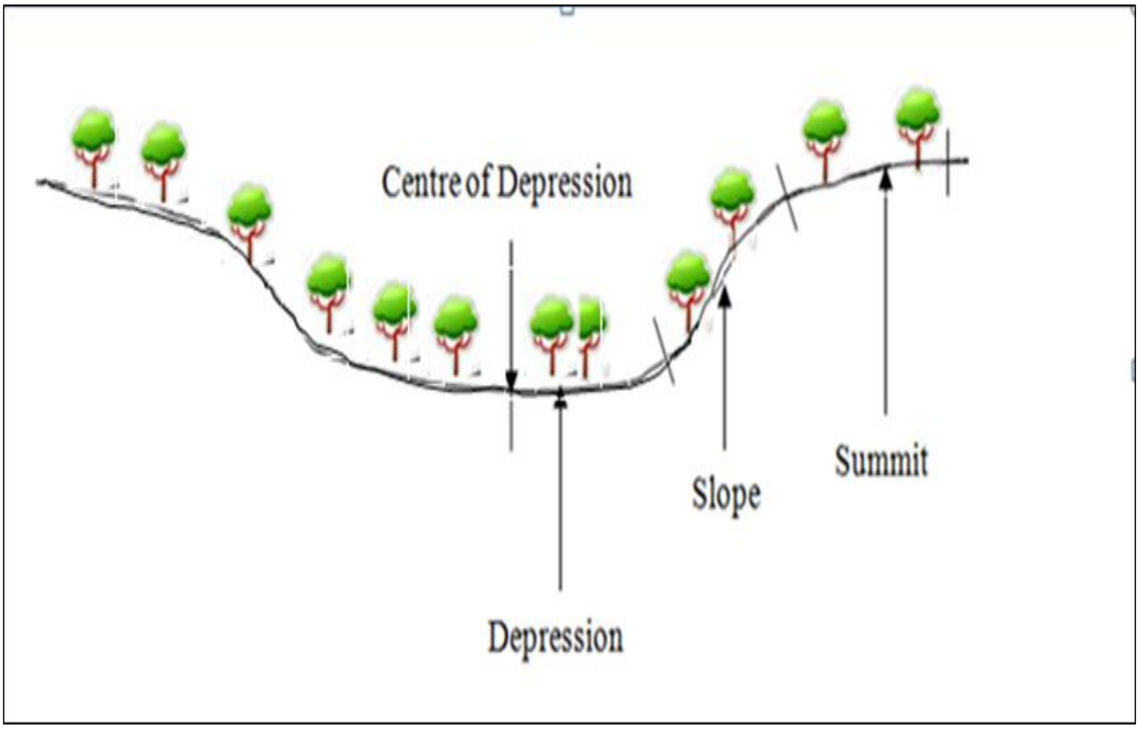


Figure 3-7: Cross-section of the Sampling Transect Showing Depression, Slope and Summit.

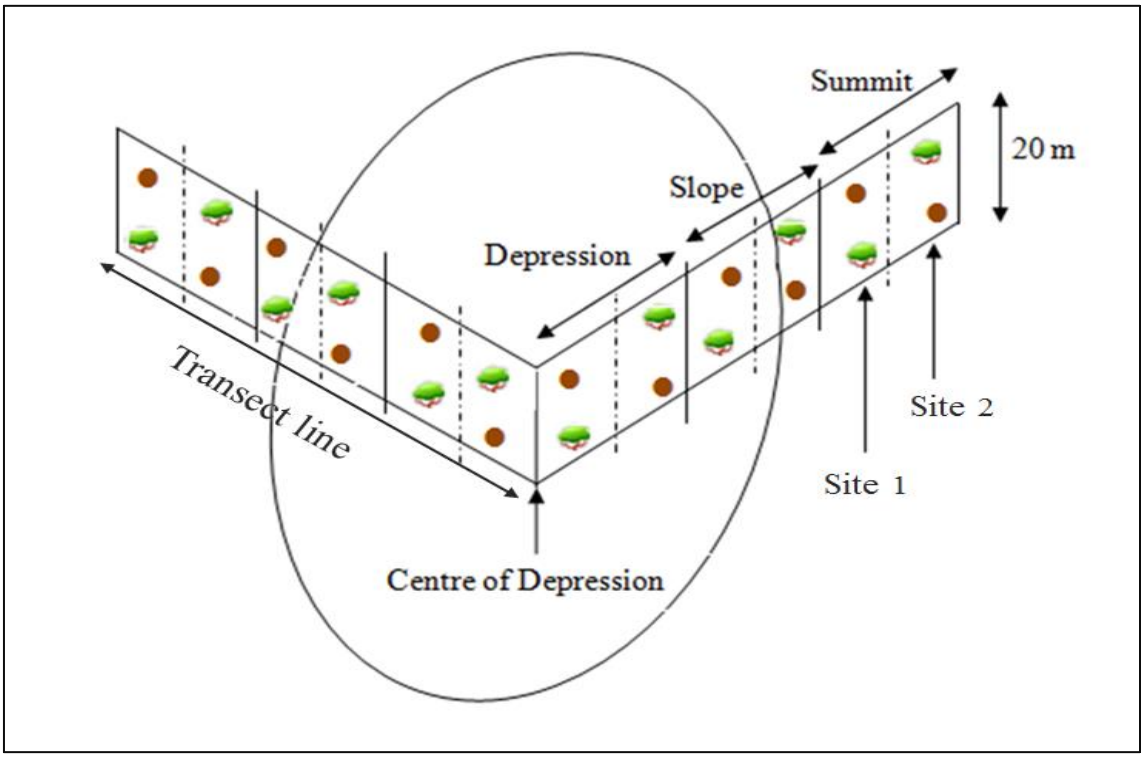


Figure 3-8: Sketch of the Sampling Transects Showing Depression, Slope and Summit.

In order to allocate soil and tree sampling points at each transect, each topographic position was divided into two sites as demonstrated in Figure 3-8. A soil and a tree sample were collected from each of the sites. Overall, twelve soil samples (under tree & bare) and twelve tree samples were collected from the two transects (six samples at each transect). Twelve sample points were collected from each transect point in the protected and unprotected sites (Table 3-4). A total of twelve transects were obtained for the protected site and twelve transects for the unprotected location. Consequently, a total of twenty-four transects were sampled in both the protected and unprotected areas with the purpose of performing a detailed investigation.

Several sets of information and samples from the plants and soils were collected from each transect, with the aim of assessing the environmental determinants for the presence and characteristics of *Acacia* trees in the study area. In addition, phytogeographical methods were used for the collection of samples in each transect with reference to their geographical locations. This method is concerned with the geographic distribution of *Acacia tortilis* and their influence on the research area. Moreover, it is also related to the factors that govern the composition of the plants in the study area, such as the *Acacia* trees. Nevertheless, it would have been too time-consuming and a waste of resources to sample the entire canopy trees in the study area. Consequently, there was a need for the adoption of a reasonable sampling strategy for the effective sampling of a subset that would represent the study area.

The stratified random sampling strategy is the most commonly used technique in agricultural science, and therefore, was adopted for this research. This approach is not only economical, but also effective in sampling a study area with a large sample population. Hence, for this study a series of random number tables were generated for the random sampling of both plants and soils within each transect, in order to minimize any bias in the data derived from the sample. These numbers are pseudo-random given that they are constrained between two values, as shown in the tables in Appendix 2. Random sampling strategy is a type of probability sampling in which each sampling location has an equal chance of being selected. Additionally, the selection of one location does not influence the choice of other locations. Statistically, the sampling locations of the research area are independent of one another and identically distributed.

Table 3-4: Summary of the Study Area I and Sampling Strategy

Description	**Quantity**
Protected area	1
Unprotected area	1
Replicates of the protected area	3
Replicates of the unprotected area	3
Depression with dense *Acacia tortilis* in each replicate	1
Depression with sparse *Acacia tortilis* in each replicate	1
Transects in each depression with dense (or sparse) *Acacia*	2
Total transects in the protected area (2×3 ×2)	12
Total transects in the unprotected area (2×3×2)	12
Trees selected for sampling in each transect	6*
Sample points (pairs) in each site of the transect	2**

* *This would apply for an ideal situation. In reality, there were no trees on some slopes or summits. Hence, the number varies depending on the transect.*

** *Two sampling points were needed in each site of the transect. However, only one sample was collected in the absence of a tree in a site.*

3.2.1.2 Soil sampling

Ideally, two soil samples were collected from each site of each transect for analysis. The first soil sample was collected under the canopy area of the sampled *Acacia* tree, as illustrated in Figure 3-8 (tree sampling) and the second soil sample collected is referred to as the bare soil sample. In the absence of *Acacia* trees in the section, only the bare soil sample was collected. The locations of the bare samples within each section were determined using the random number tables. From the position of the sampled tree, one either moves to the right or left depending on the random number given by the random directions for bare samples on transects (1 = right and 2 = left) as shown in Table 1a in Appendix 2. If the random number chosen from the table was 2, this designating movement to the left and if there was a tree towards this direction or area that may interfere with the sampling process (i.e. any possibility of introducing bias), this case should be eliminated. In such a case, the other direction (1 = left) for the bare sample on the transect was chosen. This direction of left away from the tree was followed to a point guided by the random number for distance from the transect centre given in Table 1b in Appendix 2. Maintaining this distance away from the centre, the final sampling point was located by moving a given distance on the transect (between 3 and 20m) as determined by table 1b shown in Appendix 2 for random distances for bare samples on transects.

The two soil samples under the tree and bare soil samples were collected using an augur at soil depths for the A and B horizons separately. The soil samples were placed in clearly labelled polythene bags for easy identification and preservation for analysis. Details of the sampling are recorded in the soil distribution forms shown in Appendix 3. The augur was used to penetrate the depth to the rocky or cemented layer at different geomorphological variations. Two hundred twenty two soil samples (approximately 0.5 kg) were taken from each horizon (A and B) for study area I (444 samples in total). These were air-dried, thoroughly mixed, and passed through a 2mm sieve to get rid of gravel and boulders. A 150 g of each samples were preserved in polythene bags and transported to the laboratory at Newcastle University for further analyses.

Several soil property measurements were taken in the field. These include soil structure, colour, consistency, and texture, and surface crust and calcium carbonate (FAO, 1990; Munsell Soil Colour; Key for Assessing Soil Texture; Payton, 2011).

Calcium Carbonate (CaCO3) in the soil was tested by dropping a small amount of 10% hydrochloric acid on a fragment of soil sample. The amount of calcium carbonate was then estimated by using the indicators shown in Table 3-5.

Table 3-5: Estimation of Amount of Calcium Carbonate

Calcareous class limits	**$CaCO_3$**	**Audible effects (close to ear)**	**Visible effects**
Very slightly calcareous	0.5-1%	Faintly audible	No effervescence
Slightly calcareous	1-5%	Moderately audible	Slight effervescence
Calcareous	5-10%	Easily audible	Moderate effervescence
Very calcareous	>10%	Very easily audible	Bubbles >3mm diameter

Surface crust and/or sealing at the soil surface were described according to the guidelines for soil description (FAO, 2006). Crusts which develop at the soil surface after the topsoil dries out can be described as a surface sealing, due to its effects on reducing water infiltration and inhibiting seed germination (Table 3-6).

Table 3-6: Surface Crust/Sealing at the Soil Surface Topsoil.

Thickness		**Size**	**Consistency**	
None	**N**			
Thin	**F**	(< 2 mm)	Slightly hard	S
Medium	**M**	(2 - 5 mm)	Hard	H
Thick	**C**	(5 - 20 mm)	Very hard	V
Very thick	**V**	(> 20 mm)	Extremely hard	E

Soil moisture content was measured by using a hand-held frequency-domain reflectometer (ML2x, Delta-T Devices Ltd, UK) across the monitoring depths at each horizon of the different topographic variables.

The following soil attributes were measured in the laboratory:

Soil pH and electrical conductivity

Soil pH was determined in a 1:2.5 suspension (weight/volume) ratio according to standard UK laboratory soil survey methods (Avery and Bascomb, 1982). 10g of 2mm-sieved wet soil was placed in a plastic bottle with 25ml of distilled water. The solution was thoroughly stirred and left to stand for 15 minutes to equilibrate. The pH reading was recorded using a glass electrode pH meter (Figure 3-9).

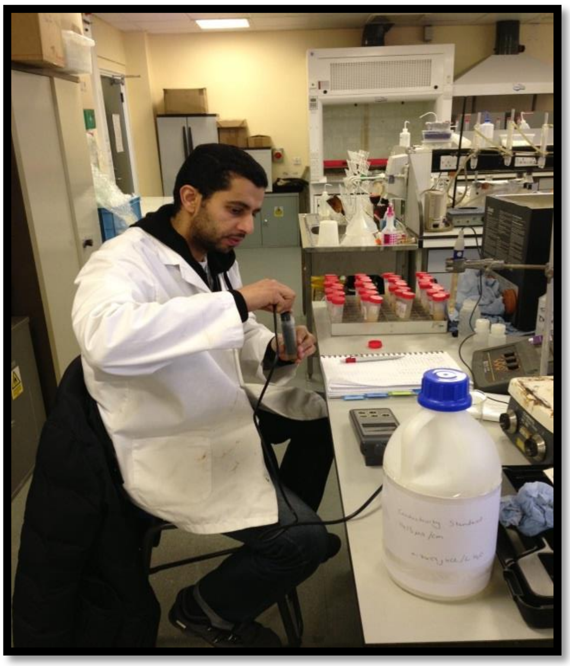


Figure 3-9: Lab Workings for Soil pH and Electrical Conductivity Analysis

The total solute concentration using aqueous extraction techniques employing extractant:soil ratios is the most conventional method of measuring salt concentration; normally determined by analysis of the electrical conductivity. Consequently, the electrical conductivity (EC) is a rapid, inexpensive and reasonably accurate way to determine the salt concentration (Janzen, 1993). The same suspension used to measure soil pH was also used to measure electrical conductivity (EC) using a digital conductivity meter (Mukhopadhyay and Joy, 2010).

Available phosphorus

It is necessary to determine the phosphorus content of the soil using the appropriate methods. This will give an indication of the available phosphorus for *Acacia* tree uptake considering the type of soil in Qatar which has been characterised as predominantly calcareous (Scheibert *et al.*, 2005). The most common methods are probably the bicarbonate method of Olsen (Olsen *et al.*, 1954) which has been found to be best suited for calcareous soils (Sims, 2000) It has also been used successfully on a wide range of acid to alkaline soils. Gilbert *et al.* (2009) have tested several methods to determine which are the most suitable for measuring available P in soils of mesotrophic grasslands, with the growth and P uptake. They found that Olsen method for P determination was significantly correlated with P uptake in plant growth. Moreover, it is a good indicator used to evaluate the availability of phosphorus, particularly, in calcareous soils (Yang and Jacobsen, 1990).

Available phosphorus in the soil samples was determined using the new Olsen method described by Carter and Gregorich (2007). A soil sample of 5g was weighed into an extraction bottle and 100 ml Sodium hydrogen carbonate (0.5 M) was added. The contents were shaken for 1 hour and filtered through a Whatman number 2 filter paper. A pipette was used to transfer 5ml of each sample extract into a clean and labelled conical flask. Similarly, 5ml of each standard and 5ml of sodium hydrogen carbonate blank were transferred into clean and labelled conical flasks. Then, 1ml of 2M H_2SO_4 was added to each flask and the contents agitated to release carbon dioxide (CO_2). Subsequently, 5ml of ascorbic acid and 20ml of ammonium molybdate working reagent were added and the contents mixed and allowed to stand for 30 minutes for colour development (Figure 3-10). As a result of the extremely low levels of available phosphorus in most calcareous soils, a second set of standard solutions with very low concentrations were prepared from the working standard solutions (µg/mL) using a similar procedure. The Biochrom Libra S12 Spectrophotometer was set at zero using the blank solution. Then the availability of phosphorus was determined by measuring the absorbance of the standards and samples at 712 nm using a Biochrom Libra S12 spectrophotometer.

Figure 3-10: Lab Workings for Analysis of Available Phosphorus.

Organic carbon

The Walkley-Black procedure is widely used because it is simple, rapid, and has minimal equipment needs (Qureshi *et al.*, 2012). However, this procedure has been shown to lead to the incomplete oxidation of organic C and is particularly poor for digesting elemental C forms. Studies have shown that the recovery of organic C using the Walkley-Black procedure ranges from 60 to 86% with a mean recovery being 76% (Walkley and Black, 1934). As a result of the incomplete oxidation and the absence of a site-specific correction factor, a correction factor of 1.33 is commonly applied to the results to adjust the organic C recovery. To overcome the concern of incomplete digestion of the organic matter, the Walkley-Black procedure was modified to include extensive heating of the sample during sample digestion (Tiessen and Moir, 1993). In this variation of the method, the sample and extraction solutions are gently boiled at 150 ^{0}C for 30 minutes, allowed to cool, and then water is added to halt the reaction. The addition of heat to the system leads to a complete digestion of the organic C in the sample; therefore**,** no correction factor is needed. Furthermore, Walkley and Black method has been found to be more reliable for calcareous soil (Ali and Jenkins, 1995) and Qatari soil has been found to have high calcareous content.

The organic carbon content of the soil samples was determined using the adapted Walkley-Black method (Tiessen and Moir, 1993). The procedure involves weighing 1g of 0.2mm ground air-dry soil into a 100ml digestion tube and then adding 40ml of potassium dichromate ($K_2Cr_2O_2$) solution. The contents were heated on a digestion block for 45 minutes at 150°C and allowed to cool. The entire contents of the digestion tube were subsequently transferred into a 250ml conical flask and approximately 100 ml distilled water and a few drops of diphenlylamine indicator were added to the 100ml mark. Similarly, the blank solution was prepared using 40ml dichromate solution and then adding about 100 ml distilled water and a few drops of diphenylamine indicator were added to the 100ml mark. The samples and blank were titrated against ferrous sulphate solution. The end point was reached when a clear emerald green colour appeared in the titrated solutions. Shortly before this point, the original brown-green colour developed a bluish tinge and from that point care was taken by adding dropwise a solution of the titrant into the solution being analysed. The chemistry of this extraction procedure is as follows:

$$2Cr_2O_7^{2-} + 3C^0 + 16H^+ = 4Cr^{3+} + 3CO_2 + 8H_2O \quad \ldots\ldots\ldots\ldots(4)$$

Organic carbon (mg/g) for air dry soil was calculated as follows

$$\text{mg C in sample} = (B - T) \times (M) \times (0.003) \times (1000) \quad \ldots\ldots\ (5)$$

where B and T are the titres of the heated blank and sample, respectively, and M is the molarity of the ferrous solution. In all calculations it is presumed that 6 moles Fe (NH4)2 (SO4)2 are equivalent to 1 mole $K_2Cr_2O_7$.

1. Knowing the molarity of the $K_2Cr_2O_7$ and the volume used in each titration, the molarity of the Fe(II) solution can be calculated as:

   Molarity (Fe (II)) = 6 x molarity (Cr_2O_7)´volume (Cr_2O_7) / volume (Fe(II)).

The results were later transferred into percentage (%).

Total gypsum content

The standard oven-drying method may not be appropriate for the analysis of gypsiferous soils due to loss of part of the crystal water of gypsum ($CaSO_4.2H_2O$) when heated to 105^oC by forming bassanite ($CaSO_4.0.5H_2O$). Further application of heat would transform the entire gypsum into anhydrite $CaSO_4$ (Porta, 1998). Hence, it is important to take into consideration the correction factor that would account for the loss of the crystal water of the gypsum soil. Furthermore, it is recommended not to exceed 40–50^oC when using the oven-drying method to analyzed gypsiferous soils to prevent gypsum transformation (Porta, 1998). To overcome the limitations of oven-drying method, several other methods have been developed for the determination of gypsum content in soils. Each of these methods has its advantages and limitations. Hence, it is important to concisely highlight the advantages and limitations of these methods below (Porta, 1998):

Wet chemical methods

These methods have been widely used and entail the dissolution of gypsum in water prior to the determination for the gypsum content in soils. The accuracy of these methods depends on the total dissolution of gypsum. The concentrations of Ca^{2+} and SO_4^{2-} will then be determined and used to calculate the original content of gypsum in the sample (Porta, 1998). Interference of Ca^{2+} and SO_4^{2-} from other sources and the loss of calcium by adsorption on the exchange complex can lead to erroneous results. Again, the dissolution rate of gypsum is proportional to the fineness of the crystals of the gypsum (Nelson, 1982). Hence, large gypsum crystals will produce low solubility of the gypsum and the total dissolution of the gypsum may never be completed. The limitations of the various wet chemical methods are highlighted below:

Determination of Ca^{2+} from dissolution of gypsum in water

This method involves the selective precipitation of Ca^{2+} from the extract using acetone and the precipitate is redissolved in water followed by the measuring the Ca^{2+} concentration in solution to give the gypsum content of the soil. The limitations of this method include interference of Ca^{2+} from other sources; overestimation of gypsum content; and underestimation of gypsum content due to loss of Ca^{2+} to the exchange complex. This method is also tedious and time cumbersome.

Determination of SO_4^{2-} from dissolution of gypsum in acid

In this case, the gypsum is dissolved in hot concentrated HCl and then the SO_4^{2-} precipitated with Ba^{2+}. Then, gravimetric method was used to determine the concentration of $BaSO_4$. Despite this method assures the solubilisation of the entire gypsum in the sample, it is long and tedious. In addition, the presence of SO_4^{2-} from other soluble salt will interfere with the results

Determination of SO_4^{2-} by ion chromatography

Chromatographic analysis has been widely used to separate various anions in a exchange column according to their selectivity for a given exchange resin. This method offers improved sensitivity over other methods and enables the simultaneous determination of several inorganic anions. However, the adsorption of Ca^{2+} on the exchange complex usually underestimates the results.

Thermogravimetric methods

Standard methods for determining the gypsum content in soils based on SO_4^{2-} is lengthy and cumbersome. In addition, the presence of SO_4^{2-} from sources other than the gypsum can lead to erroneous results. To overcome the limitations that found in some methods used to analysis the gypsum contents of the soil samples such as the method compiled and edited by (Van Reeuwijk, 2002) and published in the International Soil Reference and Information (ISRIC) and FAO technical paper 9. This approach involves thermogravimetric analysis (DTA) based on the loss of weight when a sample containing gypsum is heated (Porta, 1998). The gypsum content of the soil is totally converted to anhydrite form at about 200^{o}C. Hence, the loss of weight is a result of the dehydration of gypsum (Porta, 1998).

In current research, the total gypsum content of the soil was determined using the thermogravimetric method improved by Artieda *et al* (2006), which has been widely used in recent years (Lebron *et al.*, 2009; Mees *et al.*, 2012; Pascual *et al.*, 2012; Herrero and Castañeda, 2013; Moret-Fernández *et al.*, 2013). This method was adopted in this study to overcome the deficiencies of other methods which rely on SO_4^{2-}. The method is appropriate for this study because of the high gypsum content in soils in arid and semi-arid regions such as Qatar, as reported by Eswaran and Zi-Tong (1991). The new thermogravimetric method has been recommended as valid for soils with gypsum contents of 2%, and thus improves on previous estimation procedures (Artieda *et al.*, 2006). Finally, the method used in this research relies on the use of adequate temperature ranges so as to avoid errors arising from water release by soluble salts or other components up on heating (Herrero *et al.*, 2009).

The procedure of gypsum content analysis according to Artieda *et al.*, (2006) involves the following steps:

1. 20 g of < 2mm air-dry soil was transferred to a Pyrex crystallizing dish and weighed to the nearest 0.001g.
2. The crystallizing dish containing the sample was placed in a ventilated oven at 70ºC until a constant weight was achieved.
3. The dish containing the sample was then placed in an oven at 90ºC until a constant weight was again achieved.
4. Constant weight at 70ºC was reached in 3 days, and similarly at 90 ºC it was also 3 days.
5. After removal from the oven and before weighing, the sample was cooled completely in a desiccator.
6. The gypsum percentage in the sample was calculated by the following expression:

$$\%\ \text{Gypsum} = \left(\frac{\text{ws} - \text{wf}}{\text{ws} - \text{wt}}\right) 100\ \frac{100}{14.95} = \left(\frac{\text{ws} - \text{wf}}{\text{ws} - \text{wt}}\right) \times 669$$

where:

ws is the weight of the sample dried at 70ºC plus that of the Pyrex crystallizing dish.

wf is the weight of the sample dried at 90ºC plus the Pyrex crystallizing dish.

wt is the weight of the Pyrex crystallizing dish, and 14.95 is the recovery factor of gypsum between 70 and 90ºC.

Observations conducted from the field work revealed that gypsum was only found in some summit positions and a few slope areas in study area I. Therefore, a total of 40 soil samples were analysed (as shown in Figure 3-11); these were obtained from two transects of the protected site (one from a dense tree depression and the second from sparse tree depression) and similarly two transects from the unprotected site.

Figure 3-11: Soil Samples from the Three Topographic Positions in Study Area I Containing Different Concentrations of Gypsum.

3.2.1.3 Plant sampling and measurements

The assessment of the *Acacia* tree productivity can be achieved directly by destructive techniques of weighing trees which is difficult and often not feasible. However, indirect methods of using regression equations based on more easily measured variables of trees are frequently utilized for predicting biomass and could be better alternative (Sanon *et al.*, 2007). Many authors used regression analysis to develop biomass functions (Coughenour *et al.*, 1990; Tietema, 1993; Eshete and Ståhl, 1998; Sanon *et al.*, 2007). They found strong relations between the biomass and dendrometric parameters of *Acacia* tree such as crown area, plant height as well as stem diameters. Key parameters require the determining the amount of the yield of woody tree such as *Acacia* tree in field surveys. This may include determining the diameter at basal height, crown diameter, tree height, canopy cover, density and trunk diameter (for *Acacia tortilis* with multiple stems, a sum of individual stem basal diameters is taken) for browsing, wildlife and regeneration potentialities (Tietema, 1993; Eshete and Ståhl, 1998; Sinsin *et al.*, 2004; Sanon *et al.*, 2007; Noumi *et al.*, 2010). Such parameters are necessary towards drawing up an efficient programme (management scenarios) for the *Acacia tortilis* sustainable management.

Dendrometric parameters have been widely used to develop regression prediction models for tree age, tree height, crown diameter, crown ratio and crown depth for many plants including *Acacia* trees (Paula *et al.*, 2001; Sönmez, 2009; Buba, 2012; Diallo *et al.*, 2013). A typical example is the prediction of the crown ratio (defined as the ratio of crown diameter to tree height) directly from other dendrometric parameters such as total height and stem diameter at the breast height (Tanka, 2006). Again, comparing the dendrometric parameters of *Acacia* trees from sites with different environmental conditions could provide significant insight on the influence of the environmental conditions on the plant. Furthermore, dendrometric parameters could be used to assess the healthiness of *Acacia* trees. For example, the growth and yield of trees are usually modelled using stem diameter-at-breast height relationships with tree height, crown height, and crown diameter (Paula *et al.*, 2001). Similarly, the crown ratio can serve a vital indicator of the growth potential of individual trees, tree vigor, wood quality, stand density, wind resistance, competition and survival potential (Temesgen *et al.*, 2005).

In current study, the random orientation tables were used to randomly sample the *Acacia* trees. This involves locating position by distance from the section end into a given section using the random locations for trees shown in Table 1c in Appendix 2. From that point, the table for random direction from the transect (Table 1c-1 in Appendix 2) was used to decide whether to move right or left. Then the table of distance from the transect centre (Table 1c-2 in Appendix 2) was used to determine the distance to move away from the centre of the transect. At this final point, the nearest tree over 60cm in height (Kennenni and Maarel, 1990) was selected. Site details were then taken, such as site/profile number (e.g. section 1; dense tree depression); map/GPS reference; location (i.e. transect number); section length; date and other useful information associated with the sampling point. In addition, the morphological characteristics of the *Acacia* trees were assessed and recorded on the *Acacia* Description Form as shown in Appendix 4. Characteristics of the plant recorded included height (m); stem number; DSB (cm); crown diameter (m); crown area (m); and number of branches.

Consequently, it is essential to determine the morphological/dendrometric parameters for individual *Acacia tortilis* plants in order to evaluate their correlation with topographic variables, as indicated in Figure 3-12. Crown diameter, tree height, crown area and stem diameter at stem base (DSB) were measured in metres using a measuring tape.

Crown diameter

The crown (canopy) diameter of *Acacia tortilis* tree rarely forms a perfect circle, resulting in directional variation in crown diameter. Consequently, crown diameter is usually estimated by taking the average measurements of the longest and the shortest diameters of the crown zone (Buba, 2012). In this research, the crown diameter of *Acacia* trees was measured by projecting the edges of the crown to the ground and measuring the length along one axis from edge to edge through the crown centre. These measurements of crown diameters, D_1 and D_2, were carried out along the north-south (D_1) and east-west (D_2) directions. In other words the directional variation of the crown diameter was measured in two fixed perpendicular directions and using a compass the north-south and east-west directions were determined with a measuring tape (50 m) (Delaplace *et al.*, 2010). The crown diameter was then obtained by taking the average of the measurements along the axis: $(D_1 + D_2)/2$. The estimated crown diameters of the *Acacia* trees are then used to calculate other useful dendrometric parameters such as crown area that are relevant for decision-making processes in forest management (Buba, 2012).

Crown area

The canopy area (CA) of the trees was determined by measuring the largest canopy diameter in the N-S direction (D_1) and the diameter perpendicular of the E-W direction (D_2) from which canopy area could be calculated using the formula: $\pi(D_1/2)\ (D_2/2)$ (Eshete and Ståhl, 1998; Wilson and Witkowski, 2003).

Tree height

The total tree height of *Acacia* trees was measured as the distance from the ground level to the tip of the most vertically projected canopy surface, as illustrated in Figure 3-12. It is necessary to also estimate the crown depth of the *Acacia* tree, which was achieved by measuring the distance from the ground level to the base of the first branch of the tree (Diallo *et al.*, 2013).

Diameter at stem base (DSB)

DSB refers to the diameter at stem base of Dx where x is the height used of tree trunks and stems at their base, as shown in Figure 3-12 (adopted from Eshete and Ståhl, (1998)). It was measured as the diameter at the 0.3 m of each individual *Acacia tortilis*. When several stems emerged directly from the ground, as shown in Figure 3-13, the sum of individual stem diameters at stem base of all emerging shoots were measured and the trunk diameter estimated using Fabre (1979) formulae (Sanon *et al.*, 2007; Noumi *et al.*, 2010):

$$D = (d_1^2 + d_2^2 + d_3^2 + \cdots + d_n^2)^{½} \quad \ldots\ldots\ldots\ldots (1)$$

where D is the estimated diameter of the trunk and $d_1 \ldots d_n$, are the diameters of stem shoots.

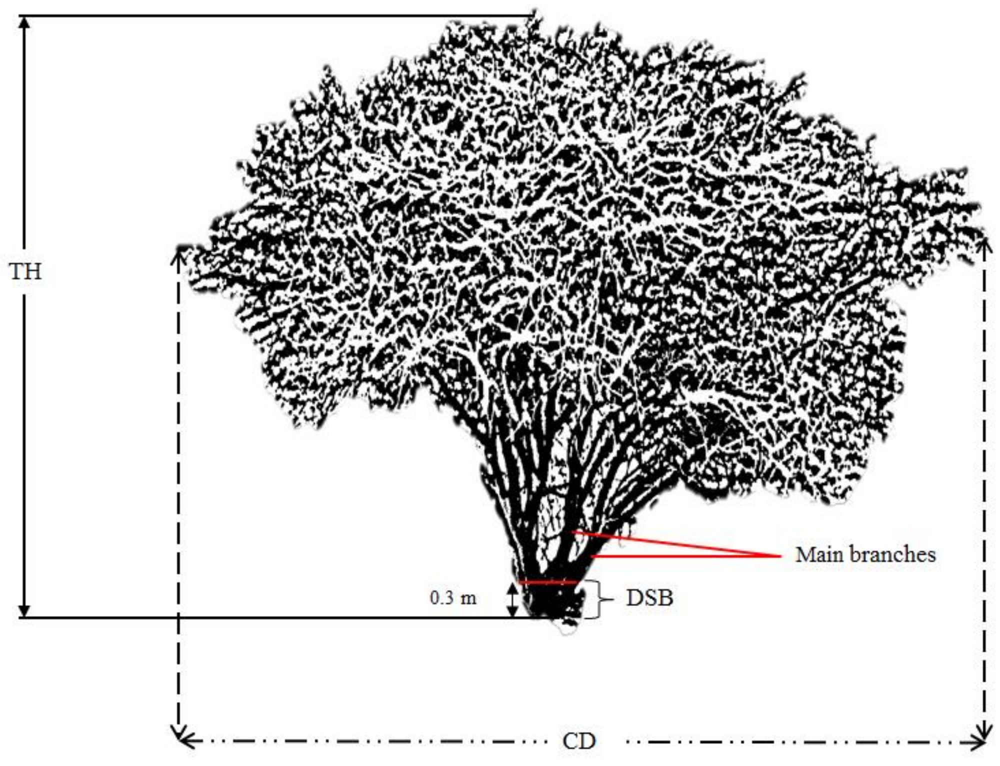


Figure 3-12: Sketch of an *Acacia tortilis* Tree Illustrating the Different Components and Measured Variables.

(*TH = total tree height, CD = crown/canopy diameter and DSB = diameter a stem base).*

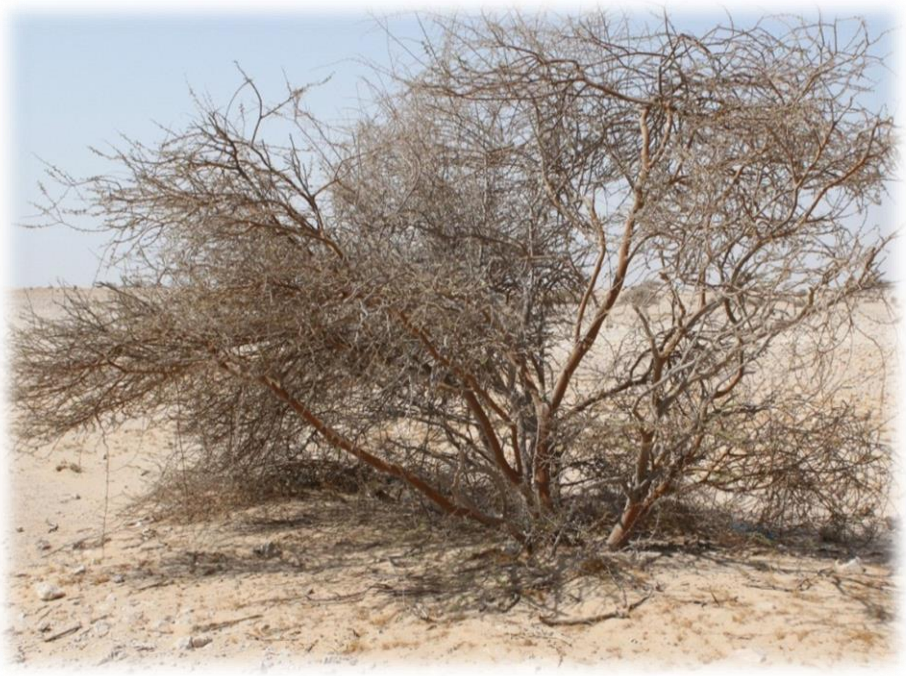


Figure 3-13: Multiple Stems Branches of *Acacia tortilis.*

Example from the study area

Number of branches

The number of branches was obtained by counting the number of sub-branches which grew directly from each stem branch (basal branch) according to the recommendations of Donohue (1995).

Roots

When sampling the soil under each sampled tree, the diameter of roots, nature and abundance of roots were described, as shown in Tables 3-7 and 3-8; to characterize the distribution of roots in the profile using the following terms (FAO, 2006). In specific cases, additional information was noted such as Root Nature: woody, fibrous or fleshy. Estimate of the number of roots were in an area of 10 cm^2.

Table 3-7: Classification of the Diameter of Roots (size).

< 1mm	Very fine
1mm-2mm	fine
2mm-5mm	medium
>5mm	coarse

Table 3-8: Classification of the Abundance of Roots

Very fine/fine roots	Medium/coarse roots	Frequency
1-10	1-2	few
10-25	2-5	common
25-200	>5	many
>200	-	abundant

All measurements recorded for *Acacia* trees, such as tree height, canopy diameter and area, and diameter at breast height (DSB) were averaged per depression, slope and summit position. From the averages, graphs were generated by plotting the various parameters (height, DSB, crown area and crown diameter) against the different positions (depression, slope and summit) for protected and unprotected areas. Graphs of the relationships between the dendrometric parameters were also plotted for the various positions in the protected and unprotected areas.

3.2.1.4 Phytosociological measurements of *Acacia* trees

A phytosociological analysis of the native common trees in Qatar was also undertaken. Each transect was divided into plots of 20 × 20m and the various native tree species (e.g. *Acacia tortilis*, *Acacia ehrenbergiana*, *Ziziphus mauritiana* and *Lycium shawii*) were counted and recorded in the transect description form (Appendix 5). The recorded values were then used in the equations below to calculate the density and frequency of *Acacia tortilis* within each depression, slope and summit position of the transects within the sites (Bonham, 1989; Kennenni, 1991; Sharma and Sharma, 2011):

$$\text{Density} = \frac{Total\ No.\ of\ individuals\ of\ a\ species}{Total\ No.\ plots\ studied} \quad \ldots\ldots\ldots\ldots\ldots\ (2)$$

Where: each plot unit area is 20m^2

$$\text{Frequency} = \frac{No.\ of\ polts\ in\ which\ of\ species\ occurs}{Total\ No.\ of\ plots\ examined} \quad \ldots\ldots\ldots\ldots\ldots\ (3)$$

The same procedure was repeated for other transects within other replicates of the protected and unprotected areas covering the dense and sparse tree depressions. Averages were taken for the three positions and used to plot graphs for comparison.

3.2.1.5 Browsing, cutting and leaf coverage attributes

Morphological characteristics of the *Acacia* trees such as proportion of damage, grazing intensity and living branches were used to assess the health or condition of the plants in the study area. This can provide insight into the effect of anthropogenic disturbance in the unprotected areas and other environmental factors affecting the *Acacia* trees in the study area.

These attributes were measured subjectively according to the method of Abd el-wahab *et al.* (2013), based on the number of field observations of each sampled *Acacia tortilis* tree, and then ranked according to the following index of the extent of first browsing, 1= no browsing; 2 = some browsed; and 3 = completely browsed), and then of cutting, 1 = no cutting, 2 = some cutting and 3= whole branch cut. The nature of the leaves of the *Acacia* trees ranked to the following index: 1= no leaves, 2 = partially covered and 3 = fully covered. These attributes were used to assess human disturbance as well as the condition of the trees in study area I (see Appendix 4).

3.2.1.6 Measurement of the depth to ground water level

A digital elevation model (DEM) of Qatar and observation well data, including the top of casing elevation, water table level and other water quality data, were acquired from the GIS centre and the Department of Agricultural and Water Research, Ministry of Environment (MOE) as well as the Public Works Authority (Ashghal, 2012). ESRI's ArcGIS 10.1 and Spatial Analyst Extension software were used to produce the depth to ground water table level maps as shown in Figure 3-14. For study site I, data from 32 monitoring wells were obtained and merged from both the MOE and Ashgal data into one dataset. Similarly, data from 108 monitoring wells were obtained to generate water table level for the whole of Qatar.

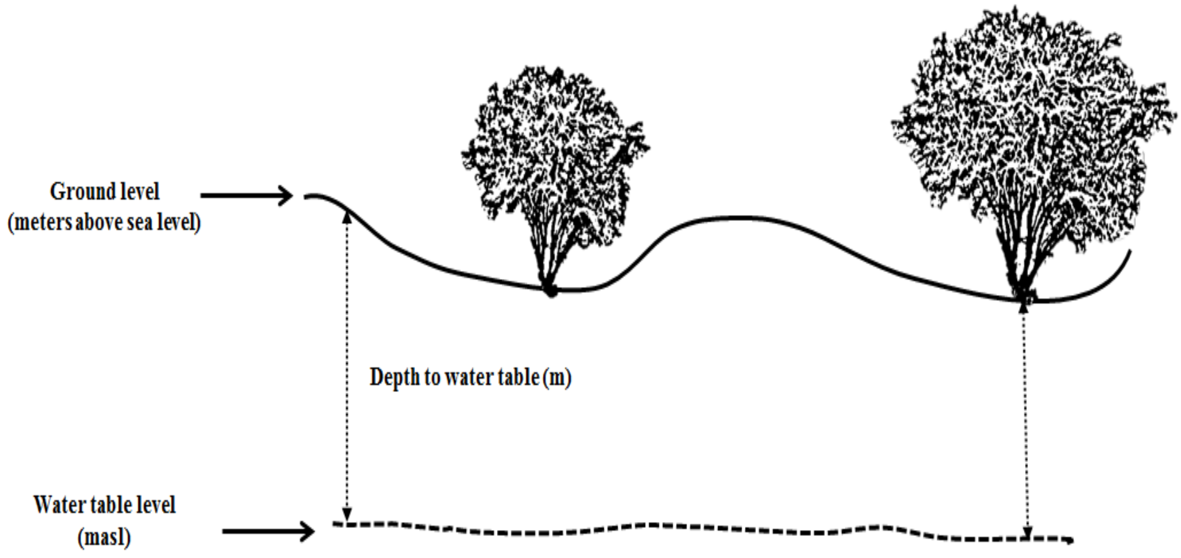


Figure 3-14: Diagram Illustrating the Different Main Parameters Used in Calculating Depth to Water Table Level.

Notes:

1. *Ground level data derived from Digital Elevation Model (DEM).*
2. *Water table level is repeated relative to mean sea level and may be + or –.*
3. *Water table data acquired from the Ministry of Environment (MOE) and Public Works Authority (in 2012).*
4. *Depth to water level derived from difference between ground level and water table level.*

3.2.2 Regeneration study

Generally, there are two sections being presented in research into regeneration of the *A. tortilis*. Firstly, in study area I the regeneration survey and seedlings under *Acacia tortilis* canopy (microsites) were adopted. Meanwhile, the second section was considered that quantitative measures would usefully supplement and extend the understanding of the environmental factors that effect on the *Acacia* recruitment. Therefore, a detailed study of regeneration has been conducted in two different areas.

3.2.2.1 Regeneration survey and seedlings under *Acacia tortilis* canopy

The regeneration of the *Acacia* trees within study area I was assessed. As illustrated in Appendices 5 and 6 forms, the regeneration survey for area I involved dividing the transects into quadrats of 20 × 20m and assessing the extent of regeneration % cover within each quadrat. This was recorded as follows: 1 = no regeneration; 2 = below 50% regeneration, 3 = more than 50% regeneration and 4 = 100% regeneration. The regeneration of *Acacia* trees in quadrats across various depression, slope and summit positions of the transects was also assessed and recorded on the density and regeneration forms (Appendices 5 and 6).

Saplings and regeneration under Acacia tortilis canopy (microsites) in study area I

The wavy line indicates the outline of the tree canopy (Figure 3-15). The seedlings established within 3 m of the tree recorded as for example, 0 – 3 m under microsite (under tree umbrella) were recorded. Also, any seedlings within 3 m of the tree, as shown in Figure 3-15, were counted and their distances away from the tree recorded.

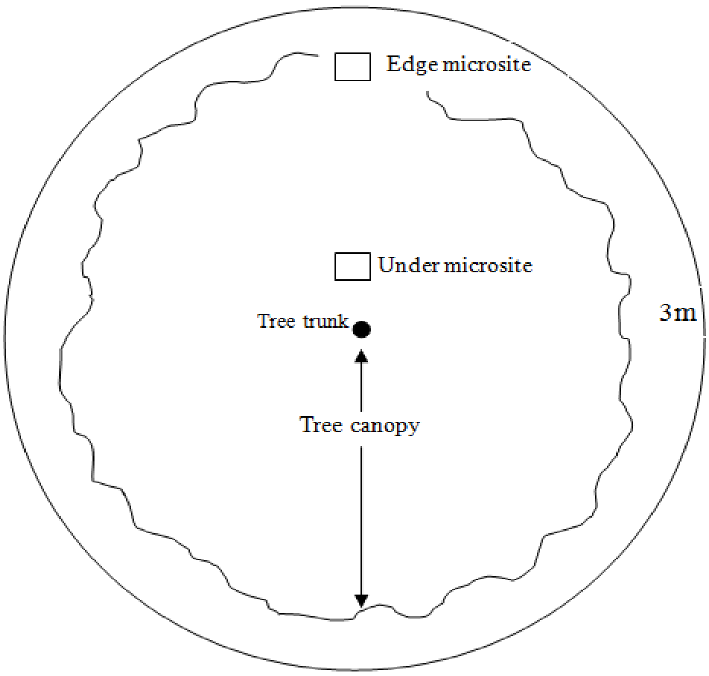


Figure 3-15: Top-Down View of Position of Saplings and Regeneration within the Microsites.

3.2.2.2 Area II and III description and data collection

Areas II and III are located in the Latitude 25° 30´; Longitude 51° 24´ and Latitude 25° 06´; Longitude 51° 08´, respectively. Study areas II and III contain the three main topographic positions of depression, slope and summit. Similarly to study area I, the depression is the most favourable environment that supports the growth of *Acacia tortilis*, and this constituted the main landform in the sampling. Therefore, more useful information on the impact of environmental variables on *Acacia tortilis* regeneration in study area II and III could be obtained. They were selected based on previously gathered remote sensing of *Acacia* distribution (phase one). The remote sensing study (Section 3.1) produced 138 global positioning system (GPS) points across Qatar. From these, the three closest GPS points, to the north road shown in Figure 3-1 were used for site II. Similarly, the three closest GPS points the south road shown in Figure 3-1 were used for Site III (Figure 3-16). Then, the sample point with the highest levels of regeneration in each of these sites was selected during a field trip for the regeneration study.

Other relevant details, such as the site/profile number, map/GPS reference, location (transect number), date of sampling, compass reading, and slope angle and length, were also recorded in the density and regeneration forms. In addition, the GPS reference start, and end, GPS elevation start and end, of each transect were recorded. The names and numbers of the various plant species in each quadrat was noted as shown in the density and regeneration forms (Appendix 6).

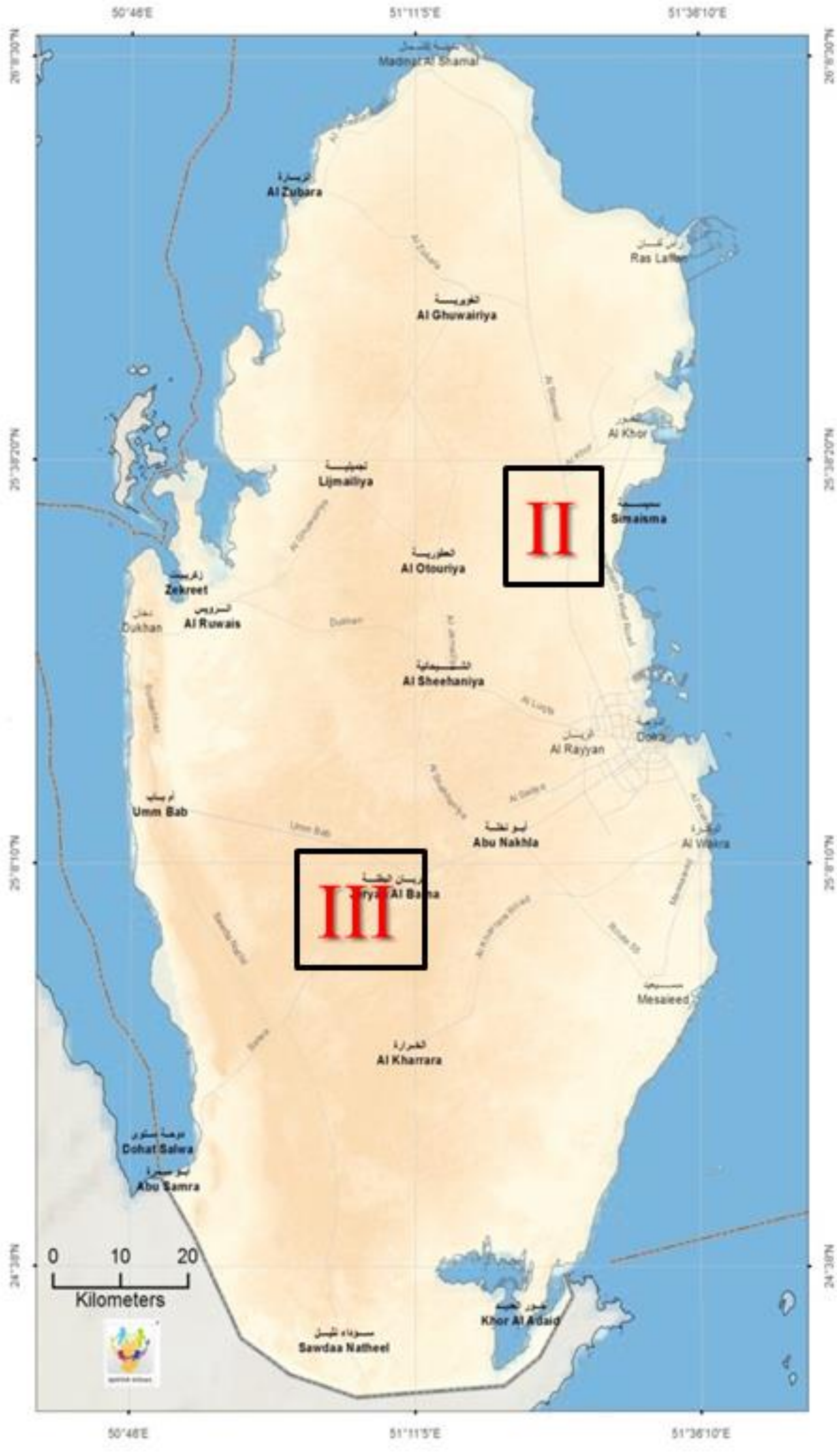


Figure 3-16: Location of the Study Areas in Qatar Area II and III were the Regeneration Sites.

A detailed regeneration study was also undertaken by allocating a plot of 100 × 100m in each of areas II and III situated in the northern and southern regions of the country. In each plot, eight sampling points (4 sampling points each for the regeneration of *Acacia tortilis* and bare soil samples) were randomly generated using a 5 m radius circle as shown in Figure 3-17. The data collection in these areas entails recording the regeneration characteristics such as the number of seedlings, and seedling branches number and heights within the four randomly selected sampling points as well as soil samples. Furthermore, bare soil samples were collected from the other four areas without regeneration sampling points for laboratory analysis. Eight soil samples (approximately 0.5 kg) were taken from each horizon (A and B = 16) for both areas II and III (32 samples in total). These were air-dried, thoroughly mixed, and passed through a 2mm sieve to get rid of gravel and boulders. A 150 g of each samples were preserved in polythene bags and transported to the laboratory at Newcastle University. Similar to study area I, soil attributes mentioned in section (3.2.1.2) were also measured for the regeneration study.

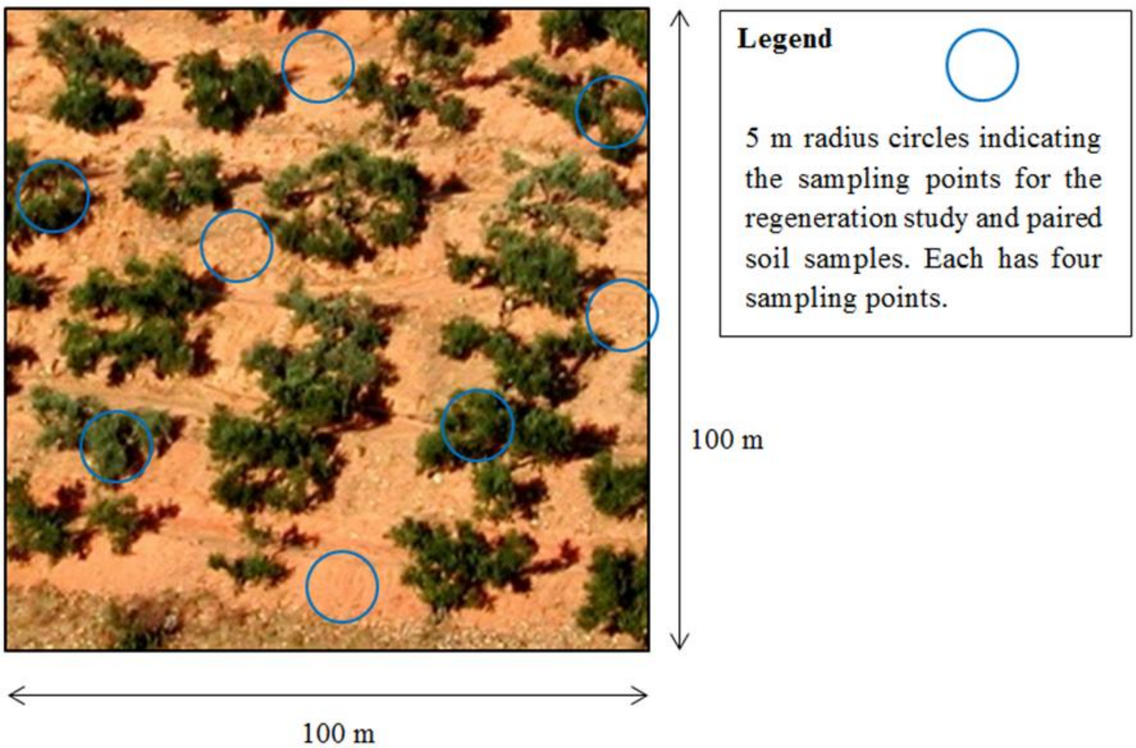


Figure 3-17: The Randomly Selected Sampling Points in the 100 × 100m Plot for the Regeneration Study in Areas II and III.

3.2.3 Statistical analyses

Analysis of variance (ANOVA) was performed to test the influence of protection status, tree density, topographic positions and sampling, and their interactions with soil chemical and physical properties as well as the morphological characteristics of trees using GLM. Data were tested for normality using Anderson Darlington Test. Data were Box-Cox or transformed using square root or log base ten if the data were not normally distributed. Mean comparisons were made using the Tukey test with $p < 0.05$. All of the analyses were conducted using Minitab (16).

Chi-square tests were used to assess the statistical significance of associations between independent categorical variables for regeneration rate and impeding layer between protection status (protected and unprotected sites); tree density (dense and sparse depressions) and topographic positions (depression/slope/summit). However, the proportion of browsing, cutting and leaf coverage were also calculated for protection status (protected and unprotected sites); tree density (dense and sparse depressions) and topographic position (depression and slope).

Further analyses were conducted using SPSS 21 for Windows (SPSS Inc., Chicago. IL, USA). Relationships between environmental variables such as protection status, topographic position and soil properties on tree morphological characteristics were evaluated using Pearson's pair-wise correlation analysis, and significant bivariate relationships were determined with significance defined as a p-value < 0.05. Correlation was followed by principal component analysis (PCA) in order to identify groups of highly interrelated environmental variables. The natural environmental factors tested were depth to water table level (DWT), available phosphorus in horizon A&B, organic carbon percent, electric conductivity in horizon A&B, soil pH in horizon A&B and volumetric water content in horizon A&B and soil depth . A Varimax rotated PCA was performed in order to reduce the natural environmental and contaminant variables to a subset of non-correlated composite variables. *Acacia tortilis* morphological characteristics of tree height, crown area and diameter, branch number, and diameter at breast height were subsequently utilized as dependent variables in a separate multiple regression analysis with the composite PCA factors as independent variables.

CHAPTER 4: DISTRIBUTION OF ACACIA TORTILIS IN QATAR USING FIELD SURVEY, REMOTE SENSING AND GIS AT A NATIONAL SCALE

Introduction

This chapter addresses the objectives of phase one of this study. It provides two related sections concerning the distribution of *Acacia tortilis* in Qatar using field survey, remote sensing and the extant GIS database at the national scale. Firstly, the tree cover and species composition of desert vegetation in Qatar is estimated using vegetation indices derived from remote sensing. Secondly, approaches are introduced through modelling to identify which environmental variables best explain the distribution of vegetation type in space, and which are significantly correlated with environmental variables. Thus, the suitability of multivariate statistical modelling techniques to determine the major vegetation and environmental variables associated with *Acacia* abundance that could potentially be used to predict its distribution, are assessed.

4.1 Estimating Tree Cover and Species Composition of Desert Vegetation in Qatar Using Vegetation Indices Derived from Remote Sensing

4.1.1 Scope

Remote sensing and GIS are known to be powerful and cost-effective tools for assessing the spatial distribution and dynamics of land cover (Tottrup and Rasmussen, 2004; Volcani *et al.*, 2005; Shao and Reynolds, 2006; Fan *et al.*, 2008; Yang *et al.*, 2012). In the current study, the spatial distribution of the natural vegetation and multi-temporal satellite imagery analysis is considered. Firstly, aerial photography was used to monitor the woody tree cover of the vegetation in the desert region of Qatar. Then, an investigation was conducted with multi-temporal satellite imagery using Landsat 5 thematic mapper (TM) and Landsat 7 enhanced thematic mapper plus (ETM+). Attributes for different vegetation types (i.e. Acacia, Mixed, No Acacia and Bare soil) were processed from image analysis into normalized difference vegetation index (NDVI) and soil adjusted vegetation index (SAVI).

4.1.2 Distribution of native vegetation in Qatar

The distribution of the natural vegetation in Qatar that was acquired from high resolution aerial photography from 2010 is shown in Figure 4-1. The distribution of plant cover for the whole of Qatar shows three distinct areas of vegetation cover: (A) northern, (B) central and (C) a belt that started from central west towards southern Qatar (Khor Al Udeid) (Figure 4-1). It is noteworthy that not only woody trees were mapped, but also some perennial herbs which are always associated with the woody trees, due to the fact that they are largely confined to the moister sites such as depressions and runnels as well as coastal vegetation. The most recognised vegetation species in the Qatari desert can be summarised as trees e.g. *Acacia tortilis*, *Acacia ehrenbergiana*, *Ziziphus nummularia* and *prosopis spp*; shrubs e.g. *Lycium shawii*, *Tamarix L*. and *Leptadenia pyrotechnica*, and perennial plant e.g. *Cybopogon spp*, *Pennisetum spp*, *Cyperus L.* and *Panicum spp*.

In Qatar, depressions or "Rawda Ar" system is the most important topographic position that often is decisive in determining the type of vegetation that grows, as well as being consided as the most favourable place for plant growth. These systems covers an area of 279 square kilometres from approximately an area of 11572 km^2 of the entire country (GIS centre, Ministry of Environment, 2010)[1]. According to the aerial photography-based mapping indicates that the natural vegetation results the natural vegetation covers an area of 323 square kilometres in which this flora is not only found in depression landforms but also in wadis & runnels, sand sheets and Sabkha's. This mapped vegetation mainly consists of trees, shrubs and perennial plants. It is apparent from this results that the extent vegetation cover is greater than area of depressions.

[1] It's worth a mention that in most recent census (not published), the country covers an area of 11,606 km^2 compared to extent quoted earlier. This is due to the coastal project extension such as the Pearl-Qatar that create over 32 kilometers of new coastline and Hamad International Airport.

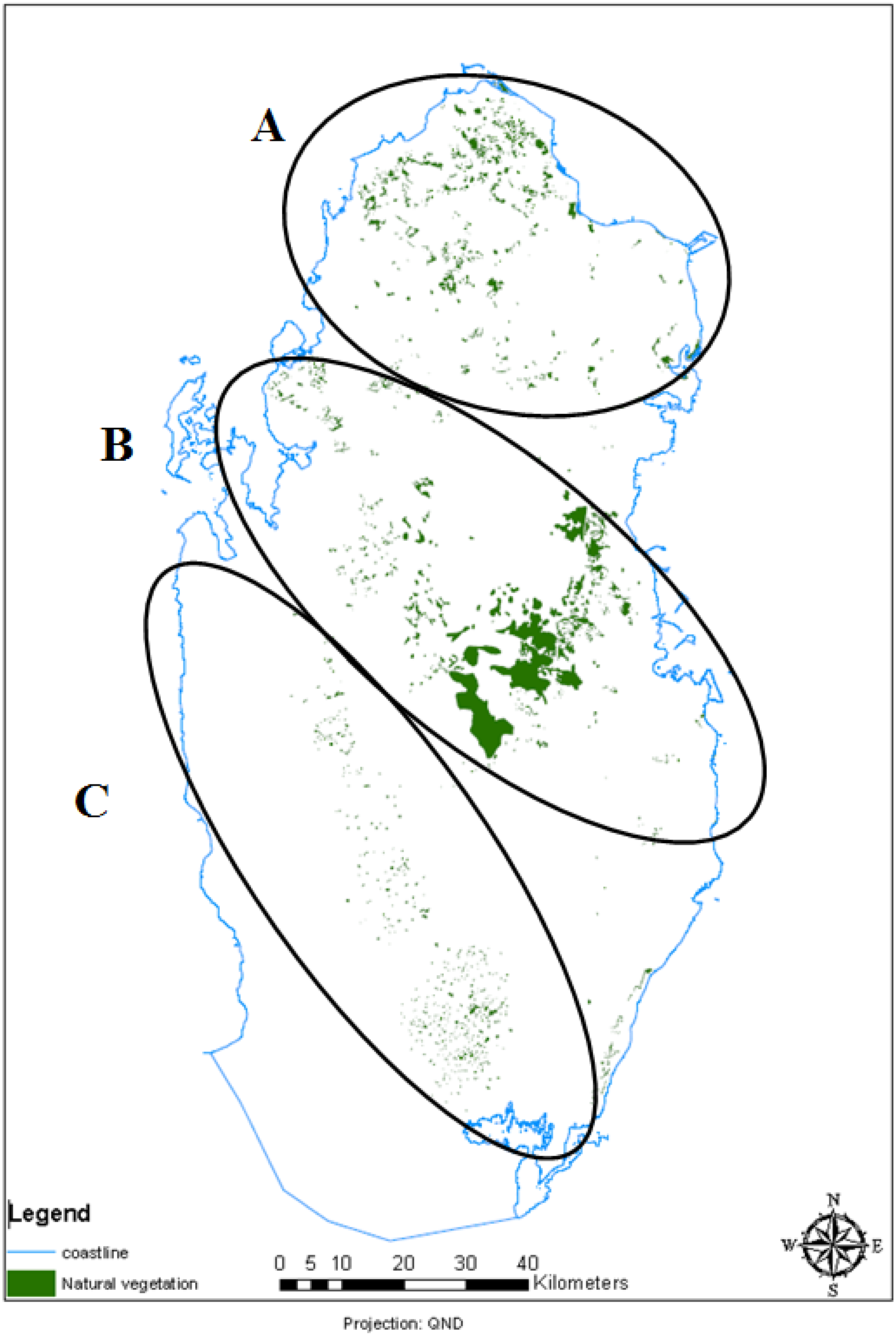


Figure 4-1: Map of Qatar Showing the Distribution of Natural Vegetation in 2010.

4.1.3 Normalized difference vegetation index (NDVI)

The NDVI approach is based on the fact that healthy vegetation has low reflectance in the visible portion of the electromagnetic spectrum due to chlorophyll and other pigment absorption and has high reflectance in the NIR because of the internal reflectance by the mesophyll spongy tissue of green leaves.

In general, the analysis of normalised difference vegetation index for all plots (Acacia, Mixed and No Acacia) showed that the mean values were relatively low in both years (Figure 4-2). However, values for 1998 were consistently higher than corresponding values for 2010. For both years (1998 and 2010) the NDVI values show a decline from April to July but appear to recover in November/December. The NDVI increase can be attributed to the phenomenon of leaf flushing after the beginning of the rainy season between September/December.

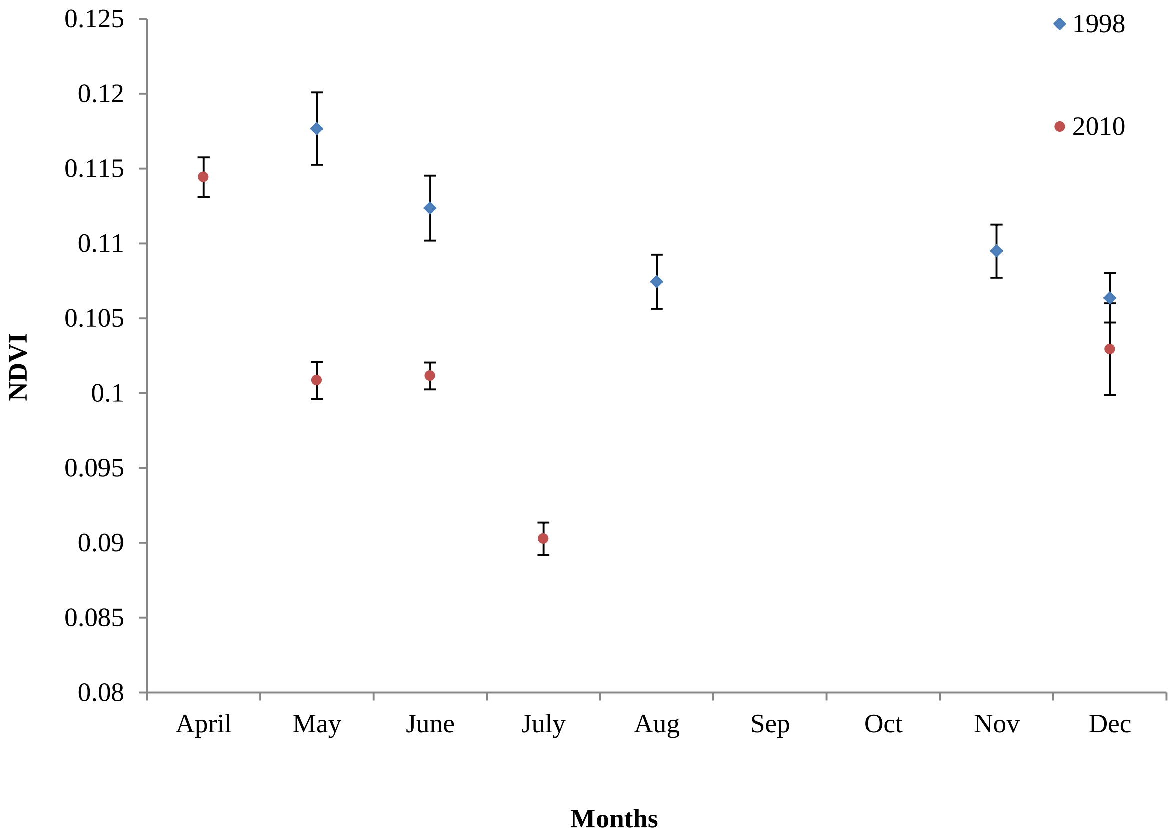


Figure 4-2: Mean of NDVI Values of All Plots (Vegetation Plots) in 1998 and 2010 (n =138). ±SE

The observed phenological changes in NDVI may be a positive sign because not all plant species or populations, however, show a shift in phenology (Visser *et al.*, 2003). Thus, it should be used the shift in the seasonal changes in the ecological conditions as a measure to assess whether the change in phenology observed is sufficient or not, to exhibit seasonal patterns between different vegetation types. Particularly, can we use differences in phenology between species to classify the vegetation type, or in other words to detect the best reproduction or growth period of the Acacia species, in order to classify study sites?

The results obtained from the analysis of NDVI data showed clear difference between plots including vegetation other than Acacia compared with Mixed and Acacia plots as well as Bare Soil in both years (Figure 4-3 and 4-4). In both years the highest NDVI values were obtained from plots not containing Acacia. This No Acacia class is characterised by large canopy cover and evergreen tree species such as *Prosopis* and *Ziziphus* species. Analysis of variance of NDVI values in 1998 indicated that plots including vegetation other than acacia (no acacia) were significantly higher than mixed, acacia and bare soil plots in both 1998 and 2010.

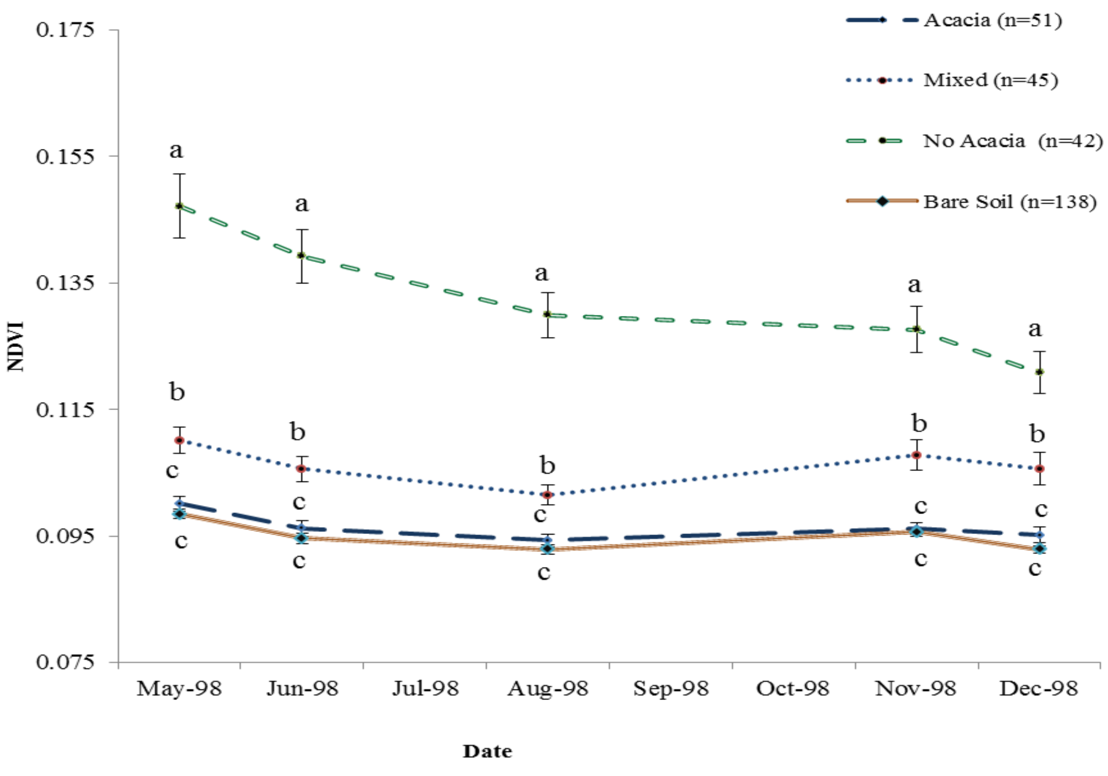


Figure 4-3: Mean of NDVI Values of Acacia, Mixed, No Acacia and Bare Soil in 1998. One-way ANOVA. Tukey’s HSD $p<0.05$. Comparison Only within Measurement Date. Different Letters Mean Statistical Significant Difference.

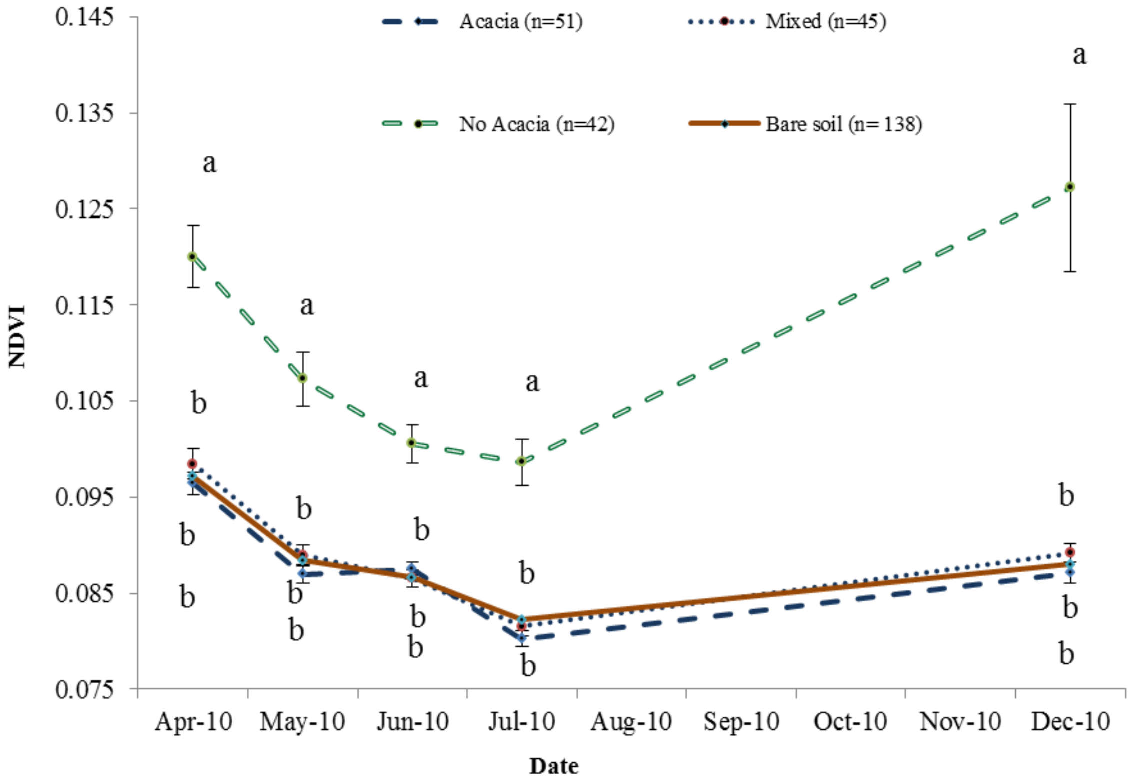


Figure 4-4: Mean of NDVI values of Acacia, Mixed, No Acacia and Bare Soil in 2010. One-way ANOVA. Tukey's HSD p<0.05. Comparison Only within Measurement Date. Different Letters Mean Statistical Significant Difference.

For both years there was no significant difference between NDVI values for Bare Soil and Acacia plots. Statistical tests also revealed that no significant difference in NDVI values in 1998 between acacia and bare soil plots (P = 0.335) as well as there was no significant different between mixed and acacia alone. In 2010, NDVI values were significantly higher in no acacia plots compare to mixed, acacia and bare soil. Also, there was no significant different between acacia, mixed and bare soil plots.

4.1.4 Soil-adjusted vegetation index (SAVI)

Soil adjusted vegetation index (SAVI) follows the same trend as normalised vegetation index except that its values were slightly smaller (Figure 4-5). In both cases, SAVI and NDVI exhibited higher values during late spring and early summer (May to July) and lower values in mid-summer which continued to the end of September. From this acquired data from satellite image analysis, we can see that the soil adjusted vegetation index (SAVI) values for the three vegetation classes acacia, mixed and no acacia, resulted in the lowest value of the data acquired from Landsat ETM+ satellite images of 2010 compared with same vegetation type plots at Landsat TM satellite images of 1998 (Figure 4-5). Similarly to NDVI, the phenological changes period observed in both years, in which SAVI values decreased slightly from April/May towards the hot season (summer) of July/August.

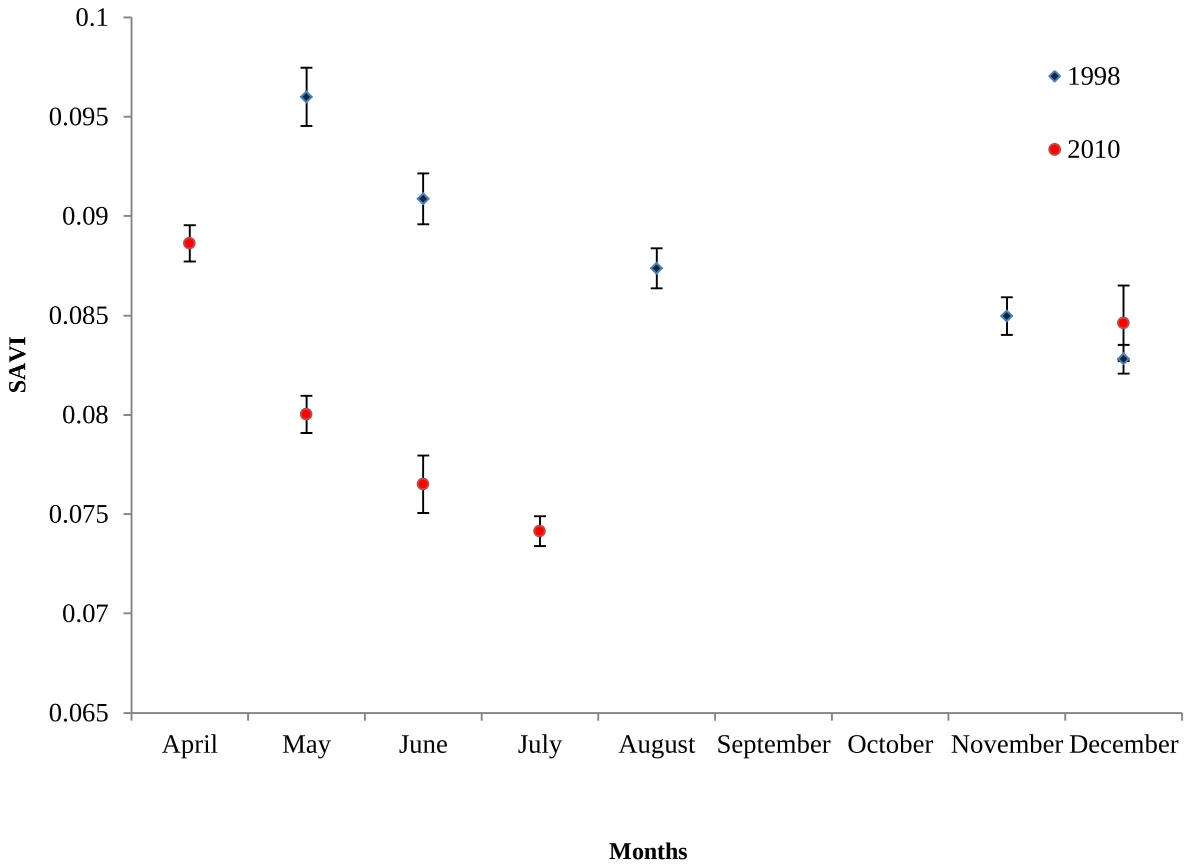


Figure 4-5: Mean of SAVI Values of all Plots (vegetation plots) in 1998 and 2010 (n =138), ±SE.

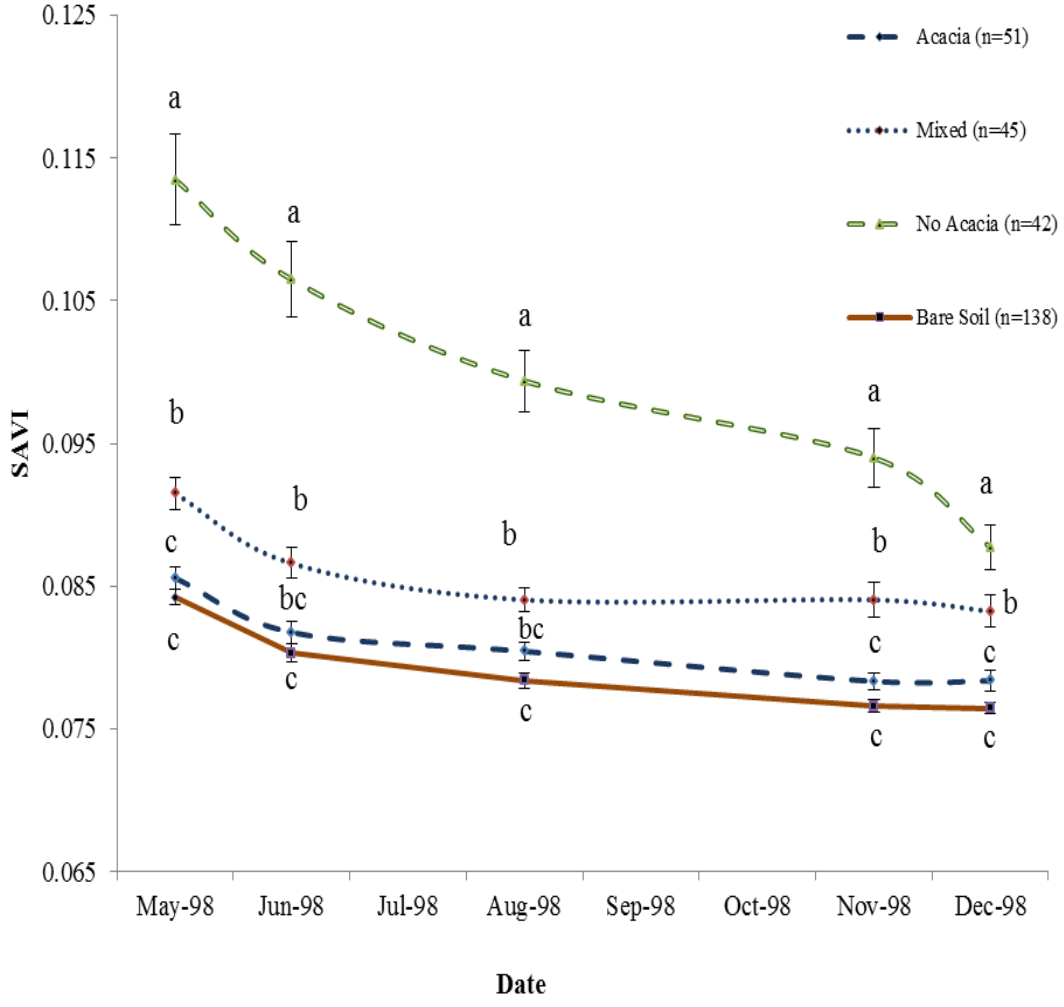


Figure 4-6: Mean of SAVI values of Acacia, Mixed, No Acacia and Bare Soil Plots in 1998. One-way ANOVA. Tukey's HSD $p<0.05$. Comparison Only within Measurement Date. Different Letters Mean Statistical Significant Difference.

Soil adjusted vegetation index values for different vegetation types also followed the same trend as NDVI (Figure 4-6 and 4-7). In both years there was a clear difference between No Acacia plots compared to the plots of Acacia and Mixed vegetation. However, there was no significant difference between Acacia and Bare Soil.

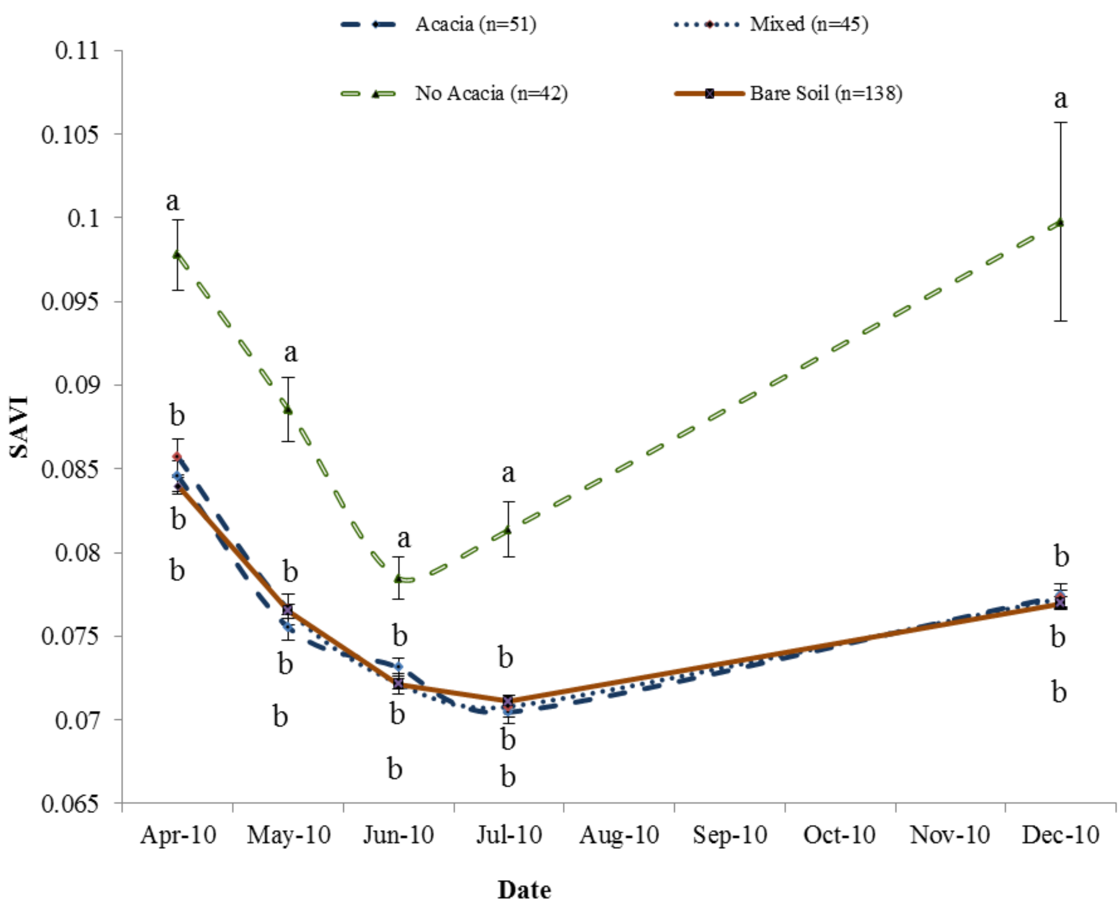


Figure 4-7: Mean of SAVI values of Acacia, Mixed, No Acacia and Bare Soil Plots in 2010. One-way ANOVA. Tukey's HSD $p<0.05$. Comparison Only within Measurement Date. Different Letters Mean Statistical Significant Difference.

4.1.5 Discussion

The general finding of this study is that Landsat data did not provide any potential discrimination between bare soil and *Acacia* vegetation types or characteristics that differentiate the two groups. Previous remote sensing studies indicate that when plant cover is less than 30-40%, the satellite sensors fail to detect vegetation, instead it is soil background that will be mostly shown (Huete *et al.*, 1984; Elvidge and Lyon, 1985; Tueller, 1987; Smith *et al.*, 1990). In this study percentage cover of acacia was very low (< % 28) and NDVI was similar to the values of Bare Soil. NDVI values of bare soil may have been affected by the presence of biological soil crusts. Richer *et al.*, (2012) reported that the presence of crusts in different parts of Qatar (depressions, intermediate and no depressions sites) were observed. Karnieli *et al.*, (2002) also mentioned that "from the remote sensing point of view soil crusts are extremely important because of their photosynthetic activity".

The higher NDVI values in 1998 than 2010 indicate that greenness (photosynthetic activity) changed from 1998 to 2010 probably due to the influence of climatic variations. Rainfall received in 1998 (148 mm) was greater than in 2010 (64 mm) which in turn increased the quantitative greenness measures either from the annual understory vegetation and/or the overall mean productivity and biomass of the existing trees. This likely explains the somewhat higher normalized difference vegetation index estimates. Similar findings were obtained by Malo and Nicholson (1990) and Aguilar *et al.* (2012). Also, O'Neill (1996) reported that NDVI works well when vegetation is green after raining season but show little relationship to vegetation cover during the dry periods.

The comparison of temporal analysis based on vegetation measures (NDVI) shows a consistent phenological pattern for the different vegetation classes, characterized by higher NDVI values during the spring and early summer period (Figure 4-2). This observation is in agreement with other satellite findings (Weiss *et al.*, 2004; Baghzouz *et al.*, 2010). In fact, the phenological cycle of natural vegetation in desert and arid environments is related to the adaptation of desert plants to the scarcity of water and drought conditions (Karnieli *et al.*, 2002). Moreover, in these regions characterised by sparse vegetation cover, plants adapt themselves to the surrounding environments in terms of morphological, physiological or behavioural features which in turn affects both pigment concentrations and leaf structures (Karnieli *et al.*, 2002). Thus, it could be said that the substantial peak in NDVI for the no-acacia vegetation class in December 2010 possibly resulted from higher greenness due to high levels of precipitation in the previous month (14.6mm), which led to an expected growth in the understory vegetation.

Differences in NDVI values in 1998 between acacia, mixed and no-acacia plots during the test period indicate the ability of NDVI to distinguish between the response of the target species across space and over time. On the other hand, in 2010 only the no-acacia class was significantly different to the other classes. This is probably due to morphological variations in *Prosopis* and *Ziziphus* species which are characterised by higher canopy cover and leaf area size. These results imply that these indices may have limited value in assessing changes in tree cover in such a hyper-arid environment. This findings is consistent with previous research (O'Neill, 1996).

Finally, despite the sparse distribution of the tree vegetation and the morphological structure of the Qatari desert plants, the analysis of the satellite imagery and spectral measurements such as NDVI have been shown to be useful tools in detecting phenological changes. Also, NDVI values helped in characterizing the unique reflectance of the No Acacia species in the No Acacia class. However, *Acacia* is the main concern in this study, and the image analysis indicates that it is not possible to use remote sensing imagery at the resolution tested here to detect the presence of *Acacia*, which cannot be distinguished from bare soil. Therefore the use of time series remote sensing imagery to detect changes in the extent and condition of *Acacia* is not possible in this hyper-arid environment. The NDVI time profiles of the Landsat TM/ETM+ time series was optimized to detect changes in rangeland areas and was able to detect gradual changes in vegetation, but these were changes within other vegetation classes. The findings of the current study are consistent with those of Stellmes *et al.* (2010) that changes in the NDVI time profiles from the Landsat TM/ETM+ time series within land-use classes, such as arable land, could not be tracked reliably.

4.2 Patterns of *Acacia tortilis* Distribution Related to Environmental Gradients in Qatar at a National Scale

4.2.1 Scope

With regard to the dynamic nature of vegetation, "species will change their distribution and abundance patterns along the gradient in response to environmental fluctuations" (Collins *et al.*, 1993). Therefore it can be assumed that some species are distributed widely across the sample region while others have localized distributions and still others have much restricted distribution. Hence, this section explores the impact of environmental gradients such as elevation, depth to water table level, disturbance, total dissolved solids (TDS), distance to coastline, soil type and topography on the different vegetation types (acacia, mixed, no acacia and bare soil) on a national scale. A geographic information system map of Qatar is shown in Figure 4-8. It attempts to illustrate some of the main land features such as settlements, roads, sand dunes, sabkha, and the distribution of natural vegetation. The eastern half of the country has the highest human impact in the form of settlements, farms or roads. This is due to two main reasons. Firstly the capital of Qatar is located in the central-eastern coast, and secondly the main gas and petroleum stations are also located in the same direction in the north-east and south-east of the country.

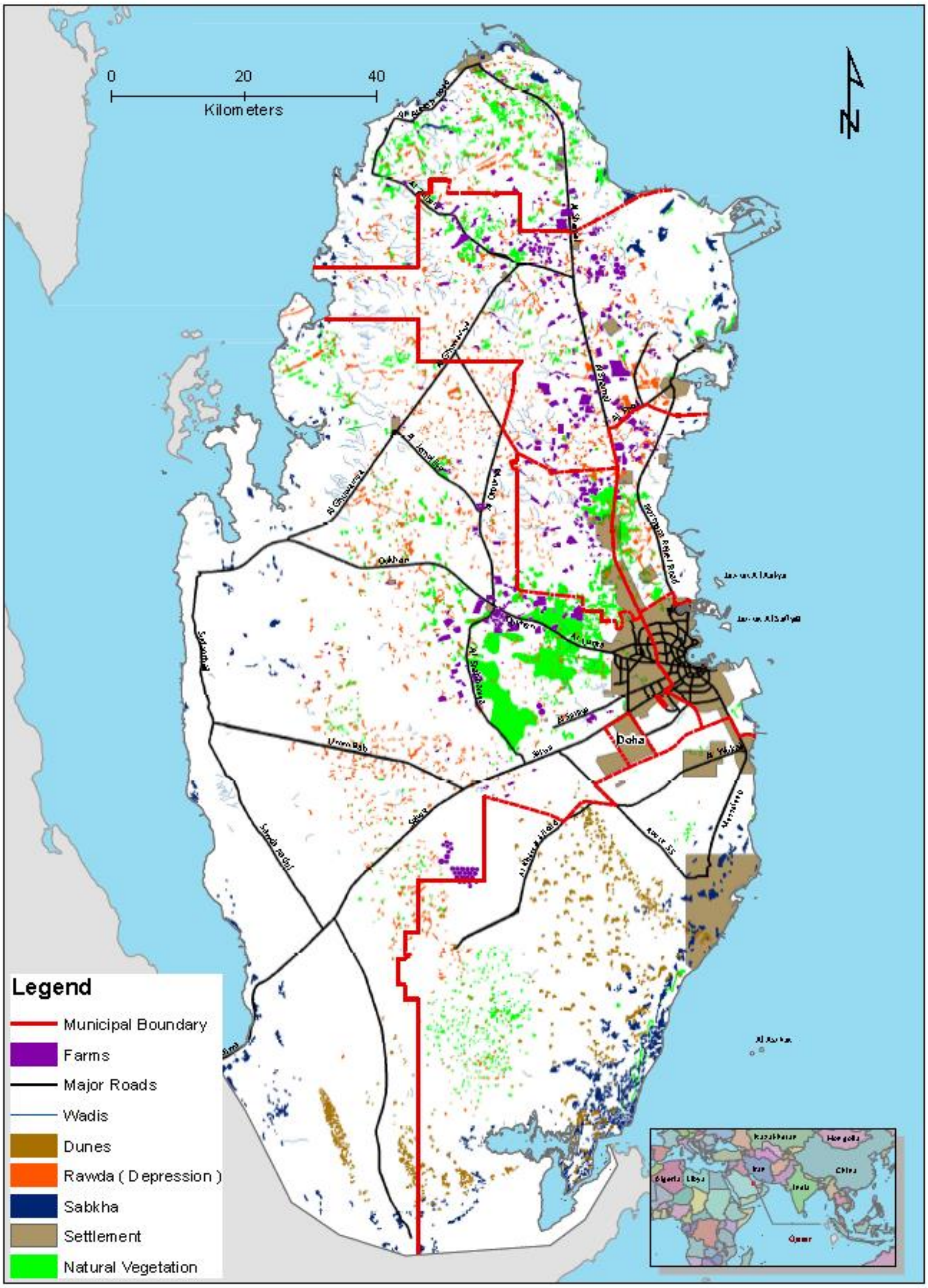


Figure 4-8: Geographic Information System Map of Qatar Showing the Major Land Cover in 2010. Vegetation Cover Acquired in 2010. Data for Farms, Rawda, Sabkha, Settlements, Municipal Boundaries and Wadis Acquired from the GIS Centre, Ministry of Environment.

Relationship between elevation and vegetation type

Descriptive statistics of elevation by vegetation type is shown in Table 4-1. On average Acacia are found around 31.90m above sea level while Mixed, No Acacia and Bare Soil are at 36.87, 14.36 and 41.67 m respectively.

Table 4-1: Descriptive Statistics of Elevation by Vegetation Type

Vegetation Type	Mean (m)	N	Std. Deviation	Median
Acacia	31.90	51	11.60	30.20
Mixed	36.87	45	12.31	36.00
No Acacia	14.36	42	9.69	10.00
Bare Soil	41.67	138	11.17	45.00
Total	34.93	276	14.65	34.00

To find out if elevation has a significant effect on vegetation type we need to conduct a formal statistical test; test of normality indicates that elevation is not normally distributed within the four groups ($p<0.05$). Because of failure of normality, Kruskal–Wallis is the appropriate formal statistical test to use to find out if elevation has any effect on vegetation type. The result indicates that elevation has a significant effect as average elevation are different across the four vegetation type (all p values <0.05), see Table 4-2.

Table 4-2: Pairwise Comparison of Elevation by Vegetation Type (probability values).

Vegetation Type	Acacia	Mixed	No Acacia	Bare soil
Acacia	1			
Mixed	0.024	1		
No Acacia	0.001	0.001	1	
Bare Soil	0.001	0.041	0.001	1

Relationship between distance to coastline and vegetation type

Descriptive statistics of distance to coastline by vegetation type is shown on Table 4-3. On average acacia are found around 23.34km from coastline while mixed, no acacia and bare soil plots are at 24.54, 11.11 and 26.33 km respectively. This may indicate that distance to coastline has a significant effect on vegetation type.

Table 4-3: Descriptive Statistics of Distance to Coastline (km) by Vegetation Type.

Vegetation Type	Mean	N	Std. Deviation	Median
Acacia	23.34	51	8.97	23.14
Mixed	24.54	45	11.68	23.11
No Acacia	11.11	42	8.52	8.23
Bare Soil	26.33	138	9.10	27.04

To find out if distance to coastline has a significant effect on vegetation type; test of normality indicates that distance to coastline is also not normally distributed across the four vegetation types ($p<0.05$). Because of failure of normality, Kruskal–Wallis is the appropriate formal statistical test to use to find out if distance to coastline has any effect on vegetation type. The result indicates that distance to coastline has a significant effect as average distance to coastline are different across the four vegetation type, however, not all pairwise comparison are significant, see Table 4-4. For example there is no significant difference between Acacia and Mixed P =0.918 (>0.05); between Acacia and Bare Soil the P =0.06. Results also show that No Acacia is the only significantly different class compared to other classes.

Table 4-4: Pairwise Comparison of Vegetation Type by Distance to Coastline; ANOVA (probability values).

	Acacia	Mixed	No Acacia	Bare soil
Acacia	1			
Mixed	0.918	1		
No Acacia	0.001	0.001	1	
Bare Soil	0.060	0.674	0.001	1

Relationship between depth to water table level and vegetation type

Figure 4-5 shows the depth of groundwater levels throughout Qatar in 2012, as estimated from isolated national well measurements. Generally, the coastal areas had shallower ground water levels compared to the middle parts of the country, whilst the deeper groundwater levels were found in the south to south-west of Qatar. A summary of descriptive statistics of the depth to water level by vegetation type is shown in Table 4-5. Acacia was found where the average depth to the water table level was 26.92m while for Mixed, No Acacia and Bare soil average depths were 27.90, 13.32 and 32.31m respectively. This may indicate that depth to water level has a significant effect on vegetation type.

Table 4-5: Descriptive Statistics of Depth to Water Table Level (m) in Sample Plots by Vegetation Type.

Vegetation Type	Mean	N	Std. Deviation	Median
Acacia	26.92	51	7.55	27.74
Mixed	27.90	45	7.53	30.03
No Acacia	13.32	42	7.66	10.00
Bare Soil	32.31	138	8.90	32.35

To find out if depth to water table level has a significant relationship with vegetation type a formal statistical test needs to be conducted. The test of normality indicates that depth to water table level is not normally distributed across the four vegetation types ($P < 0.05$). Because of the failure of normality, a non-parametric (Kruskal–Wallis) is the most appropriate formal statistical test to use to find out if depth to water table level has an effect on vegetation type. The results indicate that depth to water table level has a significant effect for the four vegetation types, where all pairwise comparisons are significant except that between Acacia and Mixed P =0.495 (>0.05), as shown in Table 4-6.

Table 4-6: Pairwise Comparison of Depth to Water Table by Vegetation Type; ANOVA (probability values).

Vegetation type	Acacia	Mixed	No Acacia	Bare soil
Acacia	1			
Mixed	0.495	1		
No Acacia	0.001	0.001	1	
Bare Soil	0.001	0.007	0.001	1

Relationship between total dissolve solids (TDS) and vegetation type

A summary of descriptive statistics of the total dissolve solids by vegetation type is shown in Table 4-7. Acacia was found where the average total dissolve solids was 4313.7 ppm, while for Mixed, No Acacia and Bare soil average TDS were 4161.8, 7335.8 and 4807.6 ppm, respectively.

Table 4-7: Descriptive Statistics of Total Dissolve Solids (ppm) in Sample Plots by Vegetation Type.

Vegetation Type	Mean	N	Std. Deviation	Median
Acacia	4313.73	51	468.62	4000
Mixed	4161.78	45	835.86	4000
No Acacia	7335.81	42	3753.21	8000
Bare Soil	4807.59	138	1729.37	5000

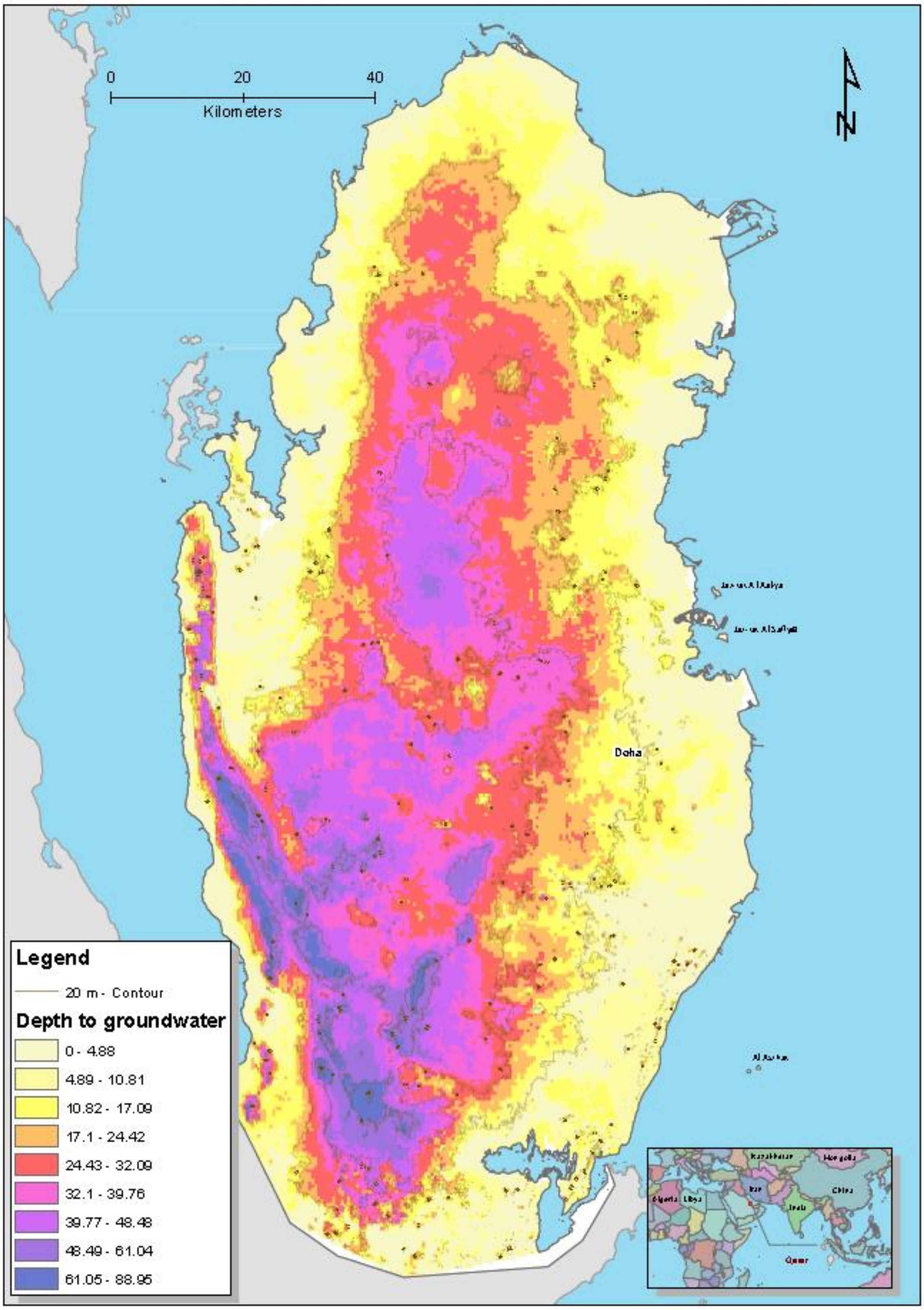


Figure 4-9: Depth of Groundwater Level at National Scale in 2012.

Groundwater table data estimated from isolated national well measurements from the Ministry of Environment (MOE) and Public Works Authority in 2012.

Associations between topographic positions and the distributions of the four vegetation types in Qatar

An additional analysis was applied using the Chi-square test to identify the association between each vegetation type with the different topographic positions. As expected, these further statistical tests revealed a significant association between the two variables (χ^2= 210.636, df = 6, P< 0.001) as shown in Figure 4-10. From the graph we can see that *Acacia* trees only occurred in depression and slope topographic positions in 29% and 35% of the sampling plots respectively. Similarly, mixed classes including *Acacia* spp were also found in depressions and slope positions in 46% and 9% respectively. Meanwhile, the no-acacia class of plots with species not including *Acacia* trees occurred in all three topographic positions of depressions, slopes and summits in 24, 21 and 5% respectively. The single most striking observation to emerge from this comparison was that 95% of the bare soil plots were detected in the summit areas.

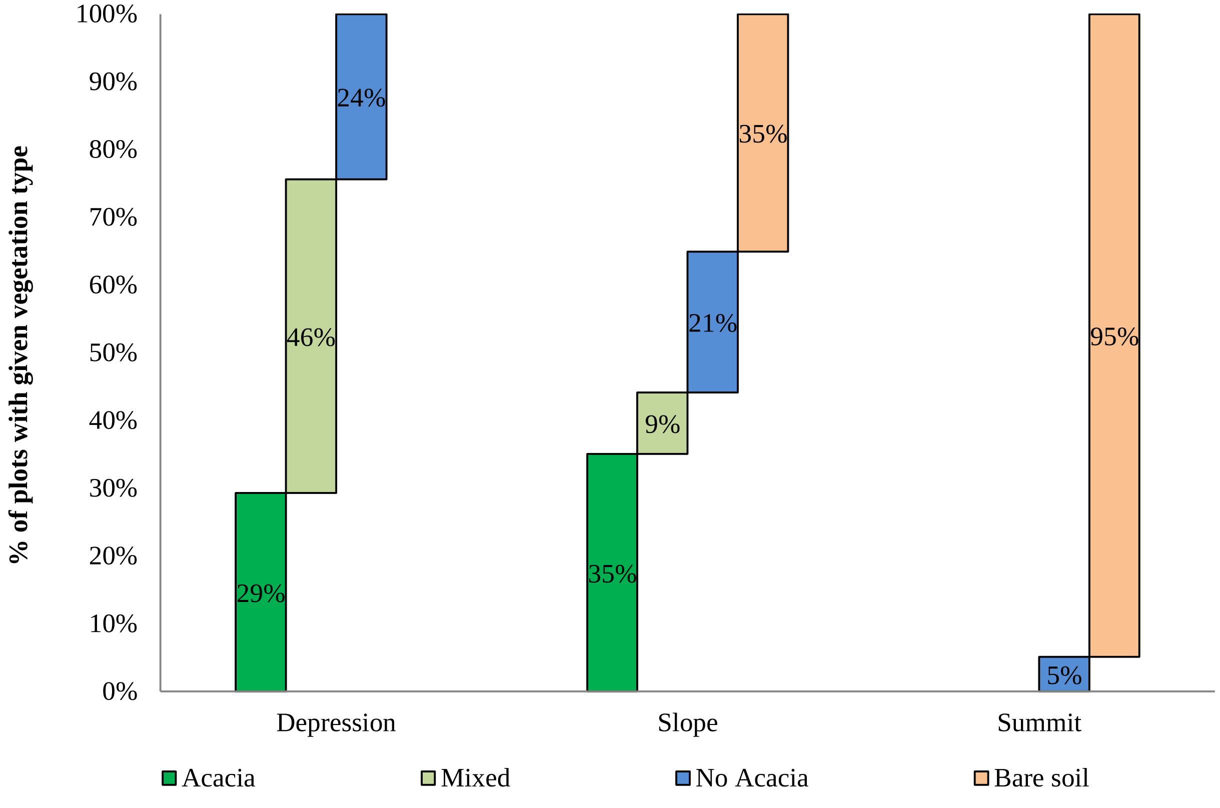


Figure 4-10: Percentage of Vegetation Type Plots in each Topographic Position.

Association between soil type and the distributions of four vegetation types in Qatar

As expected, the Chi-square test shows statistically significant relationships between vegetation type and soil type variables ($\chi2$= 168.048, df = 21, P< 0.001), as shown in Figure 4-11. From these data, we can see that Acacia can be found in four types of soil in Qatar, which are haplocalcide, lithic haplocalcids, haplocalcids and petrocalcide and calcids and torriorthents (62.7, 7.8, 17.6 and 11.8% respectively). Plots with Mixed Acacia and other trees were also found to have similar soil types. No Acacia plots were found in areas characterised by five soil types: haplocalcide, haplocalcids and petrocalcide, lithic haplocalcids and typic torripsamment, haplogypside and petrogypside and typic petrogypside. It is also apparent from this analysis that plots with other species. But No Acacia had soil characterised by gypsum. On the other hand, eight soil types were found in the plots with Bare Soil, as shown in Figure 4-11 below.

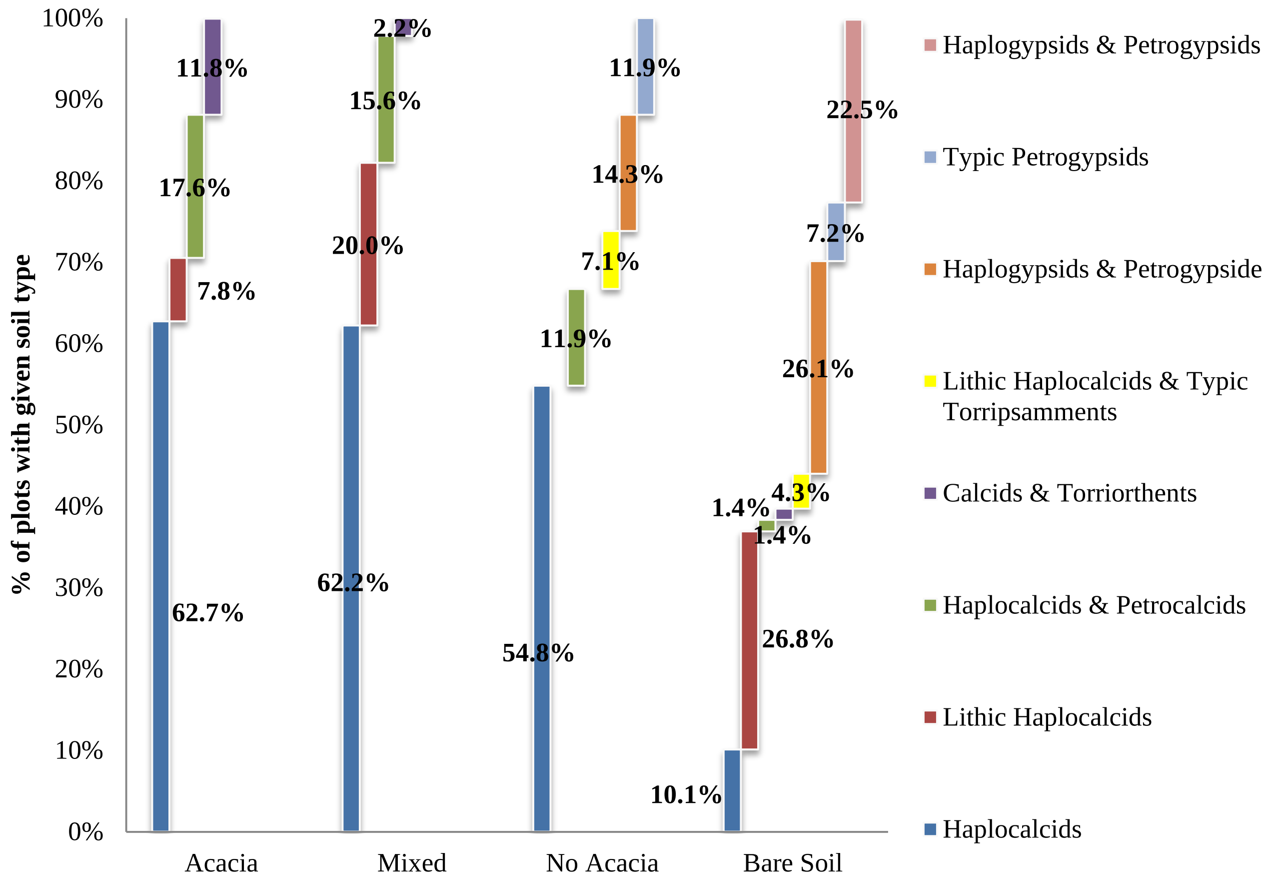


Figure 4-11: Percentage of Soil Type for Acacia, Mixed, No acacia and Bare Soil Classes in the State of Qatar.

What is interesting from this data is that haplocalcid soil was the dominant soil type for 62.7, 62.2 and 54.8 %, respectively of the Acacia, Mixed and No Acacia plots.

Associations between disturbance and the distributions of four vegetation type in Qatar

Descriptive statistics of distance to potential disturbance by vegetation type is shown on table 4-8. The disturbance index is the distance between each sampled plot and the nearest herd settlements, roads, farms or fence (human impacts). Acacia was found where average disturbance is 0.32 km while Mixed, No Acacia and Bare Soil are at 0.51, 0.83 and 0.91 km respectively. This may indicate that a significant relationship between distance to human activity and vegetation type.

Table 4-8: Descriptive Statistics of Disturbance Index (km) by Vegetation Type

Vegetation Type	Mean	N	Std. Deviation	Median
Acacia	0.32	51	0.19	0.24
Mixed	0.51	45	0.36	0.39
No Acacia	0.83	42	0.32	0.80
Bare Soil	0.91	138	0.47	0.86

The result indicates that disturbance has a significant effect across the four vegetation type. Then, Tukey's test was used to analyse the significant differences among the four vegetation types (Figure 4-12). Results indicated that the Acacia plots witnessed the highest disturbance by humans as the measured distance from these plots was found to be nearer compare to mixed, no acacia and bare soil, respectively. Meanwhile, no significant difference was found between Bare Soil and No Acacia groups. In other words, disturbance may impacting on the vegetation type or human activity is drawn to particular vegetation types – which might be suggested by the fact Acacia occurs closest to human activity.

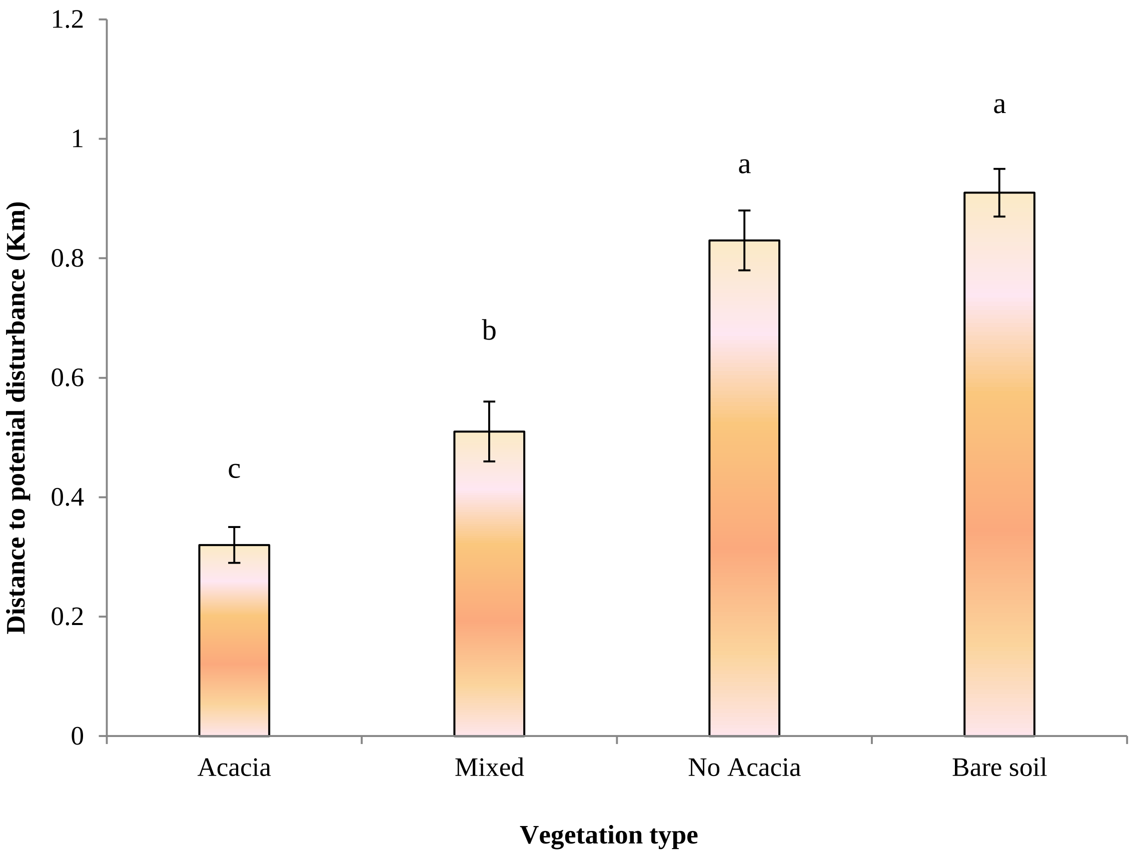


Figure 4-12: Influence of Disturbance Index (distance) on Vegetation Class as an Indicator of Human Impact. (*Tukey's HSD, $p<0.05$. Values with the same letter are not significantly different (n= 276)). Vertical bars represent standard errors*.

The previous sections have examined how elevation, distance to coastline, depth to water table level, soil type, disturbance and topography as predictors may act independently to affect vegetation type. The next section considers how the interaction of environmental variables affects vegetation type.

4.2.2 Multivariate analysis

Principal component analysis

A principal component analysis was performed on national data (276 plots) for the 7 variables under study, after checking that this data was suitable for principal component analysis by checking if the necessary assumptions were satisfied:

- the determinant of the correlation matrix should not be less than 0.00001
- the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy should be greater than 0.5, and
- the Bartlett's test of sphericity should be satisfied

The determinant of the matrix was calculated to be 0.019, the KMO measure of sampling adequacy was 0.583, and Bartlett's statistic of sphericity was significant $p=0.001$ (<0.05). These results indicate that a satisfactory principal component analysis can proceed.

The summary statistics of the PCA analysis are presented in Table 4-9, which includes components with observed variables such as factor loadings, commonalities, derived variables, variance explained, and reliability coefficients for the retained components were included. In examining the varimax rotated component matrix, 2 dimensions emerged with 3 variables substantially loaded on component 1, and 3 variables substantially loaded on component 2. The components derived from the 7 variables and their variances explained are: *PC1, which includes elevation, distance to coastline and depth to water table level* (41.15%); and *PC2, which includes soil type, topography and disturbance* (23.18%). The two components account for 64.33% of the total variance in the 7 observed variables. Cronbach reliability coefficients were calculated for component 1 (0.905) and component 2 (0.484 if TDS is deleted) as well as the overall alpha value ($\alpha = 0.737$). Summary data for the variables obtained from the PCA are presented in Table 4-9. Of particular importance is the fact that the derived variables are for the most part measuring different dimensions and were submitted for further analysis using a regression method.

This method was chosen because it is considered to be robust and uses knowledge of the existing variables. SPSS offers three methods for computing factor scales, one of which is regression. The other two are the Bartlett and Anderson-Rubin methods.

Table 4-9: Components with Observed Variables, Factor Loadings, Commonalities, Derived Variables, Variance Explained, and Reliability Coefficients

Observed variables statements	**Factor loading**	**Communality**	**Derived variable**	**Variance (%)**	**Reliability coefficient**
		Component 1			
Elevation	0.942	0.933			
Distance to coastline	0.845	0.719	**PC1**	**41.15**	**0.905**
Distance underground water	0.879	0.838			
		Component 2			
Soil type	0.775	0.608			
Disturbance	0.614	0.393	**PC2**	**23.18**	**0.484**
TDS	0.218	0.262			
Topography	0.856	0.750			

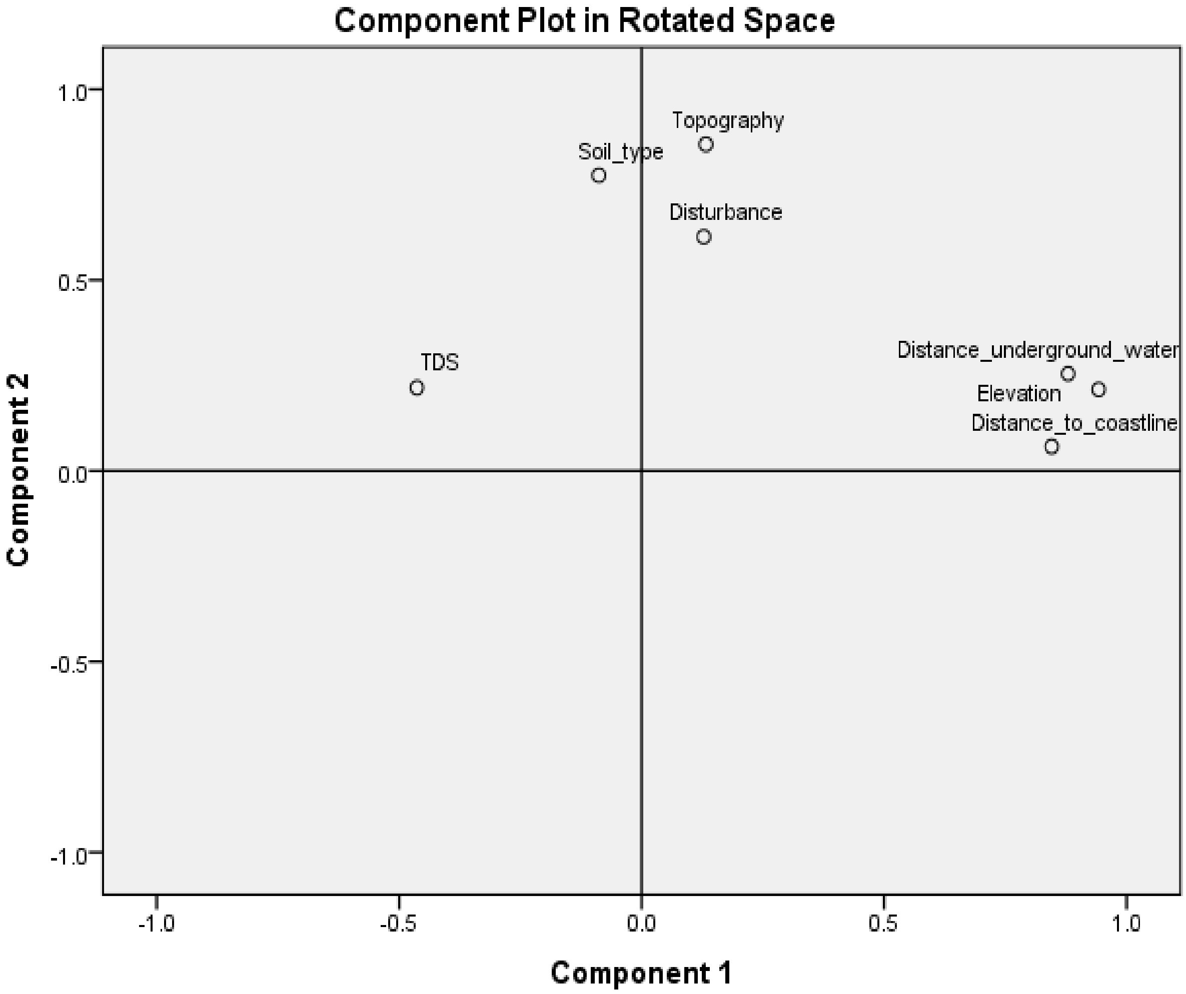


Figure 4-13: 2D Plot of the Two Components

The 2D plot of the two components is shown in Figure 4-13. It is clear from the plot that, on the one hand, topography, soil type, and disturbance form one group of variables and, on the other hand, distance to underground water, elevation and distance to the coastline form another group. TDS lies on its own and, although it was part of PC2, the distance between the indicators as shown in the component plot in rotated space clearly suggests that it is negatively correlated with distance to ground water, elevation and coastline distance in the final model.

Further analysis was performed on the derived component as their component scores are useful and carry a lot of condensed information from the observed variables. These component scores are used to compare vegetation types to determine if the scores differ according to the four vegetation types of Acacia, Mixed, No Acacia and Bare Soil.

Before carrying out any formal statistical test it is necessary to determine if the two component scores satisfy assumptions; namely that the scores are normally distributed between vegetation types and that the variances across the four vegetation types are equal across component scores. The results of the normality and homogeneity of variance tests are presented in Table 4-10. The results indicate that the scores of the two components are not normally distributed across the four vegetation types (Figure 4-12), with all p-values being less than 0.05. The variances are the same for the four vegetation types for component 1, *P* =0.0104 (>0.05); whereas for the second component the variances are different, p=0.001 (<0.05). As the component scores do not satisfy both the normality and homogeneity of variance tests, the non-parametric ANOVA is used to determine if the components have any effect across the four types of vegetation.

Table 4-10: Tests of Normality and Homogeneity of Variances for the Two Components.

Derived variables (Components)	**Tests of Normality**				**Test of Homogeneity of Variances**			
	Vegetation type	**Shapiro-Wilk**			**Levene Statistic**	**df1**	**df2**	**Sig. (p value)**
		Statistic	**df**	**Sig. (p value)**				
Elevation, coastline and groundwater level (PC1)	Acacia	0.933	51	0.007	2.075	3	272	0.104
	Mixed	0.891	45	0.001				
	No Acacia	0.881	42	0.001				
	Bare Soil	0.956	138	0.001				
Soil type, Disturbance, TDS and Topography (PC2)	Acacia	0.919	51	0.002	23.066	3	272	0.001
	Mixed	0.911	45	0.002				
	No Acacia	0.945	42	0.045				
	Bare Soil	0.083	138	0.002				

The results of the non-parametric ANOVA test are presented in table 4-11. Component scores differ significantly between vegetation types: for component 1, Chi-square=74.639, p=0.001 (<0.05); and for component 2, Chi-square=170.674, p =0.001 (<0.05).

Table 4-11: ANOVA Test of Factor Scores by Vegetation Type.

Derived variables (Components)	**Vegetation type**	**N**	**Mean Rank**	**Chi-square**	**Sig. (p value)**
PC1	Acacia	51	137.80	74.639	0.001
	Mixed	45	163.20		
	No Acacia	42	42.74		
	Bare soil	138	159.85		
PC2	Acacia	51	69.33	170.674	0.001
	Mixed	45	50.62		
	No Acacia	42	121.98		
	Bare soil	138	197.75		

4.2.3 Multinomial logistic regression using the extracted principal components

The next question is how the response variable of vegetation type can be predicted using the 2 principal components extracted in the previous section, which are PC1, (including elevation, coastline and water level) and PC2, (consisting of soil type, disturbance and topography).

The result of the multinomial logistic regression using the 2 principal components is shown on Table 4-12. Before looking at the model parameters, the model fitting information should be considered.

The -2loglikelihood of the final model is 263.5 compared to that of the intercept only model. This indicates that the final model is significantly better than the intercept only model, with a value of Chi-square of 421.4 and p=0.001 (<0.05). Additionally, the value of pseudo R-square (McFeddan) is 0.615. This indicates that the principal components account for 61.5% of the variability of vegetation types.

Table 4-12: Multinomial Logistic Regression Parameters Estimates of Principal Components by Vegetation Type

Vegetation Type	Principal Components	B	Std. Error	Wald	df	Sig.
Acacia	Intercept	-1.74	0.49	12.69	1.00	0.001
	PC1 (Elevation, coastline and water level)	-3.77	1.06	12.72	1.00	0.001
	PC2 (soil type, disturbance and topography)	-8.10	1.52	28.52	1.00	0.001
Mixed	Intercept	-3.85	0.84	21.14	1.00	0.001
	PC1 (Elevation, coastline and water level)	-3.20	1.08	8.74	1.00	0.003
	PC2 (soil type, disturbance and topography)	-9.96	1.63	37.20	1.00	0.001
No Acacia	Intercept	-2.44	0.51	22.45	1.00	0.001
	PC1 (Elevation, coastline and water level)	-5.86	1.09	29.01	1.00	0.001
	PC2 (soil type, disturbance and topography)	-6.90	1.47	21.96	1.00	0.001

Note: Bare soil is the reference category.

The parameter estimates table summarizes the effect of each principal component. The multinomial logistic regression model indicates that PC1 [Wald=12.72, p=0.001 (<0.1)] and PC2 [Wald=28.52, p=0.001 (<0.05)] are significant predictors of vegetation type.

Using the results from the table, the multinomial logistic regression model using PC1 and PC2 can be written as:

$$\ln\left(\frac{p(vegetation\ type = acacia)}{p(vegetation\ type = bare\ soil)}\right) = -1.74 - 3.77 \times PC1 - 8.10 \times PC2$$

This compares Acacia to Bare Soil. With everything else being constant, on the one hand a one-unit increase in PC1 is associated with a 3.77 decrease in the relative log odds of the vegetation being Acacia compared to it being bare soil. On the other hand, and everything else being constant, a one-unit increase in PC2 is associated with an 8.10 decrease in the relative log odds of the vegetation being mixed compare to it being bare soil.

Similarly the model comparing mixed to bare soil can be written as:

$$\ln\left(\frac{p(vegetation\ type = mixed)}{p(vegetation\ type = bare\ soil)}\right) = -3.85 - 3.20 \times PC1 - 9.96 \times PC2$$

The interpretation of this model is the same as the one above.

The important finding from this analysis is that the extracted principal components differ significantly between vegetation types. A comparison of the observed vegetation types compared with the predicted types using the model is shown in Table 4-13.

Table 4-13: Comparison between Observed and Predicted Vegetation Types Using Principal Components

Vegetation Type	**Count / percent**	**Predicted Response Category**				Total
		Acacia	**Mixed**	**No Acacia**	**Bare soil**	
Acacia	Count	24	20	6	1	51
	%	**47.1%**	39.2%	11.8%	2.0%	100.0%
Mixed	Count	13	28	4	0	45
	%	28.9%	**62.2%**	8.9%	0.0%	100.0%
No Acacia	Count	3	7	27	5	42
	%	7.1%	16.7%	**64.3%**	11.9%	100.0%
Bare soil	Count	0	1	3	134	138
	%	0.0%	.7%	2.2%	**97.1%**	100.0%

For the observed vegetation type of 51 Acacia plots, the model with the principal components correctly predicted 24 (47.1%) Acacia. For mixed, No Acacia and Bare Soil plots the model correctly predicts 62.2%, 64.3% and 97.1% respectively. The model is doing a reasonable job in predicting vegetation type. However, the % of Acacia could be better.

4.2.4 Multinomial logistic regression using the seven predictors

The next logical question is how well the response variable vegetation type, can be predicted using the 7 environmental variables of elevation, distances to coastline and underground water, soil type, disturbance, TDS and topography. Since the response variable is categorical multinomial logistic regression is one of two possible models that can be used to answer this, with the other being ordinal regression. Multinomial logistic regression assumes that there is no meaningful ordering of the categories within the response variable, while ordinal regression assumes that there is a meaningful ordering of the categories. It is plausible to assume that the ordering of the categories within the response variable is meaningful, since as it goes from 1=Acacia, 2=Mixed, 3=No Acacia and 4=Bare Soil. There seems to be an inherent order in the categories insofar as the presence of acacia is concerned. To assess the response variable, two models are run and the one that fits the data best is then selected.

The results of the first model using multinomial logistic regression are shown in table 4-14. Before looking at the model parameters, the model fitting information is considered.

The -2loglikelihood, which is a statistical measure similar to the total sum of squares in a regression of the final model is 143.928 compared to that of the intercept only model; this indicates that the final model is significantly better than the intercept only model with a value of Chi-square of 541.001 and p=0.001 (<0.005). Additionally, the pseudo R-square (McFeddan) is 0.79. This indicates that the predictors account for 79% of the variability in vegetation types.

Table 4-14: Multinomial Logistic Regression Parameters Estimates of Predictors by Vegetation Type

Vegetation type	Predictors	B	Std. Error	Wald	df	Sig.
Acacia	Intercept	-17.12	2826.11	0.00	1	0.995
	Elevation	0.07	0.28	0.06	1	0.806
	Distance to coastline	-0.64	0.36	3.11	1	**0.078**
	Depth to water level	-0.24	0.31	0.63	1	0.429
	Disturbance	-9.86	3.76	6.88	1	**0.009**
	TDS	0.00	0.00	1.59	1	0.207
	[Soil type=Haplocalcids]	20.21	2669.94	0.00	1	0.994
	[Soil type=Lithic Haplocalcids]	-0.46	2788.19	0.00	1	1.000
	[Soil type=Haplocalcids & Petrocalcids]	36.67	2670.62	0.00	1	0.989
	[Soil type=Calcids & Torriorthents]	15.88	2669.94	0.00	1	0.995
	[Soil type=Typic Torripsamments]	-10.22	5505.12	0.00	1	0.999
	[Soil type=Haplogypsids & Petrogypside]	-5.07	3098.92	0.00	1	0.999
	[Soil type=Typic Petrogypsids]	3.09	5646.86	0.00	1	1.000
	[Soil type=Haplogypsids & Petrogypsids]	0^c			0	
	[Topography=depression]	69.86	1734.61	0.00	1	0.968
	[Topography=slope]	22.73	926.42	0.00	1	0.980
	[Topography=summit]	0^c			0	
Mixed	Intercept	-20.23	2738.91	0.00	1	0.994
	Elevation	0.31	0.29	1.12	1	0.289
	Distance to coastline	-0.80	0.37	4.79	1	**0.029**
	Depth to water level	-0.34	0.31	1.19	1	0.276
	Disturbance	-7.08	3.77	3.53	1	**0.060**
	TDS	0.00	0.00	2.96	1	0.086
	[Soil type=Haplocalcids]	18.52	2582.10	0.00	1	0.994
	[Soil type=Lithic Haplocalcids]	-3.94	2704.19	0.00	1	0.999
	[Soil type=Haplocalcids & Petrocalcids]	32.42	2582.80	0.00	1	0.990
	[Soil type=Calcids & Torriorthents]	13.23	2582.10	0.00	1	0.996
	[Soil type=Typic Torripsamments]	-15.98	7163.25	0.00	1	0.998
	[Soil type=Haplogypsids & Petrogypside]	-6.41	3041.80	0.00	1	0.998
	[Soil type=Typic Petrogypsids]	0.83	5287.12	0.00	1	1.000
	[Soil type=Haplogypsids & Petrogypsids]	0^c			0	
	[Topography=depression]	72.44	1727.70	0.00	1	0.967
	[Topography=slope]	23.38	913.41	0.00	1	0.980
	[Topography=summit]	0^c			0	
No Acacia	Intercept	1.54	2806.20	0.00	1	1.000
	Elevation	-0.48	0.45	1.18	1	0.277
	Distance to coastline	-0.36	0.23	2.58	1	0.108
	Depth to water level	-0.12	0.43	0.08	1	0.782
	Disturbance	-2.03	3.13	0.42	1	0.516
	TDS	0.00	0.00	2.10	1	0.148
	[Soil type=Haplocalcids]	15.99	2806.19	0.00	1	0.995
	[Soil type=Lithic Haplocalcids]	-18.26	3502.56	0.00	1	0.996
	[Soil type=Haplocalcids & Petrocalcids]	32.06	2806.83	0.00	1	0.991
	[Soil type=Calcids & Torriorthents]	-5.44	0.00		1	
	[Soil type=Typic Torripsamments]	13.85	2806.19	0.00	1	0.996
	[Soil type=Haplogypsids & Petrogypside]	6.86	2806.19	0.00	1	0.998
	[Soil type=Typic Petrogypsids]	15.99	2810.07	0.00	1	0.995
	[Soil type=Haplogypsids & Petrogypsids]	0^c			0	
	[Topography=depression]	56.94	1466.48	0.00	1	0.969
	[Topography=slope]	6.95	3.39	4.21	1	0.040
	[Topography=summit]	0^c			0	

Note: Bare soil is the reference category. C: This parameter is set to zero because it is redundant.

Notice that the output in Table 4-14 is divided into three rows, one for each vegetation type with bare soil used as the reference category. Parameters with significant negative coefficients decrease the likelihood of that response category with respect to the reference category. Parameters with significant positive coefficients increase the likelihood of that response category.

The parameter estimates table summarizes the effect of each predictor. The multinomial logistic regression model indicates that only disturbance [Wald=3.79, p=0.001 (<0.05)] is a significant predictor of the Acacia vegetation type. All of the remaining predictors are not significant.

This compares Acacia to Bare Soil, where if everything else is held constant a one-unit increase in the variable of disturbance is associated with a 9.86 lower chance of the vegetation type being Acacia compared to it being Bare Soil. In other words, this indicates is that distance to potential sources of disturbance is a useful predictor for Acacia and Mixed vegetation types, but not for predicting ‘No Acacia’ vegetation. Disturbance such as farms, animal herds, settlements and roads has more influence on areas with Acacia compared to areas with Bare Soil and no vegetation. This is also logical, since the bare soil plots studied are far away from any kind of disturbance compared to Acacia (Figure 4-12).

Using the significant predictors only, the multinomial logistic regression model for comparing Mixed Acacia plots to bare soil can be written as:

$$\ln\left(\frac{p(vegetation\ type = mixed)}{p(vegetation\ type = bare\ soil)}\right) = -20.23 - 0.80 \times Distance\ to\ coastline - 7.08 \times Disturbance$$

Other studies have indicated that soil type and topography are significant predictors of vegetation type (Brown, 1994; Franklin, 1995), but the data from this present research using the multinomial logistic regression model has not confirmed that finding. These could be several reasons for this, such as the classification itself of vegetation types as Acacia, Mixed, No Acacia and Bare Soil. Different classifications are likely to give different results. It was noted from the univariate approach that most of the predictors differ significantly between vegetation types, however, from the multivariate approach this is not the case as the predictors influence each other in the model.

4.2.5 Ordinal regression

The results for the second model of ordinal logistic regression are shown in Table 4-15. Before looking at the model parameters, the model fitting information is considered first.

The -2loglikelihood of the final model is 379.64 compared to that of the intercept only model; this indicates that the final model is significantly better than the intercept only model with a Chi-square of 305.29 and p=0.001 (<0.005). Additionally, the pseudo R-square (McFeddan) is 0.45. This indicates that the predictors account for 45% of the variability of vegetation types.

Table 4-15: Ordinal Logistic Regression Parameters Estimates of Predictors by Vegetation Type

Source	Variables	Estimate	Std. Error	Wald	df	Sig.
Threshold	[vegetation type = acacia]	-23.90	0.89	727.54	1	0.001
	[vegetation type = mixed]	-22.82	0.88	675.85	1	0.001
	[vegetation type = no acacia]	-21.67	0.86	629.49	1	0.001
Location	Elevation	0.07	0.03	6.49	1	0.011
	Distance to coastline	-0.04	0.02	2.82	1	0.093
	Depth to water level	-0.07	0.03	4.83	1	0.028
	Disturbance	1.24	0.27	20.62	1	0.001
	TDS	0.00	0.00	0.46	1	0.498
	[Soil type=Haplocalcids]	-20.23	0.59	1159.44	1	0.001
	[Soil type=Lithic Haplocalcids]	-19.71	0.64	952.98	1	0.001
	[Soil type=Haplocalcids & Petrocalcids]	-20.51	0.67	950.98	1	0.001
	[Soil type=Calcids & Torriorthents]	-20.82	0.69	913.86	1	0.001
	[Soil type=Typic Torripsamments]	-19.12	0.86	495.78	1	0.001
	[Soil type=Haplogypsids & Petrogypside]	-19.13	0.72	706.91	1	0.001
	[Soil type=Typic Petrogypsids]	-19.74	0.00		1	
	[Soil type=Haplogypsids & Petrogypsids]	0^a			0	
	[Topography=depression]	-3.216	.516	38.781	1	0.001
	[Topography=slope]	-2.550	.477	28.562	1	0.001
	[Topography=summit]	0^a			0	

The parameter estimates table summarizes the effect of each predictor. The ordinal logistic regression model indicates that all of the predictors except TDS and distance to coastline are significant predictors of vegetation type (P < 0.05). They all have large values of the Wald statistic and low p values (sig.).

The basic form of the ordinal linear model is shown in the following equation.

$$link(\gamma_{ij}) = \theta_j - [\beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_p x_{iJ}]$$

where *link( )*is the link function, γ_{ij} is the cumulative probability of the j^{th} category for the i^{th} case, θ_j is the threshold for the j^{th} category, p is the number of regression coefficients, $x_{i1} \ldots x_{ip}$ are the values of the predictors for the i^{th} case, and $\beta_1 \ldots \beta_p$ are regression coefficients

Using the values from the table and the significant predictors only, the ordinal logistic regression model for Acacia can be written as:

$$link\ y = -23.90 - [0.07 \times Elevation - 0.04 \times Depth + 1.24 \times Disturbance - \beta \times soil\ type - \beta \times topography]$$

While direct interpretation of the coefficients in this model is difficult due to the nature of the link function, the signs of the coefficients can give important insights into the effects of each predictor in the model. The signs essentially indicate the direction of the effect. Positive coefficients (such as those for *elevation* and *disturbance*) indicate positive relationships between the predictors and vegetation type. In this example, as *elevation* or *disturbance* (distance form likely sources of disturbance) increases, so does the probability of being in one of the higher (Acacia and Mixed) categories of vegetation. Negative coefficients (such as those for d*istance to coastline* or *depth to water level*) indicate inverse relationships. For example, a unit change in *distance to coastline* or *depth to water level* is likely to increase the chances of lower categories of vegetation; where vegetation type has the categories of 1=Acacia, 2=Mixed, 3=No Acacia and 4=Bare Soil. For *soil type* and *topography*, note that the coefficients are all negative indicating that lower categories (No Acacia) of vegetation types are more probable, compared to the reference category. For example, lower categories of vegetation type (i.e. Acacia) are more probable when soil type is *haplocalcids* ($\beta = -20.23$) compared to the reference category h*aplogypsids and petrogypside* (see also Figure 4-10). In other words, the chances are higher of having plots with Acacia species when the soil type in the area includes *haplocalcids* rather than gypsum soils. Similarly lower categories of vegetation type are more probable when topography is *depression* ($\beta = -3.22$) compared to the reference category *summit* (see also Figure 4-10). Good agreement is found between the ordinal logistic regression prediction and measured data, where each of these environmental gradients significantly affect vegetation type.

Evaluation of models

Three models were developed in order to predict vegetation types from seven predictors. In order to decide which of the models is most appropriate, the three models need to be evaluated in terms of R-squared values, number of significant predictors and predictive power. The result of this evaluation is shown in Table 4-16.

Table 4-16: Models Evaluation

Model	Prediction							Significant Predictors	R-Squared
	Vegetation type	Count/ row %	Predicted Response Category Multinomial Regression Model				Total		
			Acacia	Mixed	No Acacia	Bare soil			
Multinomial Regression Using All Variables	Acacia	Count	40	9	1	1	51	Disturbance index	**79%**
		% within vegetation type	**78.4%**	17.6%	2.0%	2.0%	100.0%		
	Mixed	Count	12	30	3	0	45		
		% within vegetation type	26.7%	**66.7%**	6.7%	0.0%	100.0%		
	No Acacia	Count	0	1	40	1	42		
		% within vegetation type	0.0%	2.4%	**95.2%**	2.4%	100.0%		
	Bare soil	Count	0	0	1	137	138		
		% within vegetation type	0.0%	0.0%	0.7%	**99.3%**	100.0%		
	Vegetation type	Count/ row %	Predicted Response Category Multinomial Regression Model				Total		
			Acacia	Mixed	No Acacia	Bare soil			
Multinomial Regression Using PCs	Acacia	Count	24	20	6	1	51	PC1 (Elevation, Distance to coastline and distance to groundwater level) and PC2 (Soil type, Disturbance index and Topography	**61.5%**
		% within vegetation type	**47.1%**	39.2%	11.8%	2.0%	100.0%		
	Mixed	Count	13	28	4	0	45		
		% within vegetation type	28.9%	**62.2%**	8.9%	0.0%	100.0%		
	No Acacia	Count	3	7	27	5	42		
		% within vegetation type	7.1%	16.7%	**64.3%**	11.9%	100.0%		
	Bare soil	Count	0	1	3	134	138		
		% within vegetation type	0.0%	0.7%	2.2%	**97.1%**	100.0%		
	Vegetation type	Count/ row %	Predicted Response Category Ordinal Regression Model				Total		
			Acacia	Mixed	No Acacia	Bare soil			
Ordinal Regression	Acacia	Count	39	7	5	0	51	Elevation, Distance to coastline, Distance to groundwater level, Soil type and Topography	**45%**
		% within vegetation type	**76.5%**	13.7%	9.8%	0.0%	100.0%		
	Mixed	Count	22	8	14	1	45		
		% within vegetation type	48.9%	**17.8%**	31.1%	2.2%	100.0%		
	No Acacia	Count	9	7	12	14	42		
		% within vegetation type	21.4%	16.7%	**28.6%**	33.3%	100.0%		
	Bare soil	Count	1	1	9	127	138		
		% within vegetation type	0.7%	0.7%	6.5%	**92.0%**	100.0%		

As can be seen from the table, on the one hand, the multinomial logistic regression model accounted for 79% of the variability of vegetation type, with only two predictors being significant. The model correctly predicted 78.4%, 66.7%, 95.2% and 99.3% of Acacia, Mixed, No Acacia and Bare Soil plots respectively. On the other hand, the multinomial logistic regression model using the extracted principal components account for 61.5% of the variability in vegetation type, with two component predictors both are significant. The model correctly predicted 47.1%, 62.2%, 64.3% and 97.1% of Acacia, Mixed, No Acacia and Bare Soil plots respectively. The third ordinal regression model accounted for only 45% of the variability of vegetation type, with six predictors being significant. The model correctly predicted 76.5%, 17.8%, 28.6% and 92.0% of Acacia, Mixed, No Acacia and Bare Soil plots respectively.

4.2.6 Discussion

An initial objective of this section was to determine the relationship between a representative range of broad vegetation\habitat types from field sites across Qatar and the environment. Results showed that vegetation types are strongly related to topography, soil type, disturbance index and elevation. Meanwhile, the relationship with distance to coastline, distance to groundwater table level and TDS of groundwater was weaker.

The results partly demonstrate that the *Acacia* species are found far from the coastline at slightly elevated landscape (Table 4-1 and 4-3). The distance from the coastline and elevation for Acacia and Mixed types, ranged from 23.4 to 24.5km and 31.9 to 36.8km, respectively; whilst ‘No Acacia’ types are found between 11.1km and 14.4km, respectively. It is difficult to explain this result, but it might be related to spatial heterogeneity of landforms which have played a key role in vegetation distribution. Particularly, variations in soil characteristics is a major role in determining the zonation pattern of the vegetation (Younes *et al.*, 1983). Therefore, it seems possible that the Qatari coastline which is characterised by flats and saline zones including salt marshes (see Figures 3-2 and 4-8) could be attributed to absence of the *Acacia* species. The main factor which may have contributed to this apparent absence of *Acacia* in coastal areas is very strong to strong saline conditions with electrical conductivity ranges from 13.1 to 81.1 mmhos/cm (Scheibert *et al.*, 2005). Such high salinity concentration affects regeneration, growth and biomass production of the *Acacia tortilis* negatively (Mehari *et al.*, 2005; Al-Shaharani and Shetta, 2011; Kebbas *et al.*, 2013).

Another possible explanation for this is that under waterlogged conditions, which is common in salt marches; the dissolved sulphide leads to death of higher plants such as *Acacia* trees (Packham and Willis, 1997).

The results indicate that depth to water level has a significant influence on the four vegetation types (Table 4-6). It is worth noting that these depths of groundwater table are is in range of depths that *Acacia tortilis* has been shown capable of extracting water from (26.9m to 27.9m for *Acacia* and mixed plots respectively). Thus, it could be claimed that presence of mature *Acacia* trees in Qatar at national scale is related with groundwater level. This finding is in agreement with Cole and Brown (1976) in Botswana and Do *et al.* (2008) in Sahelian Africa who showed that *Acacia tortilis* has deep roots which enable it to draw on groundwater and to utilize constant moisture sources.

For species distributions, topography is recognized as one of the most important determinants of vegetation distribution (Eiserhardt *et al.*, 2011; Moeslund *et al.*, 2013). Topography, however, may not be the only factor determining the *Acacia* distributions. Several researchers have demonstrated that difference in soil characteristics are a key factor for plant life (Black, 1968; Rendig and Taylor, 1989; Raynaud and Leadley, 2004). Thus, soil may also influence their spatial patterns. The effects of soil and topography, however, may have a more complex interrelationship. Accordingly, the highly heterogeneous topography (topographic variations) and soil on Acacia, takes an important role in maintaining their coexistence. The present results showed a strong relationship of vegetation types to topography and soil types. Acacia and Mixed plots are distributed in topographical areas characterised by depression and slope positions. Moreover, those topographical positions found to be absence of gypsiferous soils (Figures 4-10 and 4-11). Meanwhile, No Acacia and Bare Soil plots were distributed in areas with different soil types including gypsiferous soils. The No Acacia type was found in the three topographic positions studied whilst bare soil plots were confined mainly to summit positions. The observed correlation between topography and soil type with *Acacia* distribution in Qatar at national scale could be explained as follows; firstly water supply is the principal limiting factor for plant life. Hence, moist sites are topographically controlled, being restricted to depressions and backslope microenvironments where runoff water collects and provides sufficient moisture for *Acacia* growth. Secondly, it seems possible that absence of gypsum content had significant positive effects on the distribution within these lower positions. Previous studies have demonstrated that soil type or characteristics such as gypsum content play a key role in distribution of plant species (FAO, 1990; Pascual *et al.*, 2012). Additionally, previous studies have demonstrated that the high gypsum content in the soil leads to less productive soils and impeding cemented petrogypsic horizons, which affects the distribution of vegetation and composition of species (Eftekhari and Asadi, 2001; Chigani *et al.*, 2012; Pascual *et al.*, 2012). On the other hand, there was a clear association between the vegetation distribution and depressions (Rawda) in national scale, as shown in Figure 4-1 and 4-8. This also accords with our earlier observations.

Disturbance index results indicated that the Acacia plots might have highest risk from human activity as the measured distance from these plots was found to be nearer to sources of potential disturbance (0.32km) compared to Mixed (0.51km), No Acacia (0.83km) and Bare Soil (0.91km), respectively. There are at least three possible explanations for this result. Firstly, depression areas are considered as the best land for agriculture practices in Qatar (Scheibert *et al.*, 2005), therefore, more of these lands were converted into farms (see Figure 1-10 in chapter 1). Secondly, due to the dramatic increase in the population (see chapter 1) culminated in massive infrastructural development and expansion in urban sprawl with more connection roads would lead to more degradation of the Acacia habitat (See Figures 1-8, 1-9, in chapter 1). Thirdly, over the last few years the number of livestock has increased greatly. Consequently, more herd settlements are present. Moreover, available stock figures and contemporary herding practices suggest that its numbers or population are exceeded by a large margin (Sillitoe *et al.*, 2010). These figures could possibly lead to the higher disturbance index observed on the *Acacia* habitats. These findings further support the idea of Brown, (1988) and Kouba *et al.* (2011) who noted that ‘abiotic factor’ can exert significant control over plant distribution. Previous studies have also demonstrated that different human activities lead to disturbance on the *Acacia tortilis* habitats such as Batanouny, (1981) in Qatar and Abd El-Wahab *et al.* (2013) in South Sinai, Egypt.

Statistical modelling techniques for the determination of the major vegetation and environmental variables associated with acacia abundance

In this study, three statistical techniques were used: (i) multinomial logistic regression using all variables separately, (ii) multinomial logistic regression using PCs and (iii) ordinal regression. These regression methods allow us to quantitatively model the relationship between the vegetation types as the dependent variable and the environmental variable predictors.

The results showed that the multinomial logistic regression (MLR) using all environmental variables explained 79% of the variability in vegetation types. The presence of *Acacia* plots was strongly related to disturbance index with a predicted response of 78.4% of the *Acacia* plots and 66.7% of mixed plots. This finding is in agreement with those of several studies which have shown that human disturbance plays a crucial role in plant distribution (Brown, 1988; Tilman *et al.*, 2001; Crow *et al.*, 2002; Tilman *et al.*, 2002; Kouba *et al.*, 2011). There is no simple explanation of this, result due to the multiple interactions involved, but it might be related to increasing human activities that seem to degrade the natural habitats of Acacia in Qatar (see chapter 1). Also, it seems possible that these results indicate that Acacia trees are distributed in the areas where they are found to be seriously affected by farms, settlement and roads (see Figure 4-12 and Table 4-8).

The MLR using PCs scores was found to explain 61.5% of the variability in vegetation types. As shown in Table 4-12, both components of the environmental variables tested were found to affect the distribution of different vegetation types. The model presented the accuracy of occurrence for the target vegetation types of 47.1%, 62.2%, 64.3% and 97.1% for Acacia, Mixed, No Acacia and Bare Soil respectively. Therefore, this model can provide insight into the relationships between environmental predictors from PC_1 and PC_2 and vegetation types, which will be the causal variable determining the vegetation response. For example, soil type, topography and disturbance index would be more important as predictors determining the distribution of the species within vegetation types. From an ecological perspective, these factors exert a strong influence on regulating the distribution of plants.

Ordinal regression was the least reliable prediction model. It accounts for 45% of the variability of vegetation types distribution in Qatar. However, between the classes; bare soil class is always very well predicted with response 92, 97.1 and 99.3% accuracy; whereas No Acacia had largest variation in prediction compared with Acacia and Mixed vegetation types. Mixed plots had reasonable prediction of 62.2% and 66.7% in model one and two. However, the prediction was poor in the third model for the mixed vegetation types. In terms of Acacia plots, good prediction from model one and three (76-78%) whereas moderate for model two.

CHAPTER 5: MULTIFACTORIAL APPROACH TO STUDYING DISTRUBUTION AND CONDITION OF ACACIA TORTILIS AT LOCAL SCALE.

Introduction

In this chapter classical statistics are used to quantitatively assess and explore the relative impact of protection status, topography and acacia tree densities on soil chemical (pH, % organic carbon, available phosphorus, electric conductivity and % Gypsum, CaCO3), soil physical properties (SWC, soil depth, surface crusts, impeding layer, depth to water table level), as well as their impact on morphological characteristics of *Acacia tortilis* (tree height, crown diameter, crown area, number of branches and diameter at breast height). Other parameters (tree density, frequency, root characteristics, proportion of browsing, cutting and leaf coverage) were also investigated. Lastly, relationships between the *Acacia* morphology and environmental gradients were evaluated, and multiple linear regression analysis was applied by using principal components as inputs to investigate the influence of environmental variables such as soil attributes, protection status and topographic positions (independent variables) on tree morphological characteristics (as a dependent variable). This will therefore, allow exploring how a set of environmental variables is associated with *Acacia tortilis* morphological characteristics.

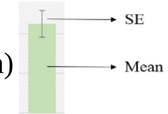
5.1 Effect of Protection Status, Topographic Position, Tree Density, Tree Canopy Cover and Horizon Depth (A or B) on Soil Properties in the Study Area I

5.1.1 Soil properties

The main features studied were those important for growth and occurrence of *Acacia tortilis* in the arid conditions of Qatar. The statistical results of soil chemical analysis are summarised in Figure 5-1.

- % OC was significantly greater in the protected sites as compared to unprotected sites. Other soil properties were not significantly related to protection status.

- All soil properties differed significantly between the sampled slope positions. Mean values of pH, available P, % OC, soil water content and soil depth were significantly smaller at higher elevations (summits) ($P < 0.05$) and increased downslope reaching a maximum in depressions; however, mean EC and Gypsum contents presented a different trend, as both were significantly higher ($P<0.05$) in summit areas and on slopes as compared to depressions.

Figure 5-1 a: Effect of Protection status, Topography, Tree Density, Sampling and Horizon on Soil Properties in the Study Area I (*n*= 222 Each Horizon) 

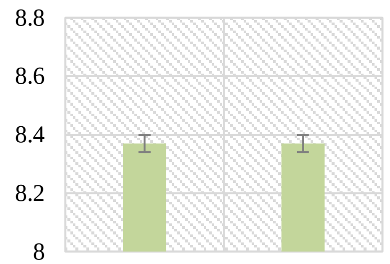
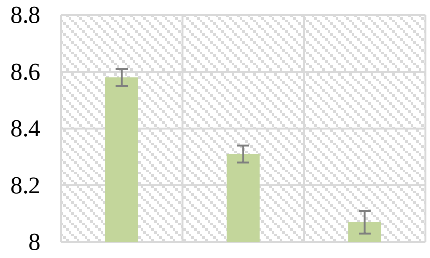
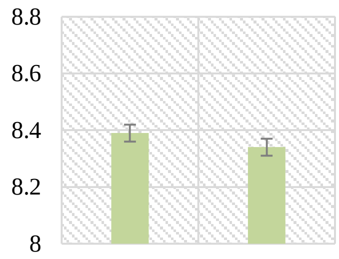
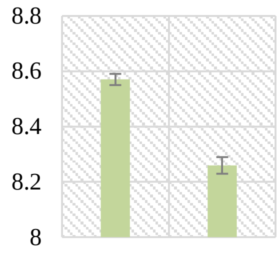
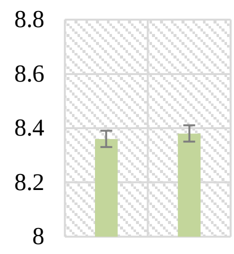
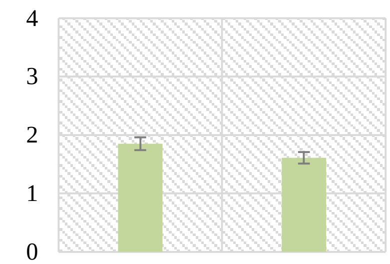
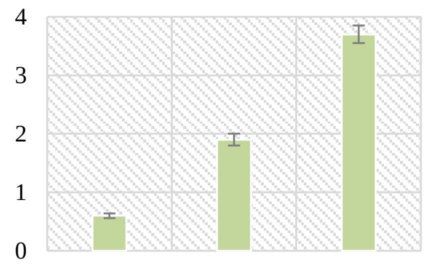
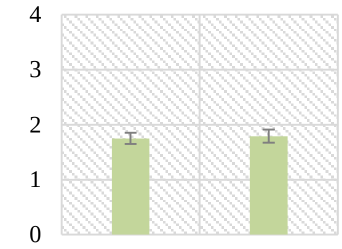
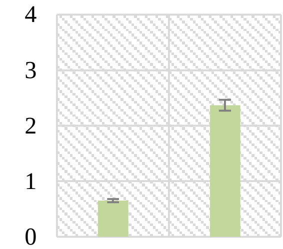
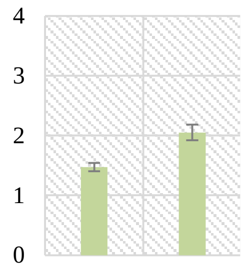
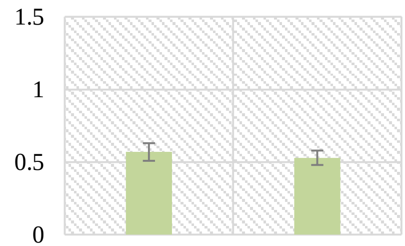
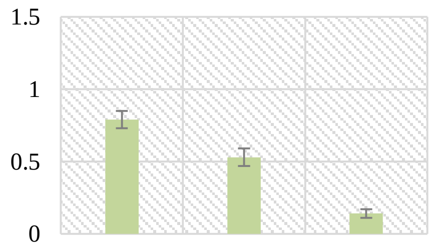
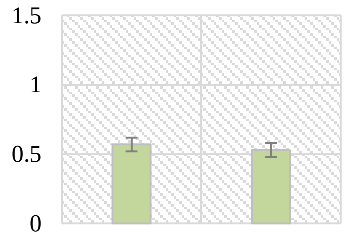
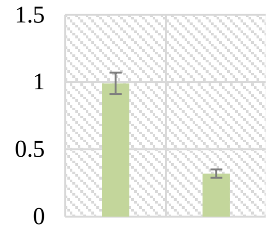
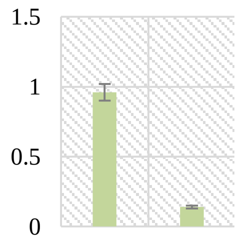
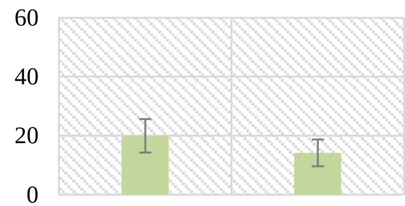
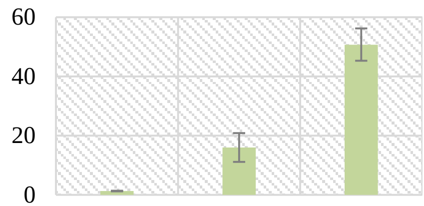
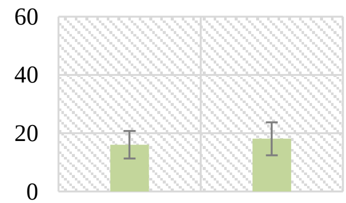
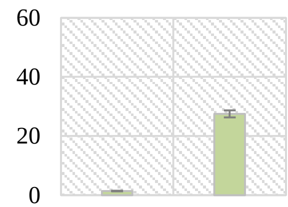
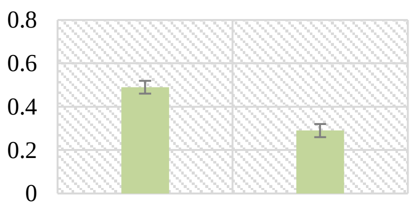
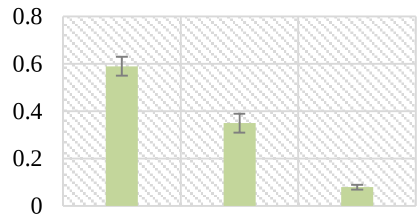
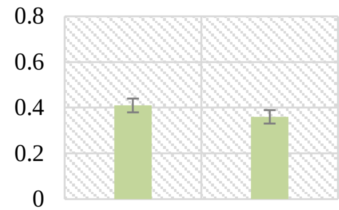
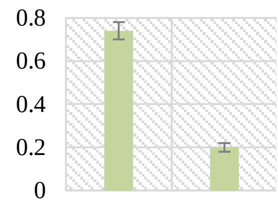
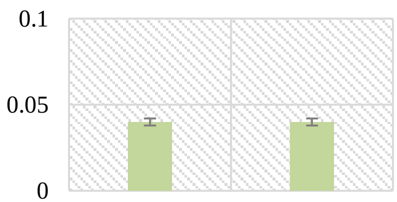
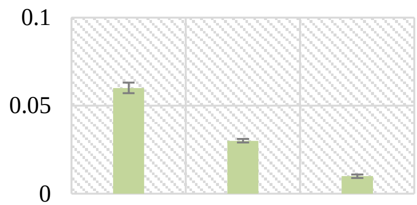
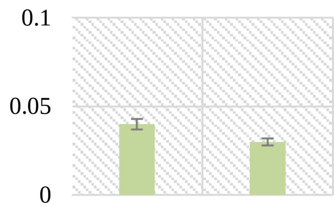
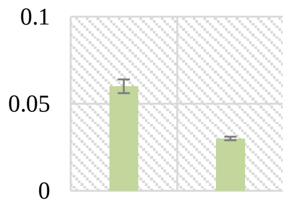
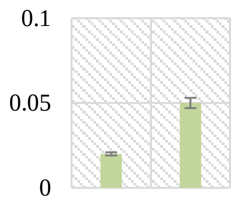
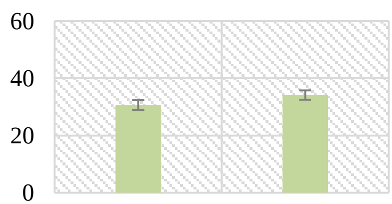
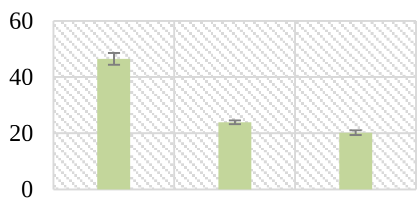
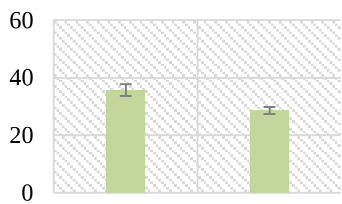
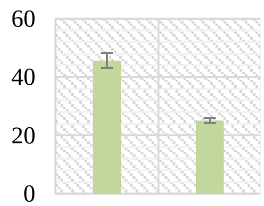
Variable	Protection Status	Topography	Tree Density	Sampling	Horizon
	Protected Unprotected	Depression Slope Summit	Dense Sparse	Under tree Bare Soil	A B
Soil pH					
EC (mS/cm)					
Available P (µg/ml)					

Figure 5-1 b: Effect of Protection status, Topography, Tree Density, Sampling and Horizon on Soil Properties in the Study Area I (n= 222 Each Horizon).

Variable	**Protection Status**		**Topography**			**Tree Density**		**Sampling**		**Horizon**	
	Protected	Unprotected	Depression	Slope	Summit	Dense	Sparse	Under tree	Bare Soil	A	B
Gypsum %										-------	------
Organic Carbon %										------	------
Soil Water (θ m^3 m^{-3})											
Soil depth cm										------	------

- Soil water content and soil depth differed significantly in relation to acacia tree density. Both properties had significantly higher values in areas having dense canopies as compared to sparse tree areas. Overall, soil properties had significantly higher values under the canopy of the *A. tortilis* trees compared with the bare soil areas, except the EC and gypsum contents, which were significantly higher in the bare soil ($P < 0.05$).

- EC and soil water content were significantly higher in horizon B as compared to horizon A, while available P in horizon A significantly exceeded that of horizon B. Soil pH values remained similar for both horizons.

Biological significance

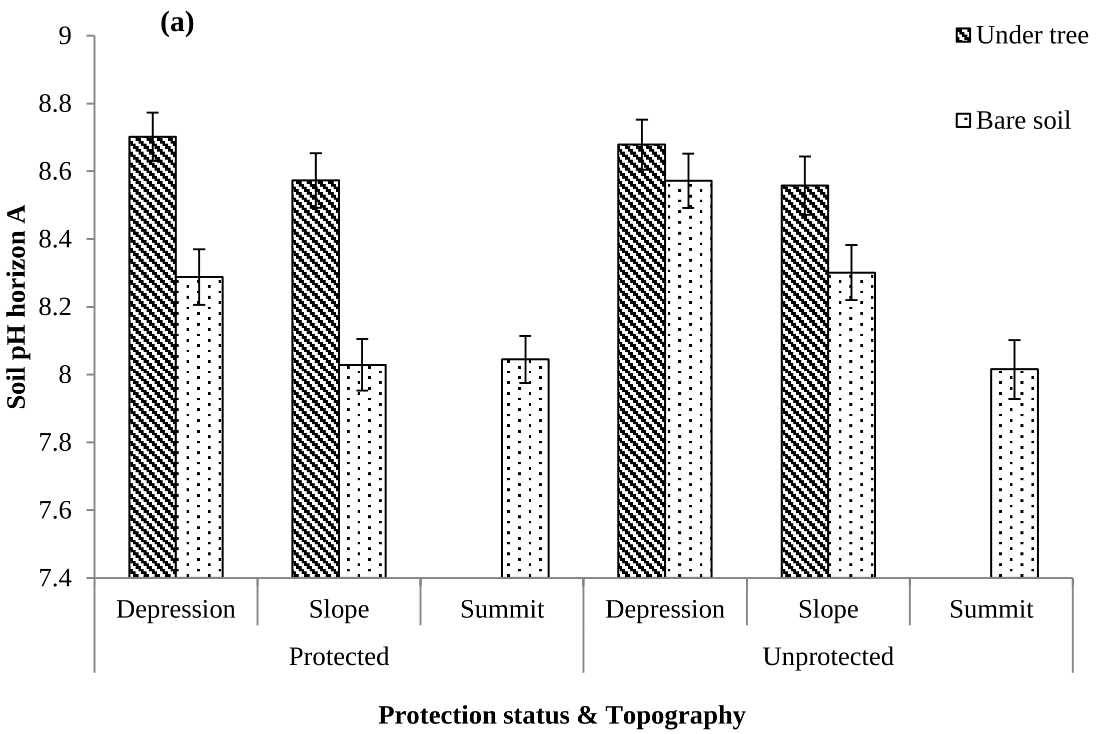
From the data in Figure 5-1a and b, it is apparent that the topographic variations and sampling (tree present/absent) had the most biological significance with regards to soil properties in study area I. The exceptions to this trend are the soil pH and electric conductivity. These were generally alkaline (pH above 8) and salt free or slightly saline (EC values between 0.5-3.7mS/cm), (for further explanation see section 5.1.2). Soil is a major storage reservoir for water and its deficit inhibits plant growth, the uptake of nitrogen, phosphorus and potassium within the plant (Kirnak *et al.*, 2001). The results obtained in this study demonstrated that the water content increased in depressions and with soil depth. Therefore, the biological significance of positions and soil depth are due to the effect of the availability of water, which is a limiting factor for plant survival. This study confirms strong evidence of additional water content located in depression positions, where soil depth is deeper (Figure 5-1 b). Consequently, depressional soils have an ecological significance on the tree, as both the water content of the soil (0.06m^3 m^{-3}) and soil depth (46.5 cm) were greater, compared with the slope (0.03m^3 m^{-3} and 23.9 cm) and summit (0.01 m^3 m^{-3} and 20.2 cm) positions, respectively.

Any value of available phosphorus below 0.2 ppm is considered to be very limiting for crop production (Landon, 1984). Despite no experimental evidence having been applied, this level of available phosphorus in the summit positions (0.14 µg/l) appears to be inhibiting tree growth. Furthermore, differences between the slope (0.53 µg/l) and depression (0.8 µg/l) positions had no biological significance (Figure 5-1 a). In other words, these particular levels will not limit tree growth. Seatz and Stanberry, (1963) reported that a level of 1 mg/l of phosphorus in the soil solution is generally considered adequate for plant growth. It is interesting that the available P is higher in depressions, therefore, more favourable for plant growth. Hence, they are (i) cycling the phosphorus as well as the organic matter; and (ii) washed organic P from a higher position into soils at a lower position. There is no work on the *Acacia tortilis'* requirement for P, however, based on other crop requirements these amounts have been established to be limiting (less than 0.2 µg/l), whereas, adequate available P on the lower positions may enhance the *A. tortilis* seedlings.

In the Aridisols, the organic-matter content is virtually less than 0.5% (Dregne, 1976). It is unlikely to control the distribution of the acacia tree; however, organic carbon indirectly affects the soil quality. Organic matter is vital to the formation of the soil structure, exchange of nutrients in the soil and the capacity of the soils to hold water. In addition, it also helps to increase the rate of water infiltration. As Figure 5-1b shows, there is a biological difference between the organic carbon content in the summit position (0.08%) compared with its content in both the slope (0.35%) and depression positions (0.59%). In arid soils, this level is adequate, which possibly means that water retention is higher and the soil structure is more favourable. Similarly, the differences between organic carbon under the tree (0.79%) and bare soil (0.2%) were biologically significant. This is because the high organic matter content tends to have more water retentions and contains more stable aggregates that resist compaction, in addition to more root penetration in to the soil.

❖ Soil pH

Variation in soil pH was highly significant (*P* < 0.001) at different topography (depression, slope and summit) as well as between under tree and bare sampling points. Accordingly, soil pH was significantly higher at depression positions as compared to slope and summit. Similarly, pH was significantly higher in the soils under the trees as compared to bare soils especially in case of horizon A (Figure 5-2 a and b). There were no significant effects of protection status, tree density or soil A compared to B horizon on pH values. Soils of the study area, whether the in protected area or unprotected area, were generally alkaline in character, as pH values exceeded 7 in both A and B horizons from all slope positions and tree densities. In general, there was greater variation in soil pH in horizon A as compared to horizon B, and within protected sites as compared to unprotected sites as shown in Figure 5-2.



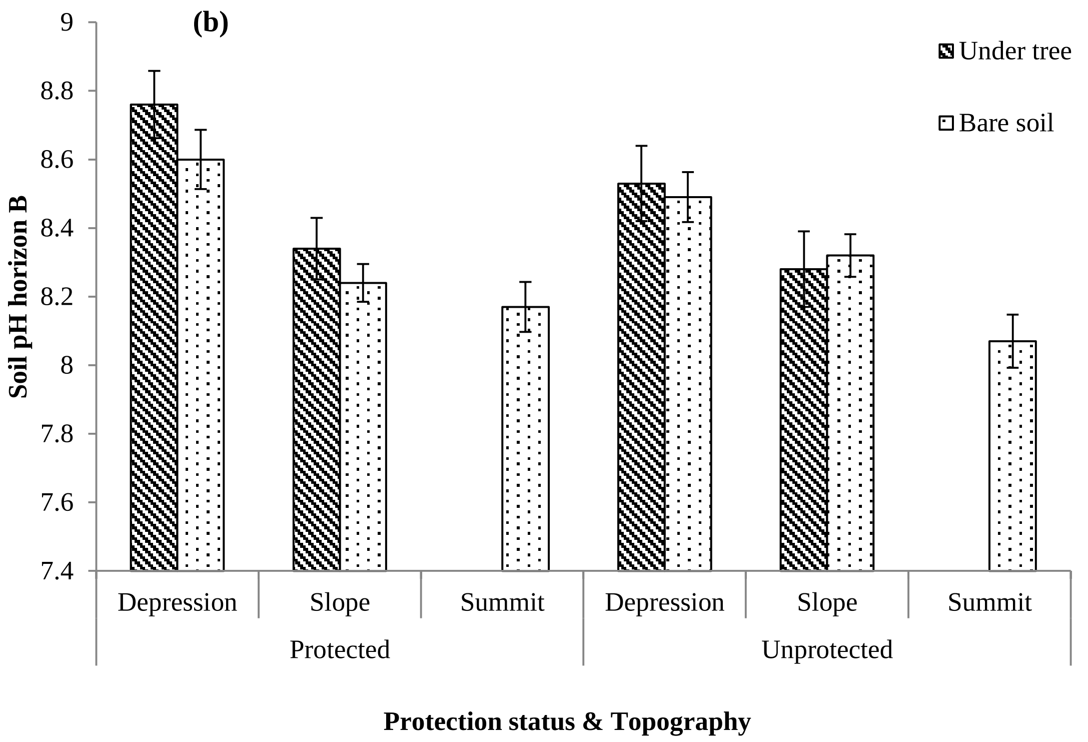
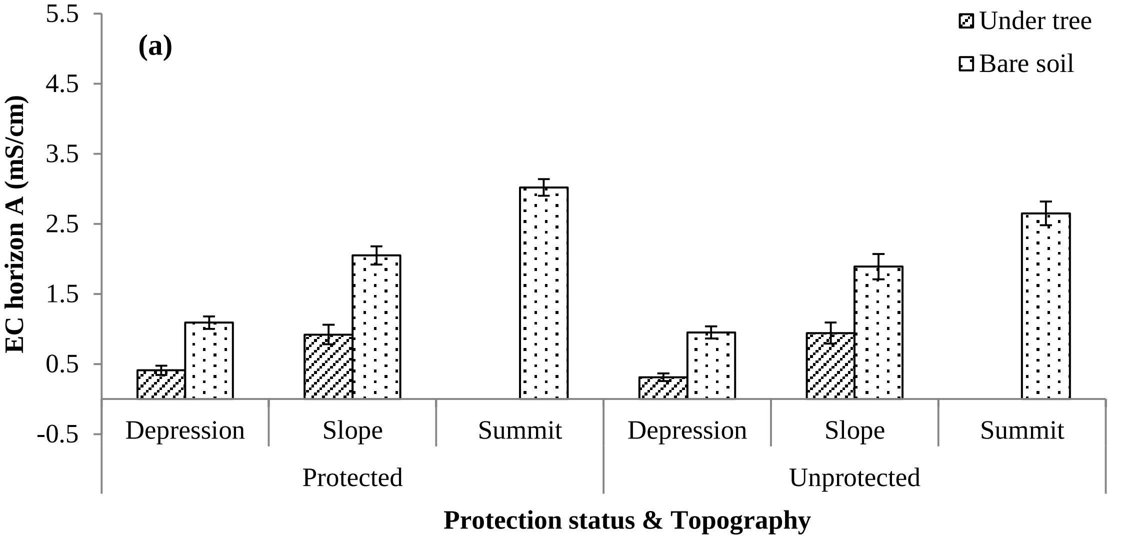


Figure 5-2: Soil pH at Horizons A and B of Protected and Unprotected Sites, From Various Positions and Samples Taken From Under Tree or Bare Soils. Error Bars Represent the Standard Errors of the Means (SE).

❖ Electric conductivity (EC)

Unlike pH, EC values were significantly different from each other in the following order: summit > slope > depression; and EC in bare soils was higher than under canopy as shown in Figure 5-3. The EC values of summits were almost two fold higher than those of slopes in both horizons A and B, which in turn, were four to eight times higher than values recorded in depressions for horizon A and B, respectively. It was also noted that soil EC increased significantly from horizon A to horizon B ($p<0.05$) as shown in Figure 5-3b. EC values in horizon B were approximately 39% higher than A.



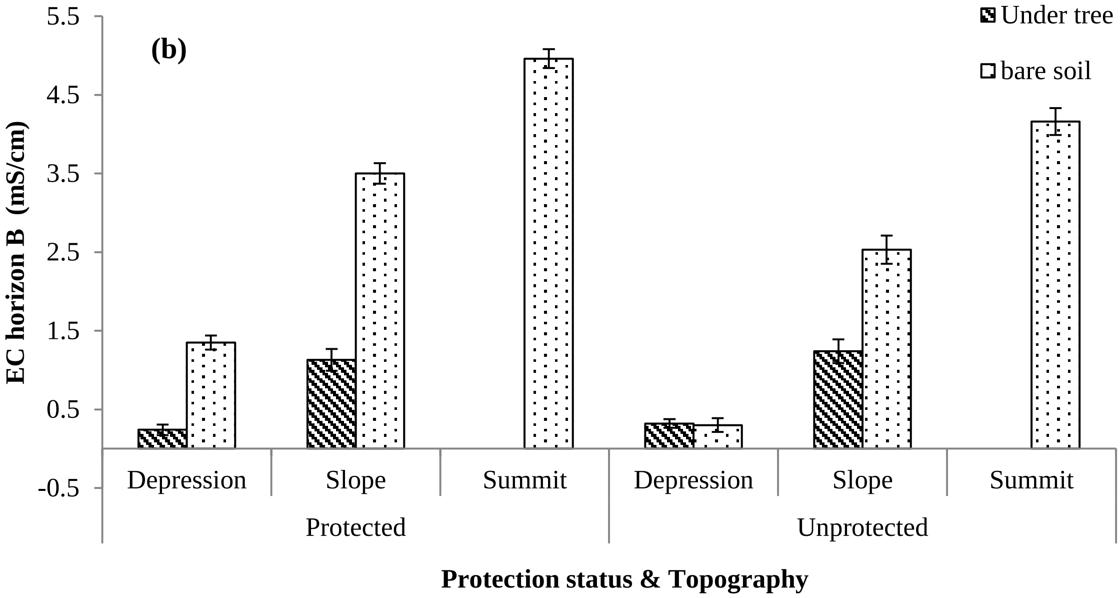
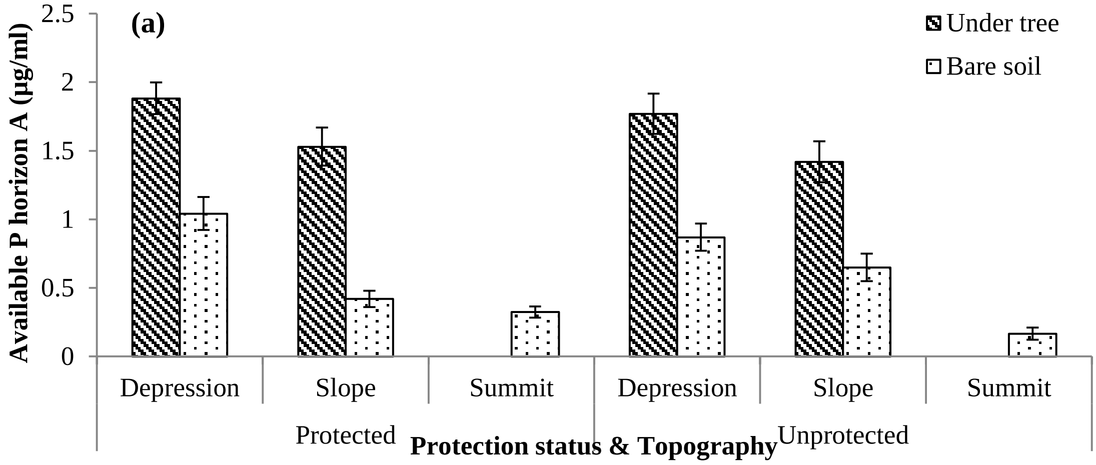


Figure 5-3: EC Values at Horizons A and B from Soils under Protected and Unprotected Sites, From Various Positions and Sampling under Tree or From Bare Soils. Error Bars Represent the Standard Errors of the Means (SE).

❖ Available phosphorus

Results have shown that slope position had a significant ($p<0.05$) effect on the available P content with depressions having the highest available P followed by slope and summit positions. P content in depressions was 47% and 84% higher than on the slope in horizons A and B, respectively. Available P content in summit positions was 5 times less as compared to other positions in both horizons. As shown in Figure 5-4, available P content of soils sampled under trees was substantially higher than those sampled from bare soil in both horizons. The A horizon had approximately 7 times higher available P content than the B horizon. In general, available P content was found in a very low range (i.e. < 2 µg/ml).



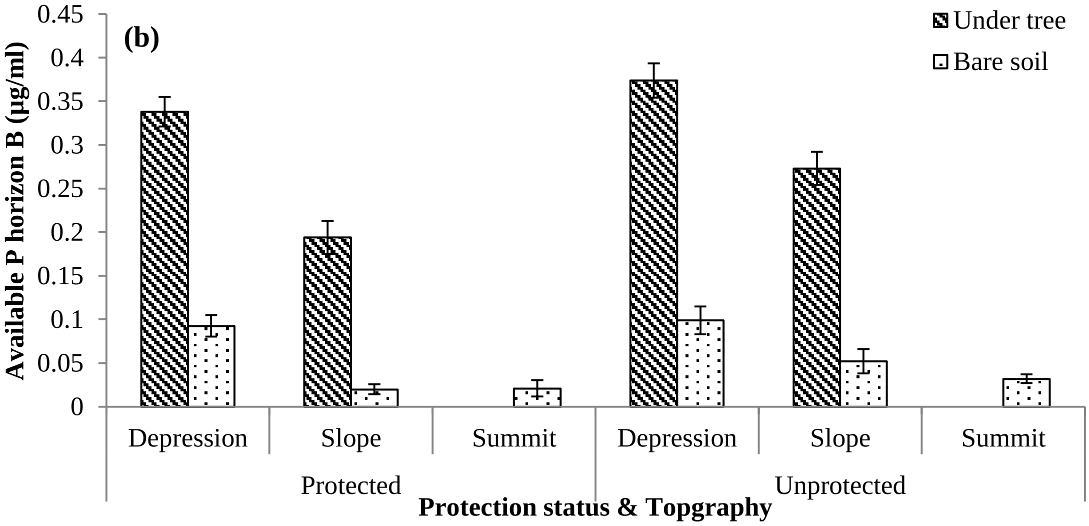
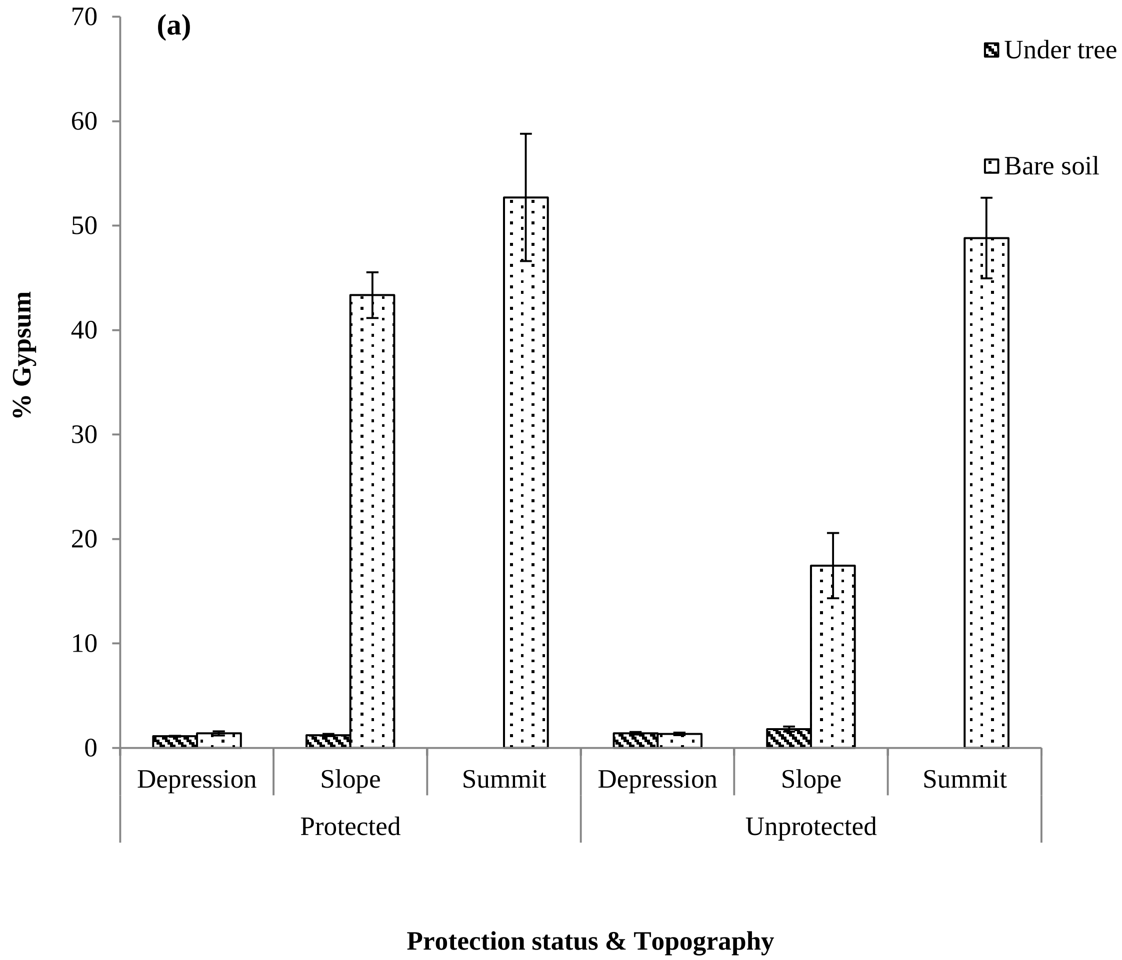


Figure 5-4: Available Phosphorus at Horizons A and B in Protected and Unprotected Sites, from Various Positions and Sampled Under Tree or From Bare Soils. Error Bars Represent the Standard Errors of the Means (SE).

❖ % Gypsum content

Gypsum concentrations at protected and unprotected sites were not significantly different although the protected site had higher concentrations in the midslope positon than the unprotected site. They were, however, significantly related to topographic position, with significantly greater amounts in soils on summits (with concentrations >50%) as compared to slopes (with >15%), whilst in soils of the depressions they did not exceed 2% and were similar both in soils under trees and in bare soil (Figure 5-5a). In contrast, bare soils had higher gypsum contents as compared to soils under tree canopies in midslope sites. Figure 5-5 (b) shows that in protected areas the gypsum content of soils increases less markedly on summits under dense tree cover compared to sparse tree cover, but this is not apparent in unprotected areas.



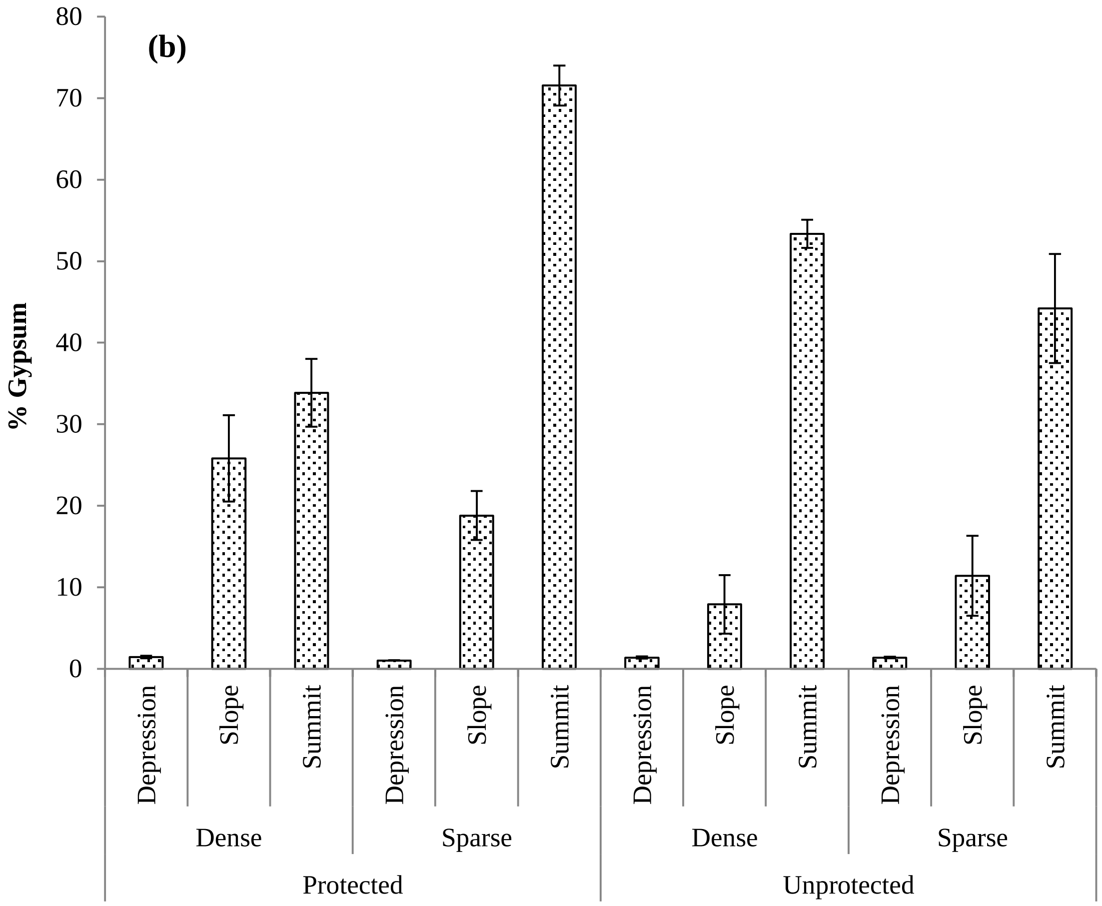


Figure 5-5: Gypsum Percentage in Soils At Protected and Unprotected Sites;From Various Positions and Sampling Under Tree or From Bare Soils (a) From Dense or Sparse Tree Areas (b). Error Bars Represent the Standard Errors of the Means (SE).

❖ Soil organic carbon

Soil Organic Carbon was generally higher in protected sites than the adjacent unprotected sites. The highest SOC was observed in the depression position and the lowest in the summit position. Organic Carbon (%OC) was significantly higher ($P<0.05$) under acacia trees compared with bare soils regardless of protection status, although absolute amount were greater in protected sites (Figure 5-6).

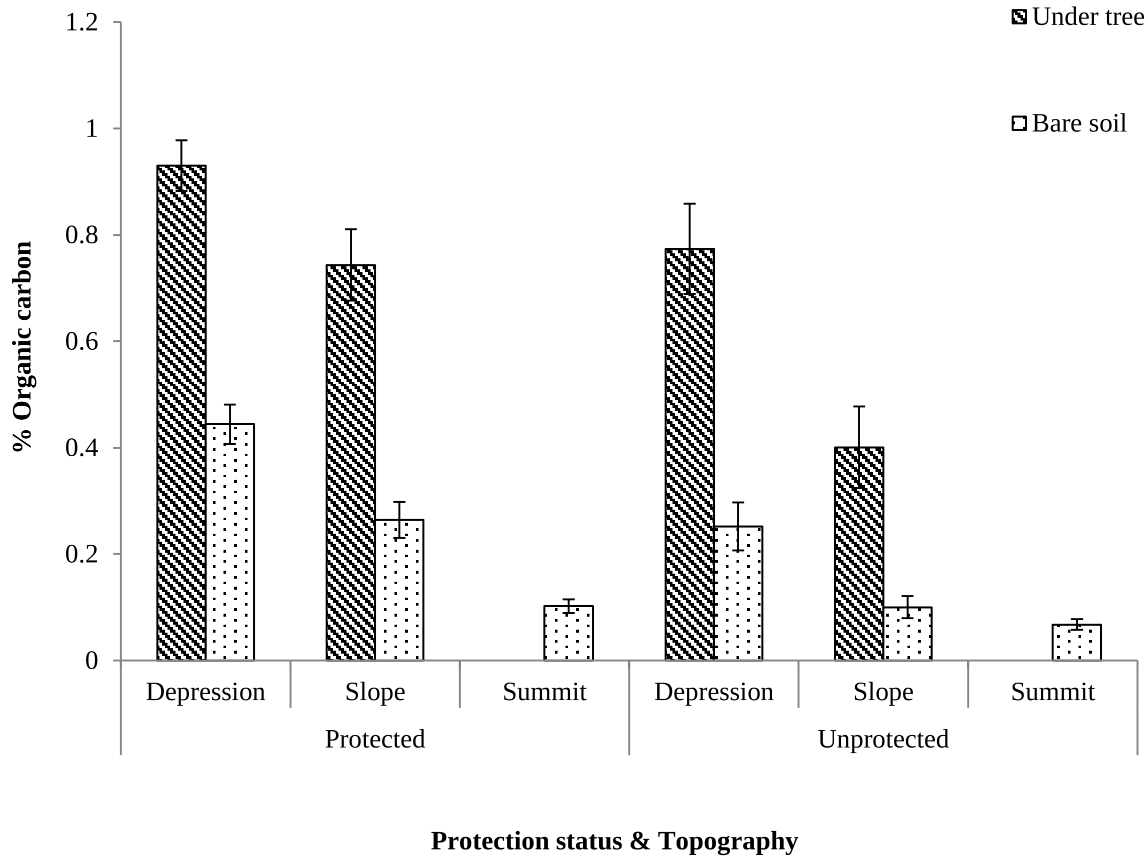


Figure 5-6: Percent Organic Carbon in Soils at Protected and Unprotected Sites, From Various Positions and Samples Drawn From Under Tree or Bare Soils. Error Bars Represent the Standard Errors of the Means (SE).

❖ Soil moisture content / volumetric water content (θ m^3m^{-3})

Volumetric water content was significantly lower in protected sites as compared to unprotected sites in horizon A. However, the differences between sites in horizon B were not significant. The highest mean water contents were found in depressions followed by slopes and summits, respectively. As expected, water content in soil samples drawn from under the trees was higher as compared to that of bare soils. This trend was similar in both horizons as shown in Figures 5-7 and 5-8. It is worth mentioning that the differential effects of topographic position, shade and organic matter content may affect water infiltration and soil water storage in bare soil versus tree-shaded sites. Higher evapotranspiration under trees in arid zones may sometimes lead to smaller soil water content, although it is usually true that they increase infiltration of water.

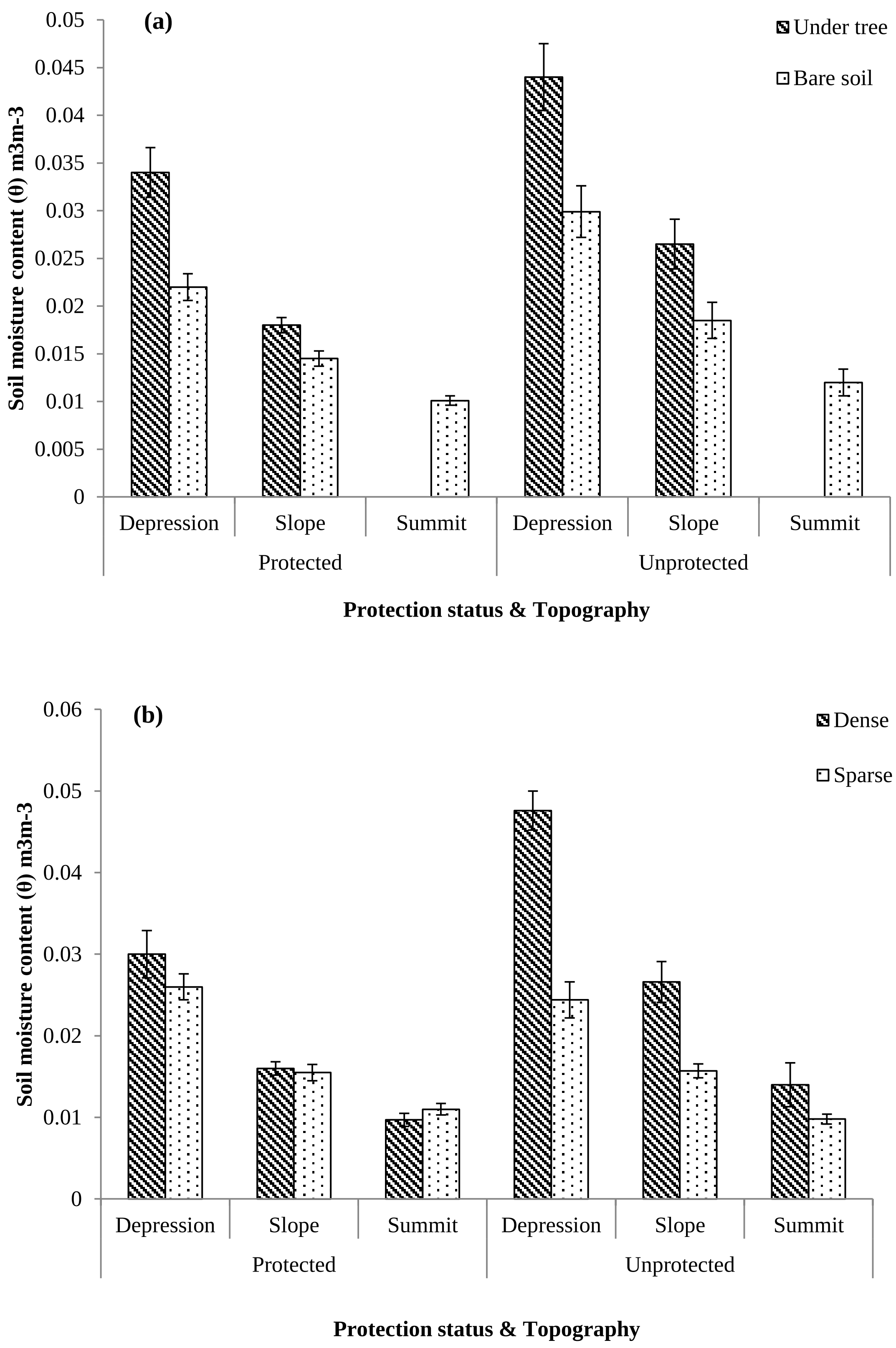


Figure 5-7: Horizon A: Volumetric Water Content in Soils (at Protected and Unprotected Sites,From Various Positions and Sampling From Under Tree or Bare Soils (a) From Dense or Sparse Tree Areas (b). Error Bars Represent the Standard Errors of the Means (SE).

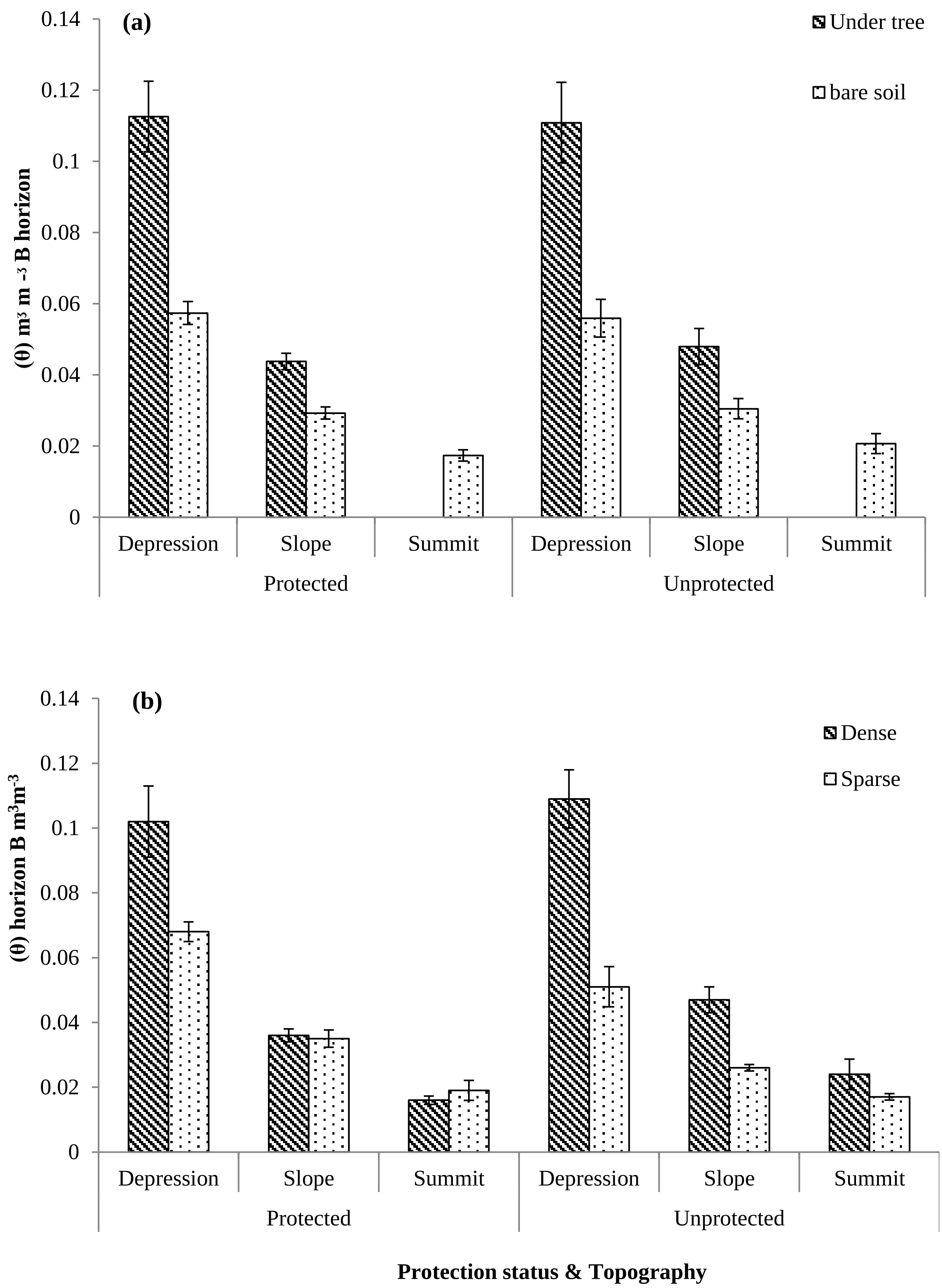
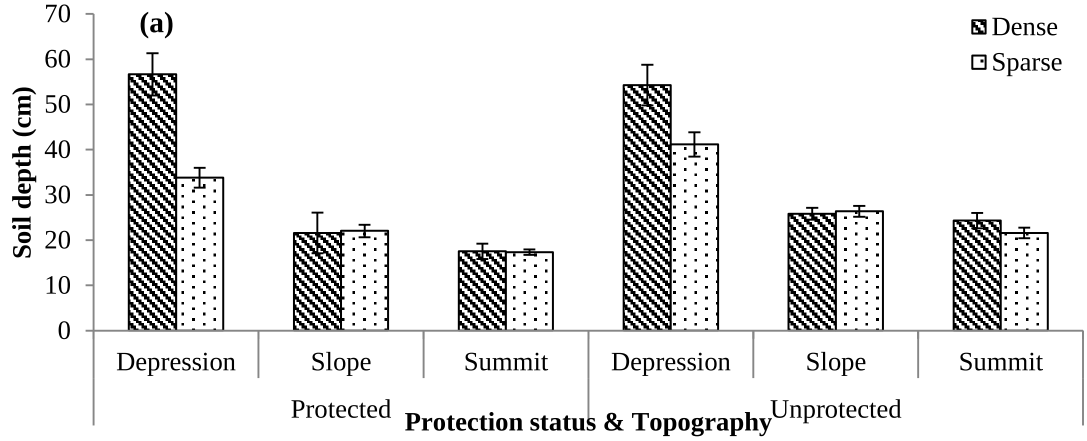


Figure 5-8: Horizon B: Volumetric Water Content in Soils at Protected and Unprotected Sites, From Various Positions and Sampling From Under Tree or Bare Soils (a) and From Dense or Sparse Tree Areas (b). Error Bars Represent the Standard Errors of the Means (SE).

❖ Soil depth

Soil depth was not significantly different in the protected sites as compared to unprotected sites. Soils were always significantly deeper in depressions as compared to slope and summit positions in both protected and unprotected areas (Figure 5-9(a)). Soils were also significantly deeper under dense compared to sparse tree density in the depressions, but not in other topographic positions, as shown in Figure 5-9. Similarly, there were significantly greater soil depths under trees compared to bare soil conditions in the depressions (Figure 5-9(b)). Thus, greater soil depth is clearly related to depressions and to tree cover in these less elevated topographic sites, but remains shallow on summits and midslopes regardless of tree density.



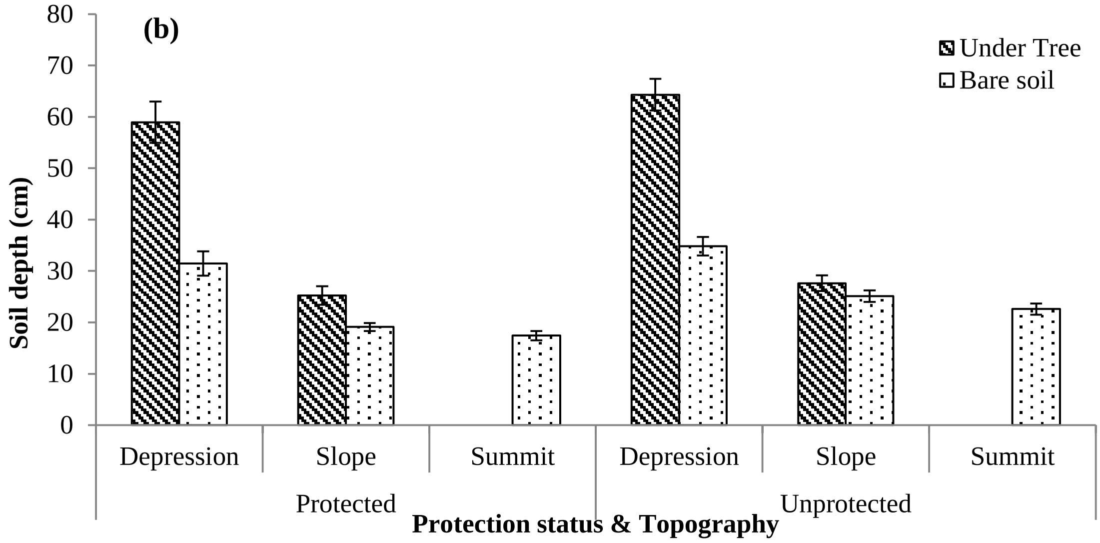


Figure 5-9: Soil Depth at Protected and Unprotected Sites, From Various Positions and Sampling (a) From Dense and Sparse Trees (b) From Under Tree and Bare Soils. Error Bars Represent the Standard Errors of The Means (SE).

❖ Carbonates

Calcium Carbonate ($CaCO_3$) estimation from 476 soil samples taken from the studied area I revealed that a vast majority of 96% of soils in both protected and unprotected, as well as regeneration sites, were ‘very calcareous’ to ‘calcareous[2]’. This agrees well with soil pH values that are consistently >7.0, and which do not vary significantly with any of the factors assessed.

The detectable audio-visual effects resulting from dropping of 10% hydrochloric acid on a fragment of soil fell within the range of ‘very easily audible’ for 457 samples while 17 results were in the category of ‘easily audible’[3]. The only exception were two soil fragments from B horizon at a summit position which showed a ‘very slightly calcareous’ profile i.e. having 0.5-1% of $CaCO_3$.

❖ Surface crust or sealing

There were no surface crusts found at the unprotected site. However, at the protected site, crusts of various categories were present in both dense and the sparse tree areas.

In total, soil crusts and their attributes were recorded in 12 depression positions at study area I[4]. No crust or sealing existed at slope or summit positions in the protected site. Crusts developed at topsoil surface within the dense tree areas, were thin (F) < 2mm to medium (M) 2-5mm in thickness, with slightly hard consistency (S) at two depression positions while the consistencies of the others found at four depression positions were hard (H). Crusts found in the sparse tree area were thinner in thickness with slightly hard to hard consistency.

[2] Very calcareous means CaCO3 > 10%; Calcareous means CaCO3 = 5-10%.
[3] A ‘‘very easily audible’ reaction shows greater amount of calcium carbonate with bubbles having >3mm diameter while an ‘easily audible’ gives moderate effervescence.
[4] At each depression there were three topographic positions tested i.e. depression, backslope and summit making a total of 72 positions for protected and unprotected sites.

❖ **Impeding horizon**

The existence of a cemented soil horizon, that impedes root penetration and may be caused by higher concentrations of $CaCO_3$ or gypsum (calcium sulphate; $CaSO_4 \cdot 2H_2O$), is likely to play an important role in *Acacia tortilis* water uptake (Figure 5-11). Chi-square test analyses were used to test the differences of presence or absence of impeding/cemented soil horizons (Figure 5-10) in the main study area I, in relation to protection status, tree density, topographic position and sampling. The following results were obtained:

- Association with protection status: Chi-square goodness of fit test was used to determine whether the occurrence of cemented horizon categories (present or absent) was related to protection status. A non-significant relation was found between the impeding layer and the protection status (χ^2= 0.001, df = 1, P=0.975) as shown in Figure 5-10a. The frequency of impeding cemented soil horizons was similar between the protected site (51.8%) and unprotected (48.2%) site.

- Association with types of depression (dense/sparse tree density): The presence of impeding cemented horizons was not significantly different in the densely wooded depressions compared to the sparsely wooded depressions. (χ^2= 0.398, df = 1, P= 0.528) as shown in Figure 5-10b.

- Association with topographic position (depression, slope and summit) and impeding layer (present/absent): a highly significant association was found when the data were analysed with a chi-square test (χ^2= 138.716, df = 2, P< 0.001). Clearly, the number of counts of the absent impeding cemented soil horizon was higher (62.8%) in the depression position compared with slope position (37.2%), as shown in Figure 5-10c. In contrast, the presence of an impeding cemented soil horizon was more frequent in the summit position in comparison with slope position, as shown in Figure 5-10c. It is noteworthy that the impeding layer was totally absent in the depression position and always present in summit position.

- Association with tree canopy/sampling (under tree/ bare soil): Differences in the existence of a cemented layer were also highly significant between the under tree and bare soil sites (χ^2= 63.857, df = 1, P< 0.000), as shown in Figure 5-10d.

The main findings of the Chi-square analysis are that the frequency of impeding cemented soil horizons is significantly related to both topographic position and tree canopy cover, but not to protection status or the overall density of trees.

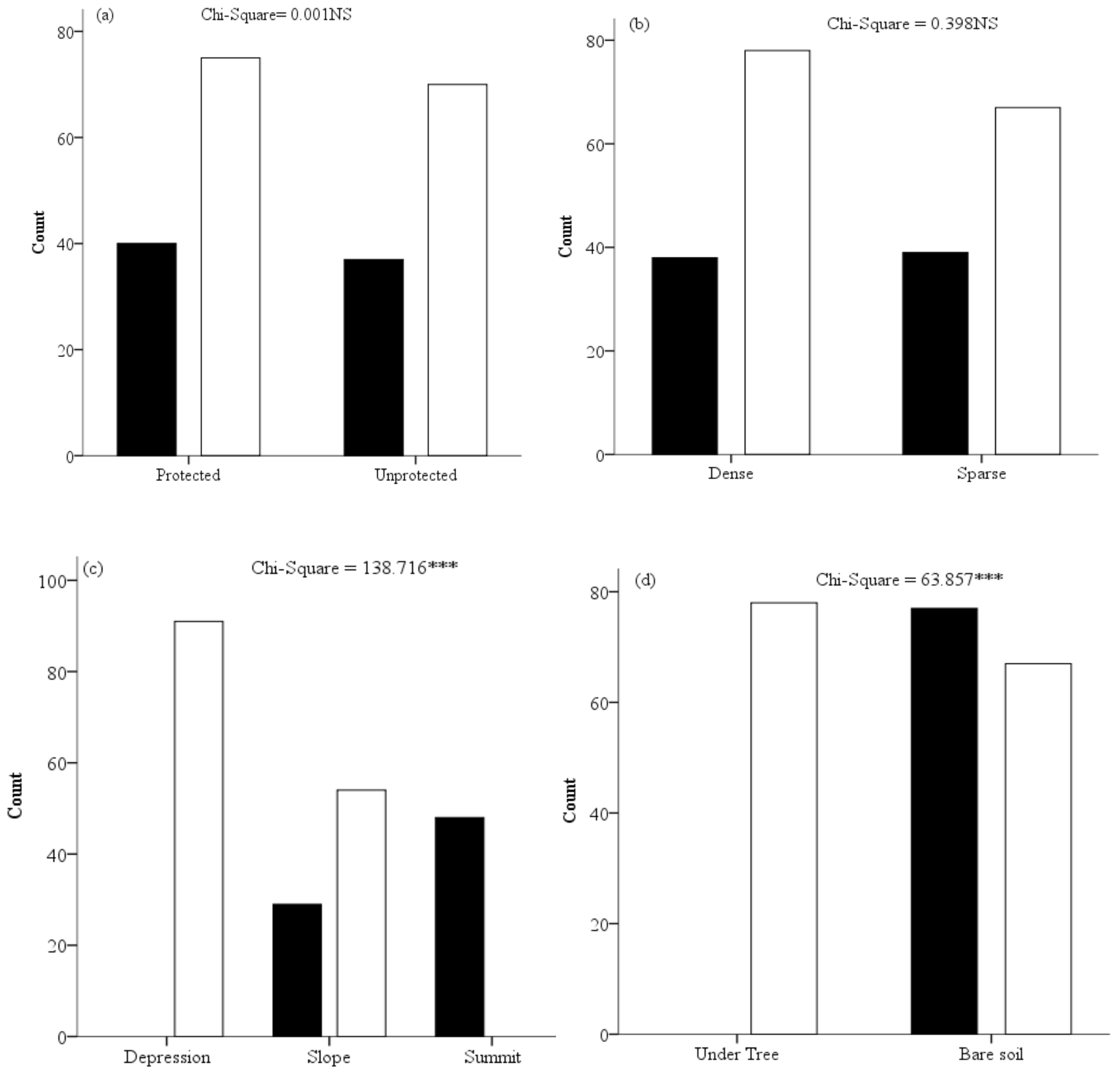


Figure 5-10: Presence of Impeding Layer (present , absent) at the Area I, Count is Observed Frequencies in Sample for the Main Effect of Protection Status (a), Tree Density (b), Topographic Position (c) and Sampling (d).

Chi-Square significance at P < 0.05 (*), P < 0.01(**), P < 0.001 (***) and NS (non-significant).

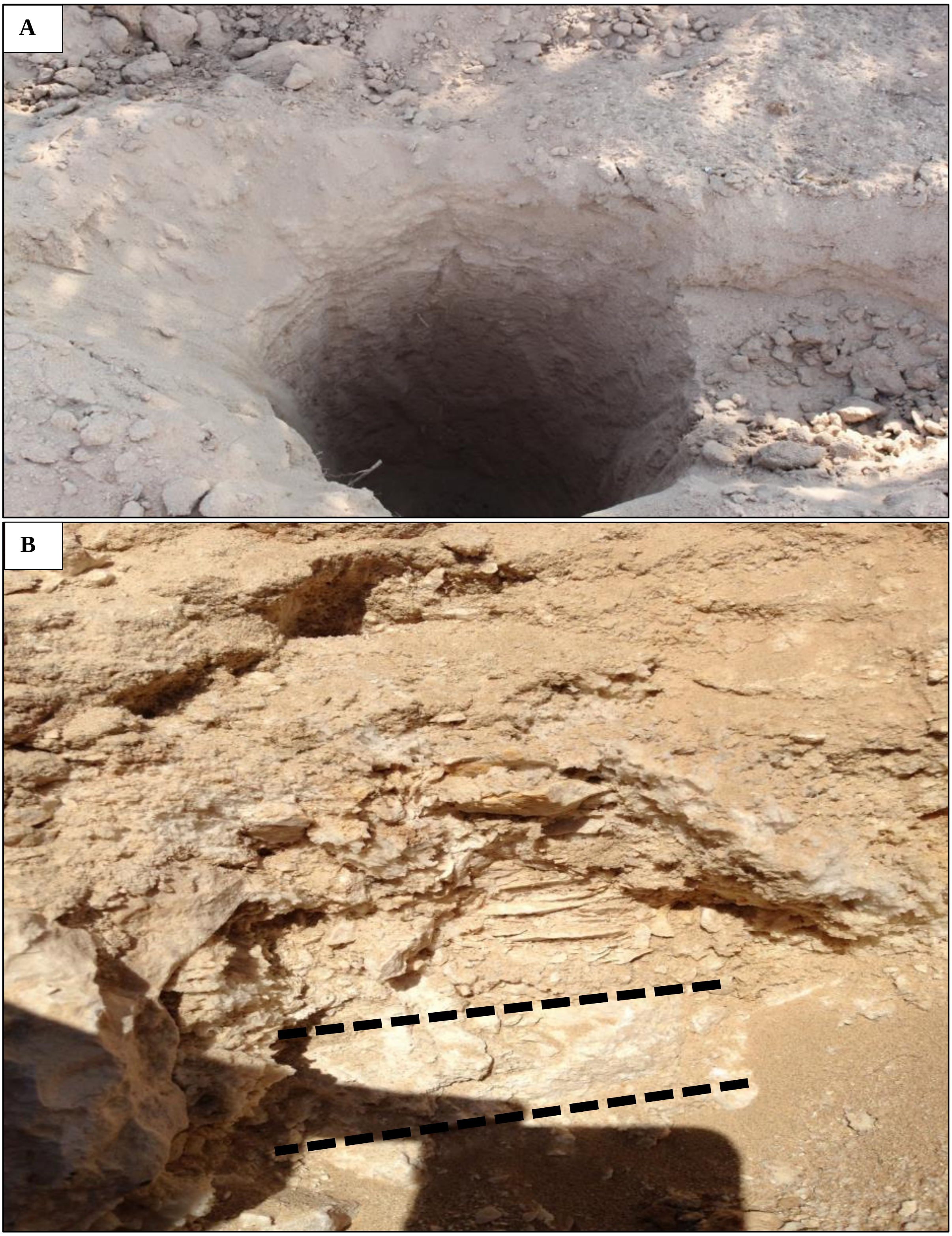


Figure 5-11: Composite Pictures Shows Differences in Soil Profile between Depression Position (A) and Summit Position (B) where in the Depression it Clearly Shows No Presence of Impeding Cemented Layer Compared to the Summit Position where the Presence of Impeding Layer Occurrence Just Few Centimetres Bellow the A Horizon (between dashed lines).

5.1.2 Discussion

One of the initial objectives of the project was to identify the main environmental factors that govern the distribution of *A. tortilis* in Qatar. The results support the effect of topographic position within the study area I, and reveals that variations in topography and soil characteristics have a clear influence on available water and consequently on the distribution of the tree population. These findings are consistent with the hypothesis that the heterogeneity of local topography and related changes in soil and water conditions are particularly important determinants of the distribution of plant species over a small geographic area in arid regions (Hegazy *et al.*, 1998; Abd El-Ghani and Amer, 2003; El-Bana *et al.*, 2007; El-Bana and Al-Mathnani, 2009). The present results corroborate the findings of a great deal of the previous work in this field (Yair and Danin, 1980; Batanouny and Ismail, 1985; Noumi *et al.*, 2010; Galal, 2011). The findings of the current study also agree with those of Hattar *et al*. (2010) and Omary (2011), who reported that soil properties such as EC, pH and organic matter in arid environments varied significantly with different slope elements.

- **Soil pH**

When considering the impact of grazing and human activities on soil characteristics, the results shown in Figure 5-1 indicate that there is no significant effect of either protection status or tree density on soil pH. However, significantly higher pH values are recorded for soil under *A. tortilis* canopies than in the bare soil. This conflicts with the findings of Belsky *et al.* (1989) and Kahi *et al.* (2010) in Kenya, Mishra *et al.* (2010) in India, and Munzbergova and Ward (2002) in the Negev desert, who reported a lower pH of soil under canopies of *Acacia tortilis* than in open areas. However, several studies have reported the opposite (Palmer *et al.*, 1988; Abule *et al.*, 2005; Fterich *et al.*, 2011). The observed increase in soil pH could be attributed to the positive association between increases in exchangeable cations and soil pH (Hatton and Smart, 1984; McGrath *et al.*, 2001; Sangha *et al.*, 2005; Jafarian *et al.*, 2011), since a higher pH under canopies of *Acacia tortilis* trees conforms more logically to the higher content of exchangeable cations in this subhabitat. Moreover, comparable results were reported by Abule et al. (2005), who also found a higher pH in soil under *A. tortilis* than in open areas. Here, the higher pH under canopies of trees was correlated with a higher content of exchangeable cations. Close relationships between base saturation and pH have also been reported in other studies (Dregne, 1976 ; Birkeland, 1999).

The small, but statistically significant, progressive increase of soil pH from summit (8.07) to backslope (8.31) to a maximum of 8.58 in depressions (see Figure 5-1 and Figure 5-2) has only limited relevance pedologically, or for plant growth, because all the soils are calcareous and therefore pH is buffered by the release of Ca^{2+} cations from dissolution of free $CaCO_3$. However, this slight trend of increasing soil pH from summits towards depression positions is in agreement with a similar, but often more marked, trend reported by other researchers in arid or semi-arid environments (Sariyildiz *et al.*, 2005; Hattar *et al.*, 2010; Omary, 2011). A possible explanation for this higher pH in depressions, is that the topography directs the course of runoff water (Winslow and El Hakim, 2009; Ashghal, 2012) and leachates in throughflow, so that free $CaCO_3$ in transported sediments and dissolved exchangeable bases, particularly Ca, accumulate in soils of lower positions. This could explain the slight increases in soil pH downslope shown by the present results and agrees with the findings of many other researchers Dregne (1976), McGrath *et al*. (2001), Sangha *et al.* (2005) and Jafarian *et al.* (2011).

The lack of any significant difference in soil pH between horizons A & B in the study area I can be explained by the highly calcareous nature of the soils and low leaching intensity. Adsorbed Ca^{+2} will dominate both horizons leading to alkaline soil materials with pH values above 8.

- **Organic carbon (%)**

The positive influence of *Acacia tortilis* in terms of soil improvement have been confirmed by several studies. In particular, it enhances soil fertility by improving soil nutrient contents such as increased nitrogen, organic carbon, phosphorus and microbial biomass, and improves soil structure (Belsky *et al.*, 1989; Smit and Swart, 1994; Wiegand *et al.*, 1999; Ba *et al.*, 2002; Moustafa and Mansour, 2003; Abule *et al.*, 2005; Abdallah *et al.*, 2008; Kahi *et al.*, 2010; Fterich *et al.*, 2011; Abdallah and Chaieb, 2012). An inspection of the present results in Figure 5.1 indicates that when all soil samples were analysed, regardless of sampling positions, there was no significant effect of protection status on available phosphorus, pH, electric conductivity, gypsum content, volumetric water content or soil depth in study area I. A possible explanation is that this is partly due to disregarding the variability induced by the effect of topographic positions, tree density, sampling beneath tree canopies and bare soil and differences between A and B horizon samples between sites. For instance, there was no statistical difference in volumetric water content (ϴ) related to protection status however, when considering topographic variation or tree density there was a significant difference (see result section 5.1.1).

However, organic carbon percent does show significant differences with respect to protection status, which is likely to be due to differences in grazing pressure. Lal (2004) demonstrated that changes in land use and management practices, such as cultivation and/or disturbance lead to reductions in organic carbon in the soil. He added that establishing plantations of *Acacia* or *Prosopis* species is an important strategy to enhance and restore soil organic carbon as an effective form of long-term soil protection. Khaledian *et al.* (2012) investigated the effect of land use on soil quality in northern Iran. The results revealed a significant decrease in organic carbon levels in urban, cultivated and pasture areas by 71%, 56% and 37% respectively in comparison with forest areas. This is similar to the findings of the current investigation, which found higher levels of OC in the protected sites. This is most likely explained by lower levels of soil degradation, as well as greater vegetation growth and biomass production, which includes litter and plant residues accumulating on the soil surface during the dry season in protected sites.

Moreover, Greater biomass, litter/debris and decompose during the short rainy season which then slow down, could be explained the greater soil organic carbon in protected areas. Other studies have also reported greater organic carbon increased with time due to greater inputs from litter and slower outputs through decomposition (Brady, 2008; Zhou *et al.*, 2012; Brazier *et al.*, 2014). The lower OC content found in unprotected sites in Qatar is in line with reports from other researchers that over-grazing is the main reason for low organic matter content in various different soils (Yong-Zhong *et al.*, 2005; Sarah, 2006).

The significantly smaller ($P < 0.01$) amounts of organic carbon (0.08%) in soils at higher elevations on summits (0.08%) and its increase to 0.35% on backslopes , reaching a maximum of 0.59% in depressions (Figure 5-1) requires explanation. Field evidence in the present study showed that litter and plant debris were transported or washed into depressions after rainfall events, which could be a significant source of the greater OC content in depressions. Throughout the partial decomposition process when soil moisture is high after rainfall, microbial activity will function well to decompose the added biomass and litter of plant debris to form soil organic matter. Subsequent drying will reduce the rate of microbial decay, thus leading to higher organic carbon content in the soil. Lower soil organic carbon contents in summit and slope positions could be attributed to the presence of less living and dead plant biomass, as well as less soil moisture through runoff, so that in these very dry conditions the transformation of plant litter into soil organic matter is reduced due to the absence of biotic activity responsible for this process. This draws attention to the role of differences in landform, which controls the availability of moisture for plant growth, biomass production and, consequently, the organic carbon content. Several other studies on the variability of organic carbon due to slope gradient have shown that down slope positions are mostly higher in OC compared to upper positions (Aguilar and Heil, 1988; Raghubanshi, 1992; Chaplot *et al.*, 2001; Hattar *et al.*, 2010; Ayoubi *et al.*, 2014).

The observed trend of increasing soil organic carbon below the tree canopies of *Acacia tortilis* compared to bare soil is in agreement with similar results reported by other researchers in arid or semi-arid environments (Abule *et al.*, 2005; Kahi *et al.*, 2010; Fterich *et al.*, 2011; Abdallah *et al.*, 2012; El Atta *et al.*, 2013). Many possible factors could be responsible for the observed increase, such as increased leaf litter inputs beneath *A. tortilis* trees (Belsky *et al.*, 1989; Kahi *et al.*, 2010), droppings from mammals seeking shade and/or grazing, as well as birds perched on tree branches and/or nesting (Belsky *et al.*, 1989; Dean *et al.*, 1999). Reduced leaching and/or lower decomposition rates may also contribute (Scholes and Archer, 1997; Kahi *et al.*, 2010). The findings of the present research that the highest soil organic carbon and available phosphorus contents are found in soils under *A. tortilis* in the Qatari desert emphasizes the importance of this leguminous tree to soil fertility in the studied area.

The observed significant decrease in soil OC in summit positions regardless of tree density, and midslopes with low tree density, compared to depressions could be attributed three factors. Firstly, available water content enhances the decomposition process in soil; secondly, the absence of tree cover in the summit position leads to very small amounts of plant litter being added to the soil; and thirdly winds and water erosion of the topsoil surface in such positions removes litter derived from ephemeral annual plants. Removal of plant litter by wind has been regarded as a factor in explaining small soil organic matter in the recent research findings of Wang *et al.* (2014), who studied the spatial distribution patterns of soil organic carbon density in the arid desert grasslands of northwest China. They found that, due to intense wind erosion, large amounts of litter were blown away by the wind, which resulted in only a small amount of aboveground organic matter entering the soil.

- **Available phosphorus**

Levels of available phosphorus, in most cases, show a progressive increase from summit to backslope and being greatest in depressions. These results contrast with earlier findings by Singh and Rathore (2013), who demonstrated that the available phosphorus content of the soil was in general greater in higher topographic positions. They attributed this reduction of available P content in lower topographic positions to the high amount of free oxides of Ca^{2+}, $Mg^{2+}$and Na^{+} which induce the fixation and subsequent precipitation of phosphorus, as well as to the low overall amount of organic matter. The present analysis revealed a strong positive correlation between available phosphorus and organic carbon in depression positions (see Table 5-8), which might explain the higher levels of phosphorus. It is encouraging to compare these results with those of Braschi *et al.* (2003), who found that the addition of organic matter to calcareous soils can increase available phosphorus and decrease P-insolubilisation. Moreover, particulate organic matter "litter and plant debris" that washed into depressions during rainfall events, could allow for increased available P release from the greater organically-bound P during decomposition of this organic debris in soils of the depression sites (see OC section above).

Higher concentrations of available phosphorus were found in soils beneath tree canopies of *Acacia tortilis* compared to adjacent bare soil. Although, this contradicts results from some published studies, such as that by Kahi *et al.* (2010) in Kenya, it is consistent with several research findings (Belsky *et al.*, 1989; Abate *et al.*, 1998; Abdallah and Chaieb, 2012; Abdallah *et al.*, 2012; El Atta *et al.*, 2013). In fact, it has been reported that leguminous plants favour microbial growth in soil and then soil microbial biomass is improved (Traoré *et al.*, 2007; Cao *et al.*, 2008). More particularly, due to the fact that *Acacia* spp. are able to fix atmospheric nitrogen through their root system symbiosis with *Rhizobium* (Ben Romdhane *et al.*, 2005; Fterich *et al.*, 2012; El Atta *et al.*, 2013), such legumes produce aromatic compounds in glycosylated forms which are then deglycosylated by members of Rhizobiacea in soil to induce the establishment of root symbiotic nodules (Morris and Morris, 1990). In this context, the increase of available phosphorus under the canopy might be attributed to microbes using organic matter as a source of energy, and through their activity they may play a partial role in increasing levels of available phosphorus in the soil (Lee *et al.*, 1990). Whereas, far from the *A. tortilis* canopy, ecological constraints such as water and nutrient stress, are always more intense, especially during the dry season.

As revealed in the findings, the level of available phosphorus in horizon A was higher than in deeper soil horizons (Figure 5-1). This may explain the relatively good correlation between organic matter and available phosphorus (Table 5-8). As discussed above, the variations in the levels of available phosphorus could to some extent be related to the amount of organic matter in the soil, thereby indicating that some of the available phosphorus probably originated from the decay of organic matter and release of organically-bound phosphorus. These results match those observed in earlier studies (Lee *et al.*, 1990; Cosmas, 2009). The analysis of variance in the data also revealed that the level of available phosphorus in horizon B in the unprotected site was significantly higher than those of the same horizon in the protected site. These differences can be explained by the fact that livestock grazing in the unprotected site add urine and faeces to the soil and that, consequently, phosphorus in solution will be translocated into the subsoil. The potential sources of phosphorus and other soil nutrients from livestock faeces and urine have been reported by various different authors who support the conclusions of livestock outputs as source of phosphorus in soils (Jusoff, 1988; Blackmore *et al.*, 1990; Zarekia *et al.*, 2012).

- **Gypsum content, carbonate and impeding horizon**

In this study a strong relationship was found between carbonates and gypsum accumulation and topographic positions in upper slope and summit positions in form of impeding cemented soil horizons (see result section 5.1.1). Such accumulations seem to cause a restriction in *A. tortilis* occurrence at summits and some slope positions. The soil profile descriptions also indicate that gypsum crystals and $CaCO_3$ coatings were found in subsurface layers at upper summit and slope positions which, in turn, provide an obvious indicator of the higher concentrations of those two elements (Figure 5-12). Some authors have speculated that hardpans or cemented layers form due to processes of accumulation, reprecipitation, under lower rainfall and hot arid climates in which virtually no leaching of the soil occurs (Bridges, 1997; Schaetzl and Anderson, 2005). In the current study in Qatar, cemented impeding horizons resulting from both accumulation of $CaCO_3$ to form petrocalcic horizons, and gypsum accumulation to form petrogypsic horizons are present on summit and many backslope sites. In both cases, this leads to the formation of an impenetrable layer. The petrogypsic horizons in study area I ranged from 7.9-25.8 % gypsum content in the backslope position and in the summit position from 33.8-71.6 gypsum content, in the form of cemented and fused crystalline masse (see Figure 5-5b and 5-12b). This finding corroborates the suggestions of Birkeland (1999) that, since some petrogypsic horizons can contain over 90% gypsum, at such high levels the original silicate grains are forced apart by gypsum crystallization. The impact of gypsum as an important factor that affect the distribution of vegetation and the composition of species has been discussed by several researchers (FAO, 1990 ; Escudero *et al.*, 2000; Abd El-Ghani and Amer, 2003; Kianian, 2012).

An idealized cross-section of a depression ecosystem in Qatar and its associated soil units/types is shown in Figure 5-13, which illustrates the main features of each topographic position and associated soil properties and types. The large gypsum or calcium carbonate contents on backslope and summit sites cannot be easily explained by the direct influence of current topographic position acting on soil forming processes. However, the absence of petrocalcic and petrogypsic horizons observed in depressions is more easily explained by erosion and deposition processes resulting in the movement of soil materials from the upper summit positions into the depressions to form colluvial deposits in which deeper, permeable, uncemented, but still calcareous, soils form. Soil erosion leads to the shallower soils at the summit and some backslope positions. This suggestion is in line with reports by other researchers this field (Yair, 1983; Yair, 1990; Gerrard, 1992). However, the presence of petrogypsic/petrocalcic horizons in summit areas still require explanation, because in other arid zones it is often the footslopes and toeslopes of depressions that contain soils cemented by calcium carbonate and/or gypsum due to accumulation of solutes from upslope (Birkeland 1999). Their anomalous existence in soils of landsurfaces on summits and upper backslopes could be attributed to "topographic inversion". This theory proposes that, over periods of thousands of years, cemented horizons that formed originally in topographic depressions have ended up as summits due to differential erosion processes. Such an inversion process accords with observations by El-Sayed (1994) in the southern part of Kuwait, which showed that calcrete (*n.b. equivalent to petrocalcic horizons*) formation was a much earlier process stimulated by climatic change during the Pleistocene. Moister climates, when calcium carbonate and/or gypsum would have accumulated in valleys and depressions, changed to drier and warmer climates when differential erosion by wind has resulted in relief inversion, leading to the formation of the present calcretic ridges.

In the current study, the lower concentrations of gypsum found under the *A. tortilis* canopy compared with soils of adjacent bare soil areas on backslope sites is most likely related to the preferential occurrence of tree growth on locally deeper soils and their avoidance of petrogypsic soils in these topographic positions, rather than any effect of the tree on soil properties. The absence of trees on adjacent summit sites suggests that shallow soils, cemented horizons and unfavourable soil moisture conditions dominate here and prevent tree survival.

Qatari soils are calsides and gypsiferous, typically of arid areas with less than 64 mm annual rainfall. A significantly high gypsum content in soil could interfere with plant growth as the soil particles in gypsiferous soils are weakly aggregated as the cohesive forces attracting single soil particles are very weak (FAO, 1990 ; Verheye and Boyadgiev, 1997). These results are consistent with those of other studies and suggest that gypsiferous soils contained low levels of nutrients and organic matter due to their chemical and physical properties (Eftekhari and Asadi, 2001). Similarly the chemical properties of gypsiferous soils are also unfavourable; but have not been fully understood (Verheye and Boyadgiev, 1997). However, because gypsum particles have no cation exchange capacity; the higher the gypsum content of the soil (the higher its corresponding EC) the lower its cation exchange capacity. According to Verheye and Boyadgiev (1997) the gypsum content in soils are usually categorized as: very low (0-2%); low (2-10%) and moderate (10-15%). However, plants vary widely in their tolerance to gypsum content in soil. It is important to highlight that the adverse effect of gypsiferous soil depends on its gypsum content and on the depth at which the gypsiferous layer occurs in the soil (Verheye and Boyadgiev, 1997). Nevertheless, the adverse effects of soils with less than 2% gypsum content can be neglected because all crops, including many of the most sensitive ones, can be grown without significant yield reduction (Verheye and Boyadgiev, 1997).

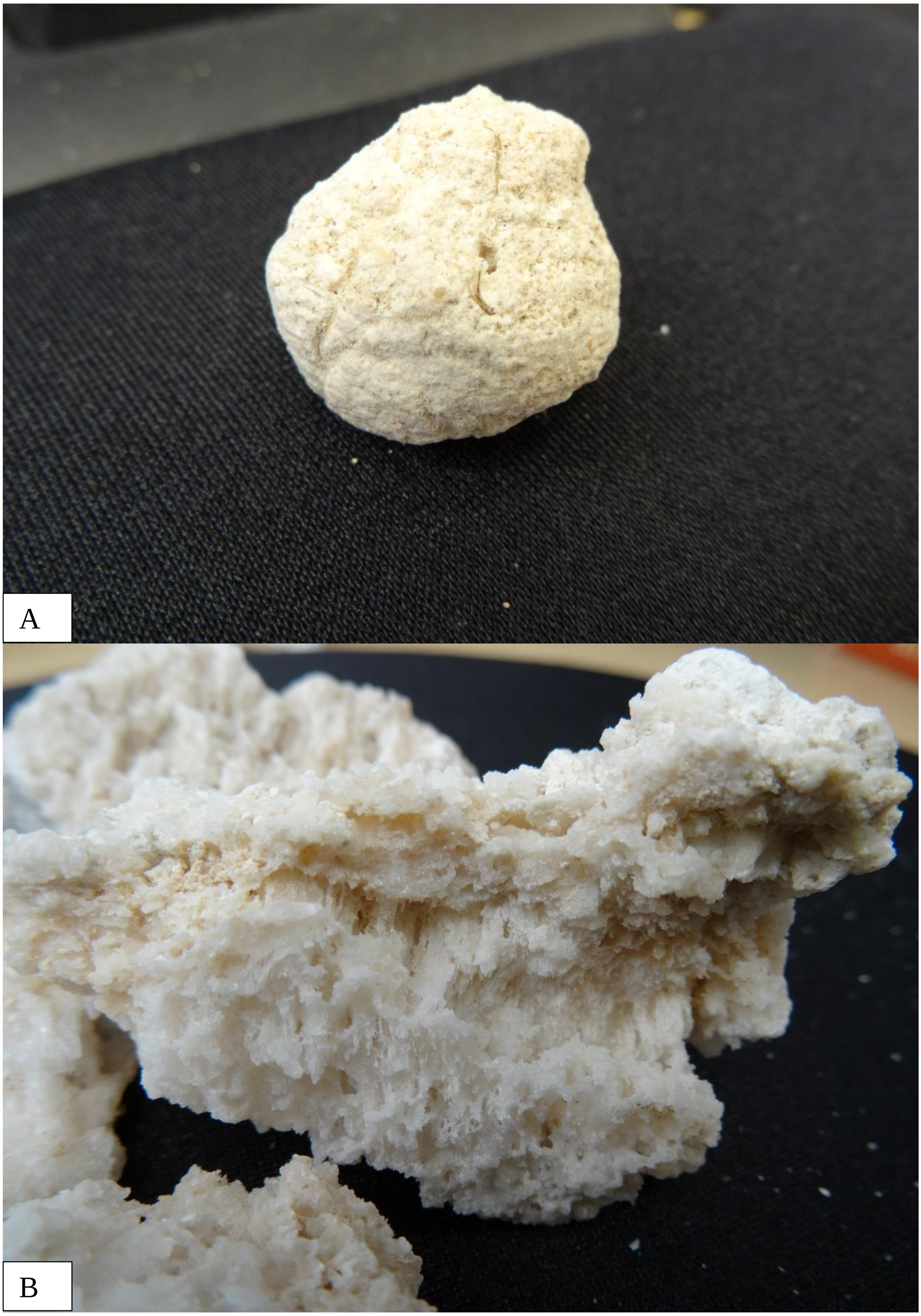


Figure 5-12: Calcium Carbonate Nodule (A) and a Cemented Mass of Gypsum Crystals (B) in B Horizons (petrocalcic & petrogypsic horizons) in the Summit Positions of the Study Area I.

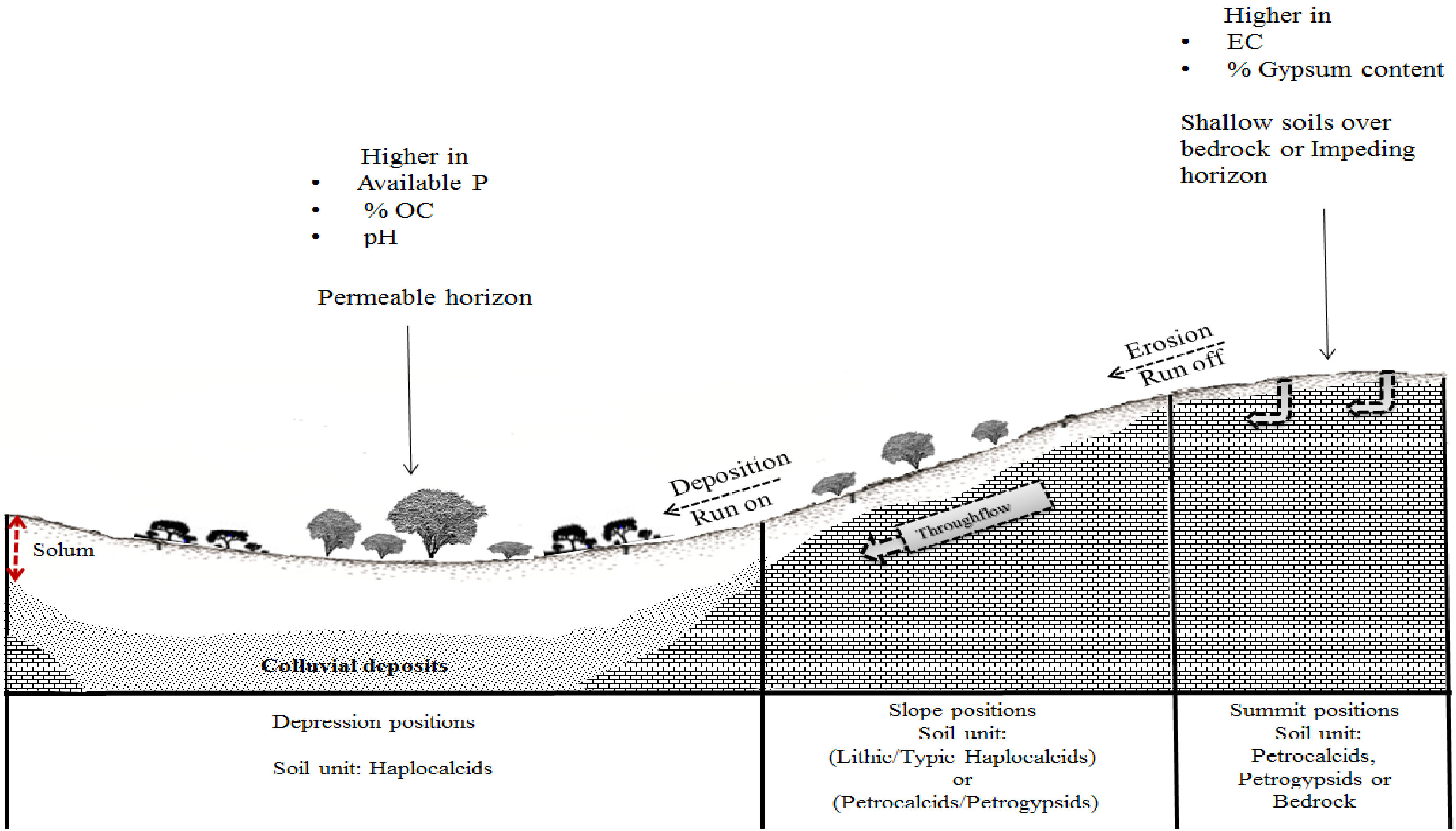


Figure 5-13: An Idealized Cross-Section of a Depression Ecosystem in Qatar and Associated Soil Units/Types.

Soil horizons with 25% or more gypsum content are morphologically characterized by the presence of an almost continuous gypsum accumulation and are considered unsuitable for most crops (FAO, 1990). This is because the roots of most plants cannot penetrate the gypsiferous layer formed in the soil (Chigani *et al.*, 2012). Chigani *et al.,* (2012) reported that an increased levels of gypsum in the lower soil horizons have led to hardpan formation, which in turn inhibits the penetration into the soil. Moreover, such hardpan formation also leads to an impenetrable layer of petrogypsic horizon.

❖ **Electrical conductivity (EC)**

Landscape position had a strong influence on electrical conductivity (EC) with the summit soils having significantly higher EC than slope and depression positions (Figure 5-1). These topographic trends in soil do not correspond to classic ideas about the movement of carbonate and salts into depressions (Powers *et al.*, 1998). It is worth mentioning here that these depressions have permeable soil horizons and that after any rainfall events the water in the depression positions, which may be temporarily ponded at the surface, does not remain for more than 1 or a maximum of 4 days (as shown in Figure 1-2). Therefore, the soil permeability of these colluvial depressions leads to the leaching of soluble salts from the soil profile, which explains in the observed lower values of EC in such positions. Other possible explanations for the lower EC in depressions compared to summit positions have been discussed by several researchers (Dregne, 1976 ; Schaetzl and Anderson, 2005). The higher EC recorded of summit or slope positions may be possibly due to higher evapotranspiration and precipitation in upper positions which are characterised by less vegetation cover and higher soluble salt concentrations, which in turn results greater EC. Alternatively, the parent material of limestone, which is high in calcium carbonate leads to such significant increases in EC at upper positions. This study was produced results which corroborate the findings of a great deal of the previous work in this field (Bridges, 1997; Schaetzl and Anderson, 2005; Hattar *et al.*, 2010; Kianian, 2014).

The results of this study did also show that electric conductivity significantly decreases in the soils under the tree canopy compared to adjacent bare soils. This result is not consistent with Abule *et al.*, (2005) findings, which showed that EC in the soils below tree canopies were higher than in corresponding open land. It is difficult to explain this, but it might be related to differences in topographic positions, where the upper position was found to be significantly higher in EC than the lower position.

Therefore, the higher EC values of bare soil samples from upper positions may have led to such effects.

The present analysis detected an increase in electrical conductivity in lower B horizons compared with A horizons, but as mean levels, even in B horizons, are <2.05 mS/cm (see Figure 5-1) most horizons would be classed as non-saline according to the USDA system. Only the B horizons of soils on summit areas are slightly saline with EC values of between 4.0-5.0 mS/cm, which is likely to be due to the leaching and accumulation of small amounts of soluble salts.

- **Soil water content (SWC)**

Soil water content differed significantly (P <0.01) across the different slope positions investigated. In most cases, a progressive increase was evident from summit to backslope and being greatest in depressions. This trend of increasing SWC in relation to topographic position is in agreement with similar results reported by other researchers in arid or semi-arid environments (Patten and Ellis, 1995; Van Wesemael *et al.*, 2000; Hattar *et al.*, 2010; Ziadat *et al.*, 2010; Ashghal, 2012).

Another important finding was that soil water content beneath the tree canopies was substantially higher than in soils in the adjacent bare soil areas. Higher topsoil moisture under woody canopies compared to treeless areas appears to be a common pattern in the rainy season and for some time afterwards (Boffa, 1999). The results of the current study are in agreement with those obtained by Akpo et al. (2005) and Abdallah and Chaieb (2012) who found that *A. tortilis* canopies produced significant changes in terms of decreasing solar radiation, air temperature and humidity in the understorey sub-habitat. Consequently, these factors may explain the higher SWC recorded in this study beneath the trees compared with corresponding bare soil. Likewise, the positive effect of shade is related to higher water availability as a result of decreased evaporation and increased efficiency of water use due to lower plant transpiration (Whitford, 2002).

There was no significant effect of tree density on pH, electric conductivity, levels of available phosphorus, gypsum content and organic carbon content. However, soil water content was significantly higher in densely wooded depressions compared to sparsely wooded depressions. This was contrary to expectations since depressions with more trees should transpire more water and the presence of trees speed up evapotranspiration. An explanation for this would be the fact that fog and dew is common in Qatar every day in certain seasons, and this was the case when this study was conducted. The condensation fog causing leaf drip could thus contribute to higher moisture in the dense depressions and can be significant for tree growth. The findings of other studies also show that during periods of drought the amount of water from dew or fog can exceed that from rainfall, and may even be the sole source of water for plants in arid environments (Willis, 1985; Jacobs *et al.*, 1999; Richards, 2004; Agam and Berliner, 2006). A study by Lekouch *et al.* (2011) reported that, during a one-year period the quantity of accumulated dew (18.9 mm, 178 events) corresponded to almost 40% of the yearly rain contribution (48.7 mm, 31 events) in the dryland area of south-western Morocco. In the desert of Oman, which is situated in a region similar to Qatar, Spalton (1999) reported that water content level was higher in the flower component due to fog and dew, which enabled some plants to continue to produce green leaves.

The study of soil horizons showed that soil water content was significantly higher in the B horizons than in the A horizons. This may be explained by the fact that Qatar soils are Aridisols, and is characterised as a very dry environment with high temperatures, which, in turn, leads soil water to migrate in an upward direction throughout evaporation. Therefore, soil water content tends to be higher in the lower horizon compared to the upper horizon, possibly for two main reasons. Firstly, given the sandy loam soil texture of study area I, rainwater or dew/fog was readily absorbed downwards thus also reducing the surface runoff, especially at lower positions. This accords with earlier observations by Zohary and Orshan (1956), who reported that in the desert sandy soil is one of the most favourable habitats for plants, due to the fact that it readily absorbs rainwater without allowing surface runoff. Secondly, when there are higher temperature differences between the surface and deeper horizons, there may be considerable movements of water in the form of vapour from warmer to cooler regions (Kramer and Boyer, 1995).

For each horizon A and B, a significant interaction between protection status tree densities was observed in influencing soil water content. For depressions with denser tree density in the unprotected site, soil water content was always significantly higher in depressions compared with both densely and sparsely depressions of the protected site. This could be explained by the high frequency of root in the protected site (see results in section 5.3.1) which will lead to higher uptake water through evapotranspiration. In accordance with the present results, a previous study by Ludwig *et al.* (2004)

demonstrated that root trenching led to increased soil water content under *Acacia tortilis* trees. They added that this meant that the trees took up more water from the topsoil than they lost. In other words, better water-use efficiency in the protected site with dense trees, which had an abundance of roots with common frequency (woody & fibrous nature), are expected to reduce soil water content compared to unprotected sites.

In each horizon A and B a significant interaction was also found between tree density and topographic position in influencing the soil water content. The GLM analysis indicated that depression position in the densely wooded depression for the horizon A and B, were significantly higher in soil water content than those of the similar position in sparsely wooded depression. In fact, the present results suggest that the depression position were the most favoured areas for most of the Qatari vegetation, including trees, shrubs and perennial plants. Therefore, the observed increase in SWC could be attributed to the effect of topographic position, which was found from field observations in the present study to govern the flow of water from upper to lower positions, resulting in higher moisture availability at lower positions. This has also been reported by other researchers (Ziadat *et al.*, 2010). In addition, there were greater declines in temperature under large, dense canopies than under small, light and erect tree crowns. This, in turn, would imply lower soil evaporation as well as increased soil humidity (Boffa, 1999; Akpo *et al.*, 2005). The increased soil water content in the depression position with dense tree cover in this study corroborates the ideas of earlier researchers (Boffa, 1999; Raz-Yaseef *et al.*, 2010).

- **Soil depth**

Soil depth varied significantly among the three topographic positions. The deeper soils were encountered in depressions at the bottom of slopes compared to the backslopes and summits. This indicates that soil depth tends to increase across the toposequence from upper positions to lower slope positions. A possible explanation for these differences is likely to be the transportation of eroded material from upper slope positions to depression areas. These results are consistent with those of other studies and demonstrate that, over time, the effects of topography and geomorphology become increasingly important to soil development, especially further down the slope (Schaetzl and Anderson, 2005). Therefore, the deposition of sediment predominates and the accumulation of mineral material by wind or water on the surface of soil, can occur on lower slopes (Schaetzl and Anderson, 2005; Maniyunda and Gwari, 2014). Another important finding was that the depth of soil was significantly deeper in depressions with dense *Acacia* trees compared to those with sparse tree cover. This may simply mean that *Acacia* trees favour depressions characterised by deeper soils. However, it might also be related to the interception of wind-blown material or sediment by the *Acacia tortilis* and other tree species in the dense depressions, leading to a reduction in wind speed. Therefore, a denser depression over the long-term more of coarse textured material that carried by wind is deposited in, which in turn leads to an increase in the soil depth. This explanation corroborates the ideas of Kainkwa and Stigter (1994), who investigated wind speed patterns in Tanzania, along lines parallel to the wind flow into woodland made up of scattered trees, which were mostly *Acacia tortilis* and a few other species. They found that wind speeds decreased approximately linearly further into the woodland until becoming almost constant. Earlier observations by Batanouny (1981) showed that the *Acacia tortilis* community in Qatar dominates and abounds in depressions where the deposits mainly consist of sandy wind-blown material.

Statistical analysis showed that soil depth under the *Acacia tortilis* was significantly higher than in adjacent bare soil. Also, significant interactions between topographic position*tree densities were observed in influencing the depth of soil, but these factors are less important.

5.2 The Effects of Protection Status, Tree Density, Topographic Position on Morphological Characteristics and Population of the *Acacia tortilis*

5.2.1 Morphological characteristics

Statistical analysis of the effects of protection status, tree density, position and their interactions on morphological characteristics of the *Acacia tortilis* was assessed using General Linear Model. The results have shown that all morphological characteristics were affected significantly by position while crown diameter, crown area and number of branches were significantly affected by site as well. Density had no significant influence on the morphological characteristics except in case of the number of branches. There were no significant interactions except the effect of site and position interaction on the branch number as shown in Table 5-1.

Table 5-1: Effects of The Protection Status, Tree Density, Topographic Positions and their Interactions on the Morphological Characteristics of the *Acacia tortilis* at the Study Area I (Tree Height, Crown Diameter, Crown Area, Branches No. and Diameter at Stem Base, [n= 78].

Source of variance	**ANOVA (probability values)**				
	Tree height (m)	**Crown diameter** (m)	**Crown area** m^2 $tree^{-1}$	**Branches No.**	**DSB** (cm)
Protection status	0.001^{***}	0.001^{***}	0.001^{***}	0.001^{***}	0.403^{NS}
Tree density	0.706^{NS}	0.089^{NS}	0.053^{NS}	0.009^{**}	0.917^{NS}
Topographic positions	0.001^{***}	0.001^{***}	0.001^{***}	0.006^{**}	0.001^{***}
Protection status *Tree density	0.902^{NS}	0.081^{NS}	0.080^{NS}	0.157^{NS}	0.689^{NS}
Protection status * Topography	0.818^{NS}	0.434^{NS}	0.587^{NS}	0.006^{**}	0.285^{NS}
Tree Density*Topography	0.866^{NS}	0.640^{NS}	0.514^{NS}	0.419^{NS}	0.915^{NS}
Protection status *Tree density* Topography	0.581^{NS}	0.227^{NS}	0.202^{NS}	0.919^{NS}	0.624^{NS}

Significantly different at P < 0.05 (*), P < 0.01 (**), or P < 0.001 (***); NS non-significant

Tree height

Effect of protection status (protected and unprotected) and topographic position (slope and depression) on the height of *Acacia tortilis* was highly significant ($P < 0.05$). Mean height of trees was significantly greater in the protected sites as compared to unprotected sites. Similarly, heights of trees growing in depression positions were significantly greater than then those positioned on slopes in both sites. On an overall basis, trees growing in the protected sites were 20% taller compared to trees at unprotected sites while trees growing at depression were 80% taller than those present on slopes (Figure 5-14).

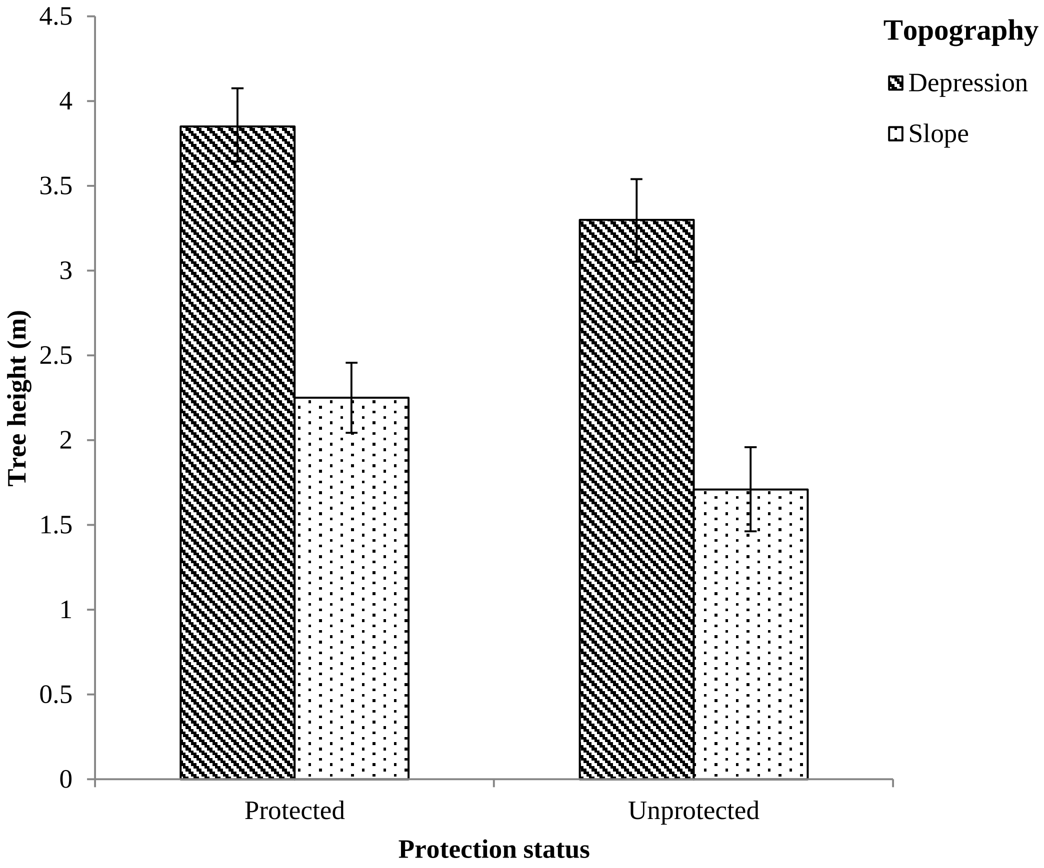


Figure 5-14: Effect of Protection Status and Topographic Position on the Height of *Acacia tortilis.*

Crown area

Similar to tree height, protection status and slope position had significant effects over crown area (Figure 5-15; $P < 0.05$). On average, trees growing in protected sites had significantly larger crown area than those growing in the unprotected sites. The difference between the two was more than 1.43 fold. Similarly, trees in depression positions had significantly larger crown areas as compared to trees in slope positions; the difference in crown areas between the two positions was more than 1.36 folds.

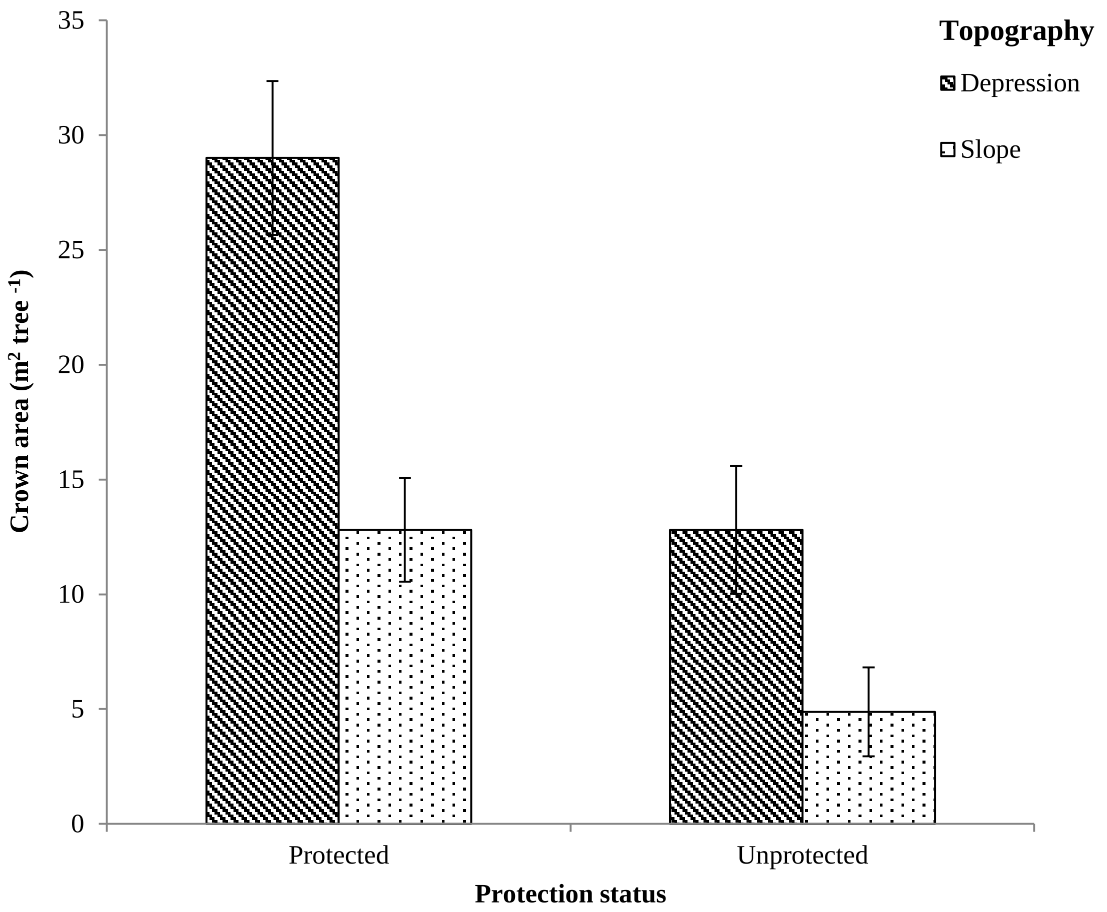


Figure 5-15: Affect of Site (protection status) and Topographic Position on *Acacia tortilis* Crown Area (m^2 $tree^{-1}$).

Crown diameter and directions

Summary statistics for crown diameter directions (North-South and East-West) have been presented in Table 5-2. Although the difference in crown diameters between both directions was not significant statically, on average, crown diameter was somewhat larger in N-S direction as compared to E-W direction. However, crown diameters were significantly larger in the trees growing at protected sites as compared to the ones growing at unprotected sites. A similar trend can be seen from trees growing at depressions compared to trees positioned at slopes and summit areas as shown in Figure 5-16.

Table 5-2: Effect of Protection Status and Topographic Positions on Mean Crown Diameter in Two Directions. ±SE Mean (Between Brackets)

Protection status	Topographic Position	N-S Direction(m)	E-W Direction (m)	Mean
Protected	Depression	6.20 (± 0.418)	5.50 (± 0.319)	5.85 (± 0.30)
	Slope	3.88 (± 0.385)	3.71 (± 0.321)	3.79 (± 0.28)
Unprotected	Depression	3.42 (± 0.529)	3.35 (± 0.47)	3.39 (± 0.35)
	Slope	1.94 (± 0.364)	1.99 (± 0.42)	1.965 (± 0.27)
	Mean	4.08 (±0.279)	3.82 (±0.237)	

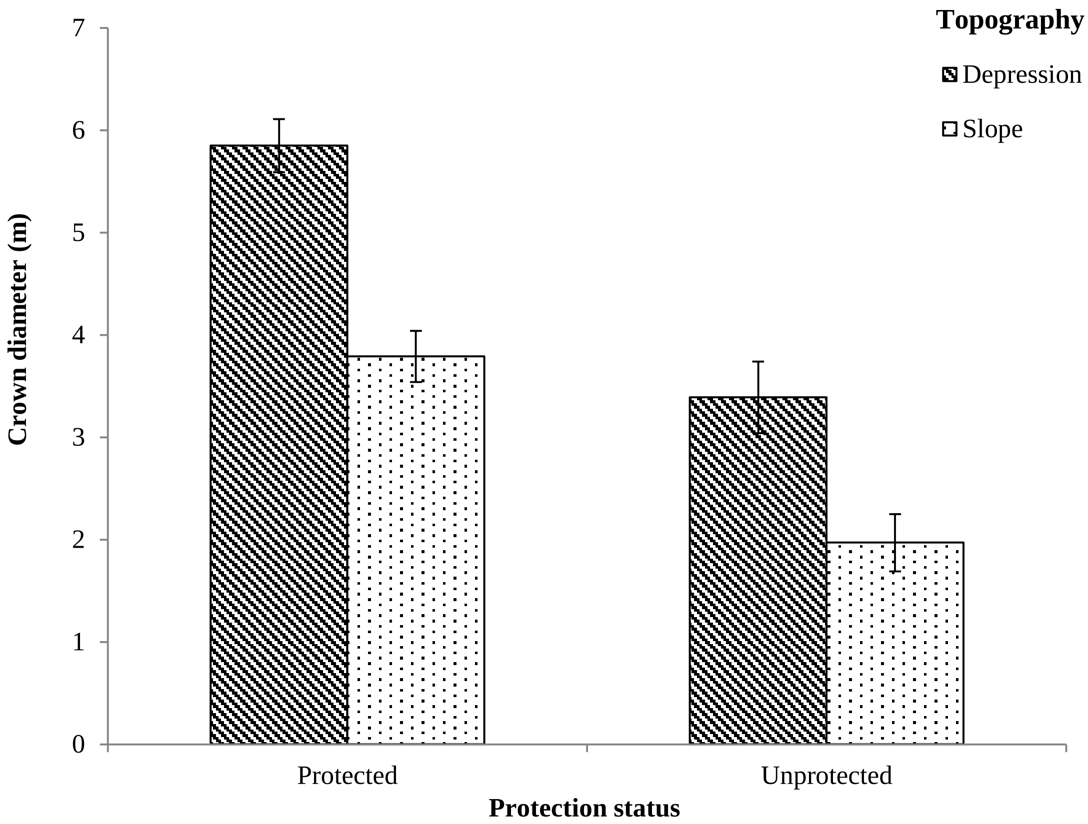


Figure 5-16: Effect of Protection Status and Slope Position on *Acacia* Crown Diameter (m).

Number of branches

Effects of site, density, position and the interaction between site and position on number of branches were found to be significant ($P<0.05$).The mean number of branches per tree at the protected site was significantly higher than that at the unprotected site with the difference being more than two fold. Similarly, the mean number of branches per tree in depressions exceeded that of the slopes by more than 50% as shown in Table 4. However, at the unprotected site, the average number of branches per tree was similar for both positions (see Table 5-3 and Figure 5-17). Number of branches per tree in the dense tree areas was 43% higher than the average numbers reported from sparse density areas.

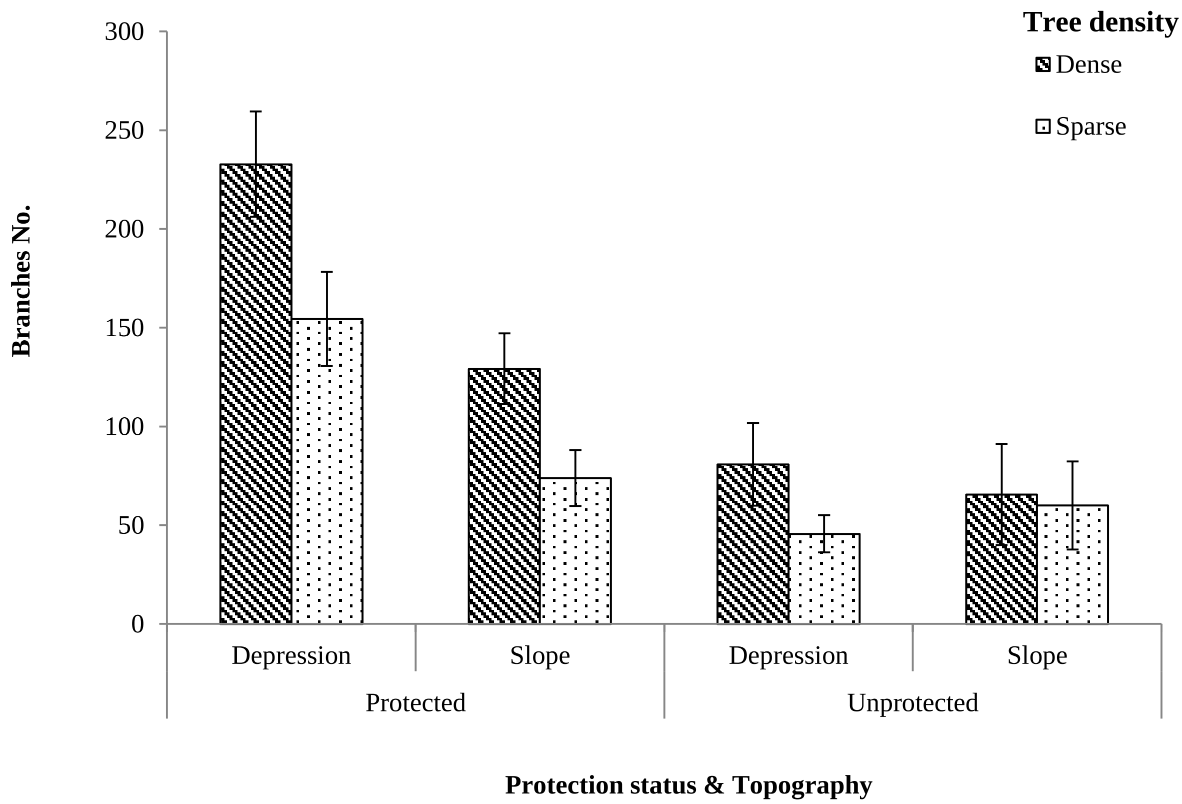


Figure 5-17*:* Effect of Protection status and Topographic Positions on Number of Secondary Branches of *Acacia tortilis*. Bars ±SE standard error of mean.

Table 5-3: Effect of Protection Status and Topographic Positions on Number of Branches ±SEM.

	Depression	**Slope**	**Mean**
Protected	193.6 ±19.3 *a*	108.8±13.3 *b*	156.1±13.9 A
Unprotected	64.1 ±12.3 *bc*	63.4±17.5 *c*	63.8 ±10.3 B
Mean	136.4±15.5 a	88.1±11.4 b	

Means which are followed by the same letter from the suite of either lower case (a, b,c), italic (a,b) or capital (A,B) are not significantly different according to Tuky's test (P<0.05).

Diameter at stem base (DSB)

There was no significant difference in mean DSB of *Acacia* at protected and unprotected sites. However, as shown in Table 5-4, average diameter at stem base was significantly larger in depression than slope positions (P<0.05). This trend was consistent in both protected and unprotected sites as shown in Table 5-4.

Table 5-4: Effect of the Topographic Position of Trees and Protection Status on the Diameter at Stem Base (DSB) of *Acacia tortilis*. ±SEM standard error of mean

	Depression	**Slope**	**Mean**
Protected	24.45 (±1.82)	14.71 (±1.25)	20.15 (±1.37) A
Unprotected	20.86 (±1.81)	15.12 (±2.21)	18.24 (±1.47) A
Mean	22.86 (±1.31) a	14.9 (±1.20) b	

Means which are followed by the same letter from the suite of either lower case (a, b,c), or capital (A, B) are not significantly different according to Tuky's test (P<0.05)

5.2.2 Population parameters

Tree density

Density was calculated from the total number of *Acacia tortilis* trees within each 20 m^2 section along transects. Variation of tree density between the protected and unprotected sites was not significant statistically; however, variations between dense and sparse areas as well as between depression and backslope positions were highly significant. Density in the dense tree area was twice the density in the sparse tree areas; a similar ratio was found between densities at depression and slope positions as shown in Figure 5-18 and Table 5- 5.

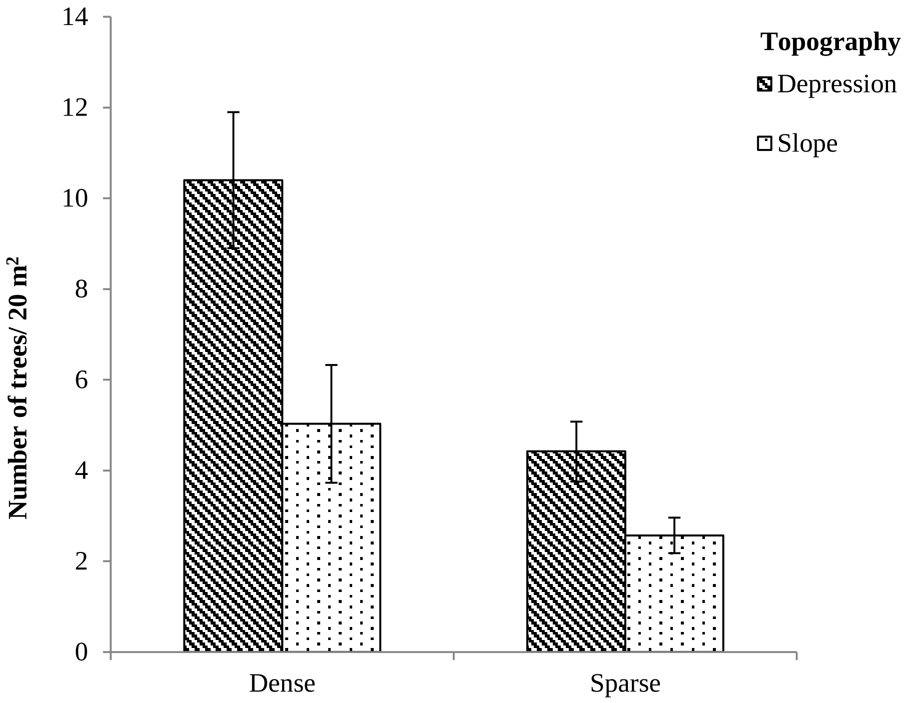


Figure 5-18: Effect of Depression and Slope Positions on Tree Density in Dense and Sparse.

Bars ±SE standard error of mean.

Table 5-5 : Effect of Topographic Position on *Acacia tortilis* Density (±SEM standard error of mean).

	Dense	**Sparse**	**Mean**
Depression	10.4 (±1.5)	4.42(0.66)	7.92(±1.13)
Slope	5.03(±1.3)	2.57(±0.39)	3.41(±0.41)
Mean	7.91(±1.1)	3.79(±0.72)	

Frequency

Effects of protection status of the site, tree density, topographic position and their interactions on the frequency (total No. of individuals of species/total No. of quadrats of occurence) of *Acacia tortilis* were statistically non-significant. However, tree frequency at unprotected site exceeded that of protected site by 7.6% i.e. 57.26 compared to 53.22, respectively. On the other hand, tree frequency in sparse tree areas was lower than dense tree areas by 11% i.e. 51.66 as compared to 58.06, respectively. The difference in tree frequency between depression and slope positions was very minor i.e. approximately 2% higher in depression as compared to slope.

5.2.3 Proportion of browsing, cutting and leaf coverage

The proportion of browsing, cutting and leaf coverage were determined between protection status, topographic positions and tree density with following results:

- Association between browsing and site: Chi-square goodness of fit test was used to determine whether or not the extent of browsing (i.e. no browse, some browse and completely browsed) differed significantly across the protected and unprotected sites. As expected, there was very strong association between extent of browsing and the type of site (χ^2= 78.000, df = 2, P<0.001). As shown in Figure 5-19a, the percentage of non-browsed trees was higher in the protected site; while all *Acacia* trees in the unprotected site were either browsed partially (72%) or completely (28%).

- Association between cutting and site: Proportion of cutting (no cutting, some cutting and whole branches) followed the same trend as of the extent of browsing between the studied sites. Trends for cutting were significantly different in the protected area and the unprotected area. (χ^2= 74.049, df = 2, P< 0.001) as shown in Figure 5-19b. No cutting was detected in the protected site whereas more than 90% of the sampled trees in the unprotected site had some cutting.

- Association between leaf coverage and protection status: Differences in the leave coverage categorised as no leaves, partial leaf coverage and full leaf coverage were highly significant between the protected and unprotected sites (χ^2= 40.640, df = 2, P< 0.001) as shown in Figure 5-19c. Number of *Acacia* trees with full leaf coverage was higher in the protected site i.e. 70% as compared to only 7% in the unprotected site. The number of trees with no leaf coverage was higher in the unprotected site than the protected site, whilst a slightly higher number of trees had partial coverage at the unprotected site.

- Association between proportion of browsing and position: There was no significant difference between the browsing and position (depression and slope) on the *Acacia tortilis* (χ^2= 1.416, df = 2, P< 0.493). As shown in Figure 5-19d, the browsing percentages were similar on the depressions and slopes.

- Association between proportion of cutting and position: Despite the higher number of trees with 'some cutting' in depressions as compared to slope sites, the differences between the position and cutting rate were statistically not significant (χ^2= 1.284, df = 2, P< 0.526) as shown in Figure 5-19e. The results have also shown that the *Acacia* trees with cutting of whole branches were mainly located in the backslope positions compared to depression.

- Association between leaf coverage and position: A highly significant association existed between leaf coverage and position of trees (χ^2= 16.133, df = 2, P< 0.001) as shown in Figure 5-19f. The percentage of the trees with full coverage was higher in the depression i.e. 55.8% as compared to 22.9% at slope position. Trees with partial coverage were higher in the slope position i.e. 62.9% as compared to trees in the depression position i.e. 18.6%.

- The relationship between browsing, cutting and coverage and tree density: Type of density (dense/sparse) and different rates of browsing (χ^2= 1.687, df = 2, P< 0.430), cutting (χ^2= 0.853, df = 2, P< 0.653) and leaf coverage (χ^2= 0.993, df = 2, P< 0.6.9) showed no significant association as shown in Figure 5-20a, 5-20b and 5-20c, respectively.

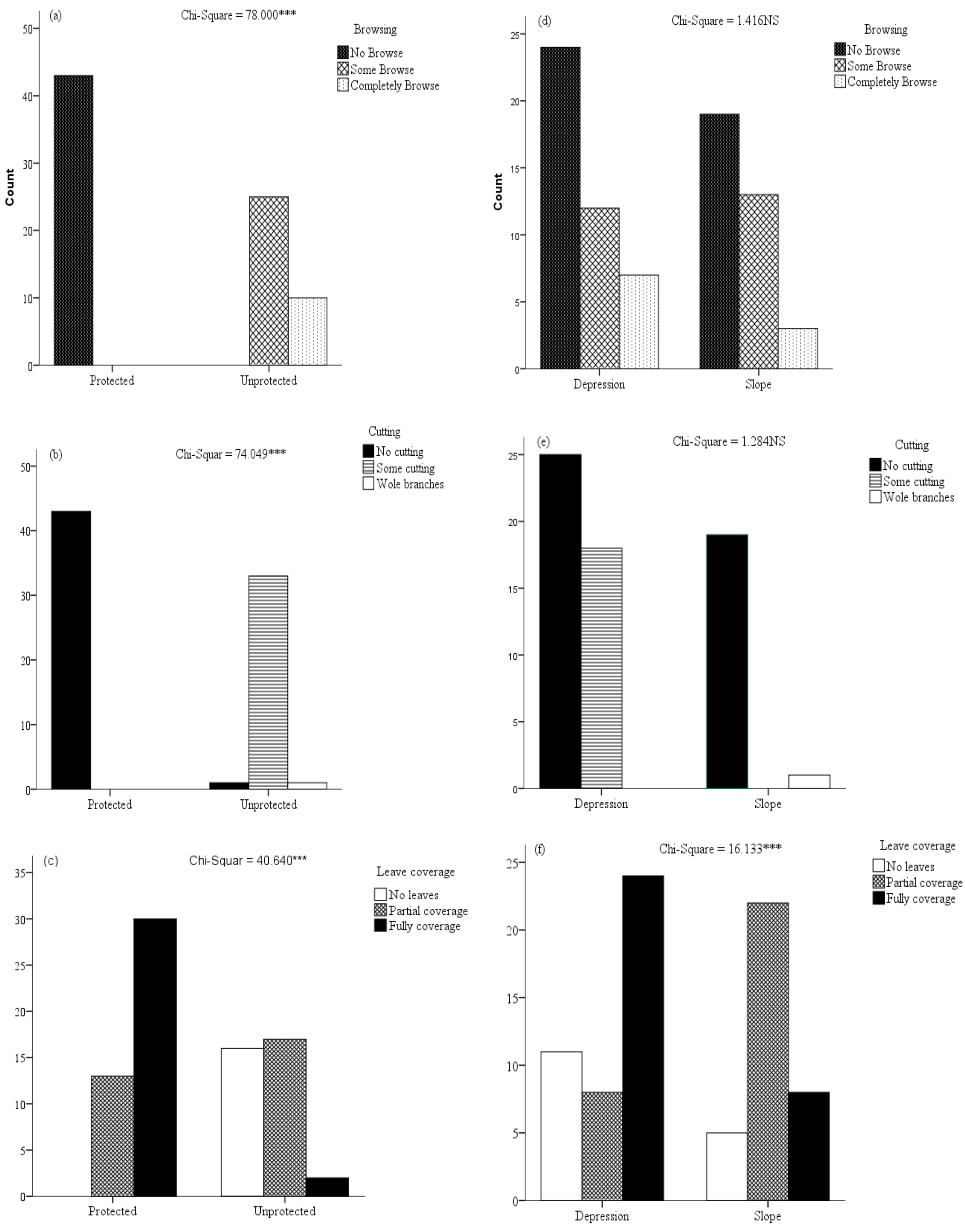


Figure 5-19: Proportion of Browsing, Cutting and Leaf Coverage of the *Acacia tortilis* in the Study Site I, Count is Observed Frequencies in Sample for The Main Effect of Protection Status (a, b and c) and Topographic Position (d, e and f).

Chi-Square significance at P < 0.05 (*), P < 0.01(**), P < 0.001 (***) and NS (non-significant).

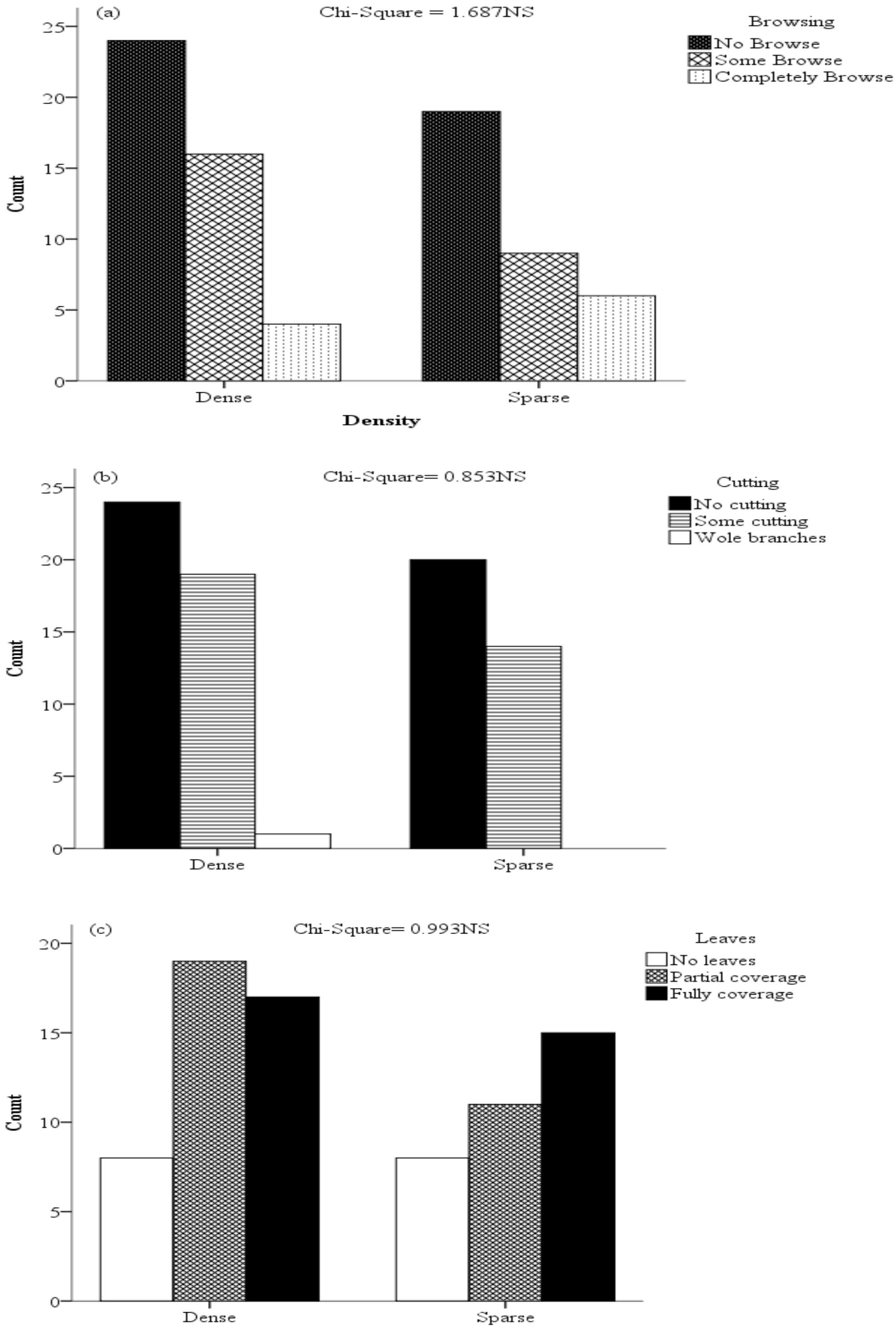


Figure 5-20: Proportion of Browsing, Cutting and Leave Coverage of the *Acacia tortilis* in the Study Area I, Count is Observed Frequencies in Sample for the Main Effect of Tree Density.

Chi-Square significance at P < 0.05 (*), P < 0.01(**), P < 0.001 (***) and NS (non-significant).

5.2.4 Correlation analysis between *Acacia tortilis* morphological characteristics and human impacts of browsing and cutting

The correlation between human impacts (i.e. browsing and cutting) and *Acacia tortilis* morphological parameters (branches No., TH, CA, CD and DBH) was tested. In general, most of the study localities in the unprotected site showed massive signs of human interference including cutting for different purposes as well as overgrazing by herds (mainly camels and goats). On the other hand, as expected, absence of cutting and browsing was recognized at the protected site. The results of the correlational analysis are set out in Table 5-6.

There were a significant positive correlation between browsing and cutting intensity (r = 0.993, $P < 0.01$). Browsing has negative correlation with *Acacia* branches No. (r = -0.584), crown area (r = -0.526) and crown diameter (r = -0.527). However, no significant correlation was founded between browsing and tree height (r = -0.191) and diameter at breast height (r = - 0.082). Similar trends were observed between cutting and vegetation parameters of *Acacia* tree.

Table 5-6: Spearman Correlation Coefficients among the Five *Acacia tortilis* Morphological Characteristics and Human Impacts (i.e. Browsing and Cutting). Correlation Values Larger than 0.30 are Printed in Bold.

	Browsing	**Cutting**
Browsing	1.000	
Cutting	**.993****	1.000
Branches No	**-.584****	**-.544****
TH	-.191^{NS}	-.186^{NS}
CA	**-.526****	**-.469****
CD	**-.527****	**-.470****
DBH	-.082^{NS}	-.056^{NS}

Notes: *Morphological variables Branches No., Tree Height m, Crown Area m^2 $tree^{-1}$, Crown Diameter m and Diameter at breast height cm; * Correlations are significant at p < 0.05 (two-tailed); **correlations are significant at p < 0.01 (two-tailed); NS non-significant. [n=78].*

5.2.5 Discussion

This study set out with the aim of assessing the importance of the environmental and anthropogenic factors affecting the growth, condition and distribution of *Acacia tortilis.* Generally, the life-form of plants provide information which may aid in assessing responses to different environmental factors in diverse habitats (Ayyad and El-Ghareeh, 1982). Hultine and Marshall (2000) and Qiang *et al.* (2003) indicated that the morphological and physiological properties of most woody plants are affected by different abiotic factors, in particular at different elevations on a slope. The current study improves the general understanding of the factors explaining the occurrence and growth of *A. tortilis* populations in Qatar. In terms of topographic position, impacts on the *A. tortilis* population and its characteristics, and morphological or dendrometric parameters such as diameter at breast height, tree height, density, crown area and canopy diameter; significant differences have been detected in study area I, between different topographical positions. Therefore, it is apparent that levels of protection and topographic position have considerable effects on tree performance. This section focuses on potential effect of the protection status and type of management and topographic position on the morphological and dendrometric characteristics of *Acacia* trees, whereas the combined influence of the environmental variables of protection status, topographic position and soil attributes on tree characteristics are discussed in detail later in this chapter.

The analysis of protection status has focussed on evaluation of impact of browsing on the structure and condition of *A. tortilis*. The results show that browsing by livestock significantly decreases canopy area and diameter, number of branches and tree height in unprotected sites. These findings are in agreement with the study by Abdallah *et al.* (2012), who surveyed the *Acacia tortilis* cover and species richness in protected and unprotected areas in southern Tunisia. The authors reported that these parameters correlated well with type of management. Similar findings by Noumi *et al.* (2010) indicated that tree density, canopy cover and canopy diameter in an *A. tortilis* population were affected by browsing. In the present study, a trend has been found of degradation in the morphological characteristics of trees with an increase in cutting and browsing in *A. tortilis* woodland in depressions in unprotected areas (Table 5-6). Damage from cutting and browsing occurred mostly in the forms of the breaking of branches and the stripping of tree bark (Figure 5-21). Observations on the ground proved that *A. tortilis* species had the most damage to trees compared to *Ziziphus* *mauritiana*, *Prosopis spp* or *Lycium shawii* trees or shrubs. Increased human impact from, for example, cutting/browsing on the *A. tortilis* in this study corroborate earlier findings (Nge'the and Box, 1976; Al-Sodany *et al.*, 2011; Abd el-wahab *et al.*, 2013). This human impact on the *Acacia* trees has at least two explanations. Firstly, the high crude protein content of *Acacia* makes it a good source of feed for livestock in such an arid environment (Du Toit, 1990; Al-Easa *et al.*, 2003; Rubanza *et al.*, 2007). Secondly, *Acacia* is harvested for fire wood and safari tours by local people (personal observation). Other impacts on *Acacia* of human activities, such as cutting for medicine, charcoal production and firewood, have been reported by various authors (Batanouny, 1981; Hines and Eckman, 1993; Abulfatih *et al.*, 2001; Andersen and Krzywinski, 2007b; Abd el-wahab *et al.*, 2013; Seleem *et al.*, 2013).

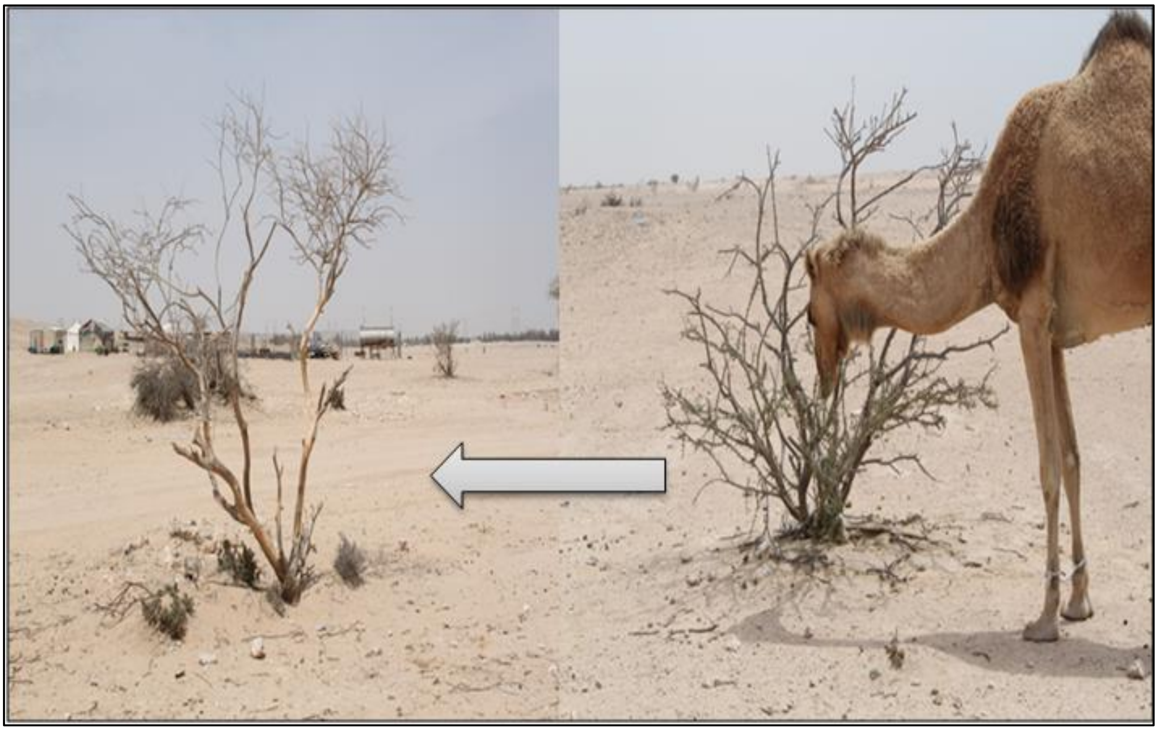


Figure 5-21: Example of the Effect of Camel Grazing on the *Acacia tortilis* Tree in an Unprotected Site [November, 2013].

It is interesting to note that tree density showed no significant difference between the protected and unprotected samples, and this is can be explained by a low regeneration rate within the protected area compared with the unprotected area (Chapter 6). On the other hand, anthropogenic activities did influence the morphological characteristics and populations of the tree, especially in the unprotected site which had more small-sized individuals in this disturbed land. This finding is in agreement with results from the studies of Noumi *et al.* (2010) and Dangerfield *et al.* (1996). Finally, generalizing these results to other sites where data are unavailable may be possible. However, further study is also needed at other sites in order to determine the trends of browsing and cutting of *Acacia* trees within unprotected sites in Qatar.

5.3 Acacia *tortilis* roots and depth to water table level

5.3.1 *Acacia tortilis* roots

Acacia tortilis roots were frequently found under the tree canopies within the top 50 cm of soil sampled at depression and slope positions, as shown in Figure 5-22. From a total of 78 points, roots were recorded from 63 tree samples. The results related to the size, nature and abundance of roots have been described below:

- Abundance of roots based on their number in an area of 10 cm^2 were few in 84% of cases and common in 16% of cases in the samples taken at unprotected site. However, in samples derived from the protected site, roots were common in of 68% cases and few in 32%.

- The nature of the roots was similar in the protected and unprotected sites with fibrous roots in 48% of sampled soils followed by woody roots in 30% and fibrous plus woody roots in 22% samples.

- In terms of roots size, about 71% were fine (i.e. diameter 1mm-2mm) followed by 24% coarse (i.e. diameter >5mm) and 5% were very fine roots (i.e. diameter <1mm).

Figure 5-22: Picture of *Acacia tortilis* Roots within the Soil Profile.

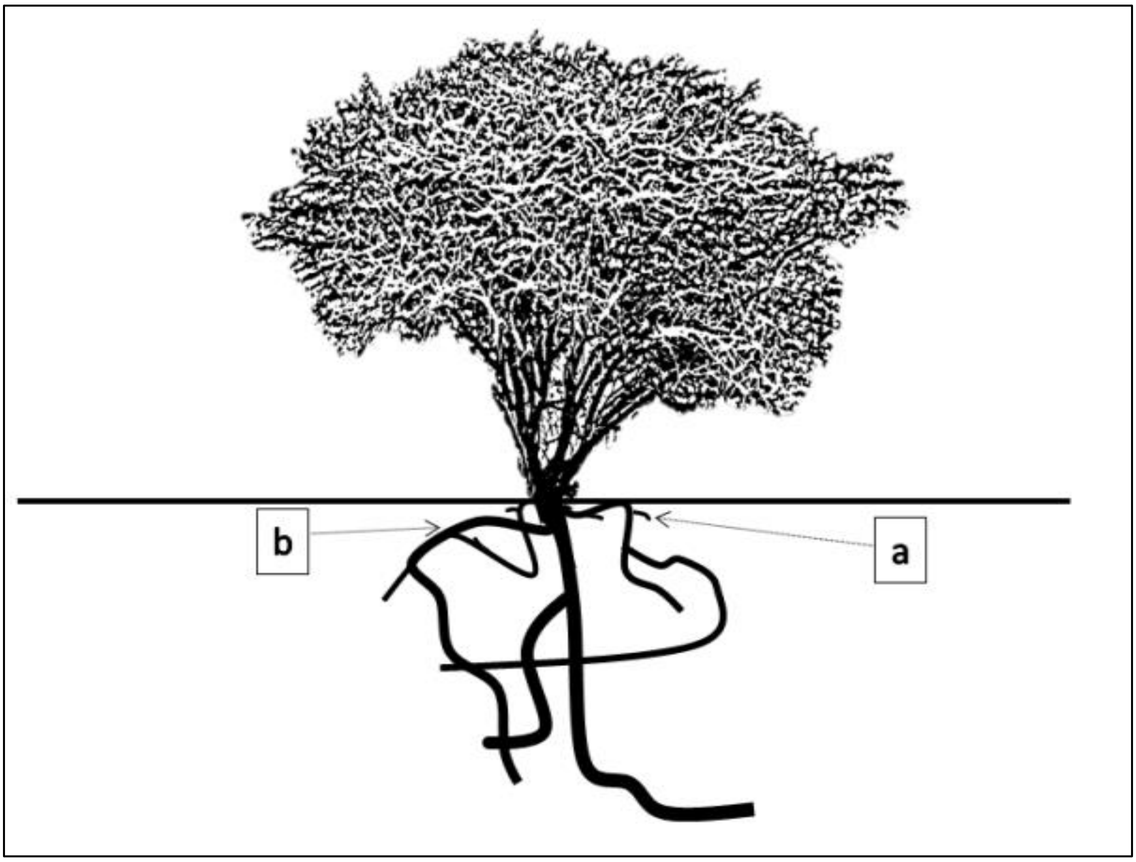


Figure 5-23: *Acacia tortilis* Root System Based on Field Observations. (a) is Recently Developed Fine Root, (b) Woody Root with Contorted Shape.

Based on the root characteristics described above, a typical tree in study site I had woody contorted roots as well as newly developed fine roots in the top soil horizons as shown in Figure 5-23.

5.3.2 Depth to water table level

In order to assess the depth between ground surface and water table level, data of underground water acquired from Public Works Authority (Ashghal) and Ministry of Environment were used to calculate how far the depth of water table level as a source of water from each sampled *Acacia tortilis* tree at study area I. Figure 5-25 presents the produced map including both protected and unprotected areas. From the data in Figure 5-24 and Table 5-7, it is apparent that the water table was deeper at the unprotected site. For majority of sampled trees, i.e. 85% of total, depth to underground water table ranged from 20 and 30m while another 9% the distance ranged between 30 and 35m, as shown in Table 5-7.

Table 5-7: Distance to Underground Water Table for *Acacia tortilis* Trees in Study Area I (n=78).

Ground water depth (m)	Protected	Unprotected	total
< 20	0	0	0
20-25	16	1	17
25-30	27	22	49
30-35	0	7	7
>35	0	5	5

The statistical analysis showed that mean depth to underground water table level was significantly less at the protected site as compared to unprotected sites i.e. 25.49 m compared to 29.34 m, respectively ($P < 0.05$). Effect of landscape position in the unprotected site was not significant but mean distance values for slope positions were slightly higher than depression positions i.e. 27.8m compared to 26.74m, respectively (Figure 5-24). Differences in distance to underground water from tree density areas (dense or sparse tree areas) were not significant and neither were those from different protection status sites nor topographic positions.

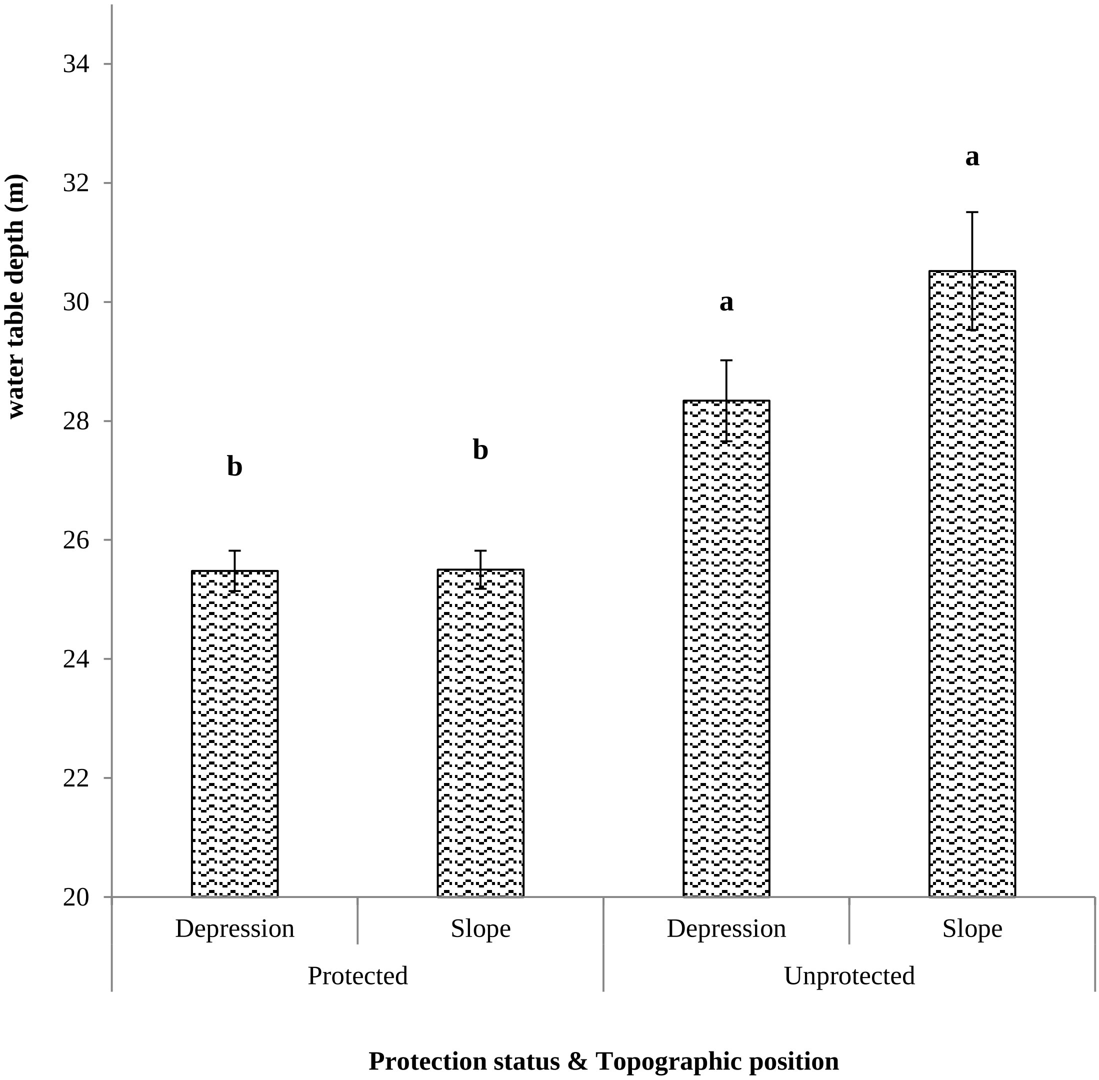


Figure 5-24: Mean Distance to Underground Water Table: Between Sites (Protected and Unprotected) and Positions (Depression and Slope).

Statistical significant ($p<0.05$) determined by Tukey's HSD-test; ±SEM standard error of mean.

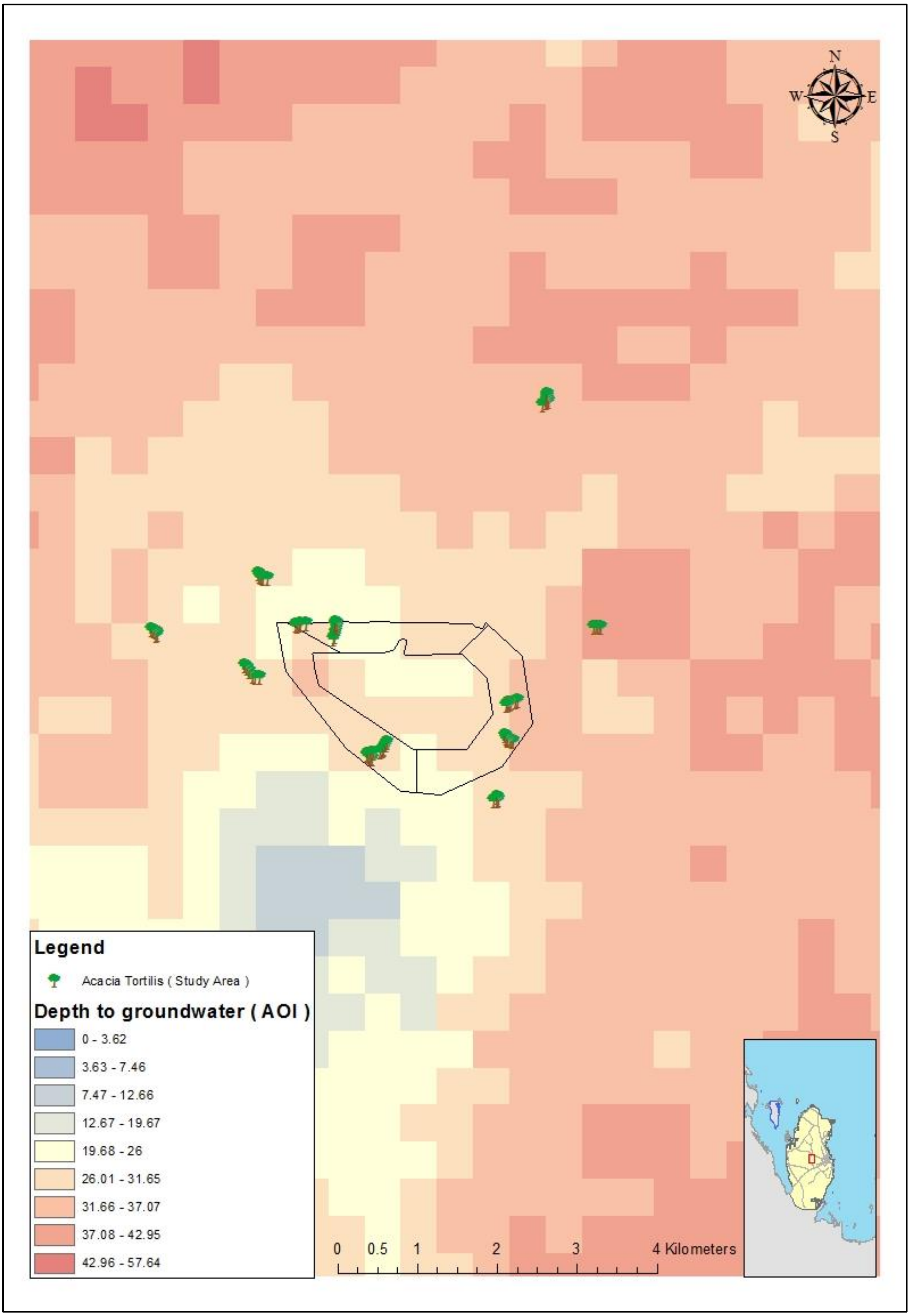


Figure 5-25: Map of Depth to Water Table level at Study Site I. Trees within the Black Line is Located inside the Protected Site.

5.3.3 Discussion

The root systems of *Acacia tortilis* tree are either long taproots or lateral roots which are one of the main characteristics that enable it to draw on groundwater to utilize the more stable available soil moisture. Such roots located within shallow soil layers can also rapidly access water soon after rainfall (Cole and Brown, 1976; Deans *et al.*, 2005; Otieno *et al.*, 2005; Do *et al.*, 2008). In this respect, this allows the tree to survive and meet their water requirements in water-limited environments throughout the year. Hence, one of the questions in this research was to determine the level of the underground water table in study area I as well as to highlight size, nature and abundance of lateral roots for each sample of trees.

The results of this study have shown that 71% of fine roots were found within the top 50cm of soil. These findings may explain the ability of the *A. tortilis* to utilize the limited soil moisture available either after rains or from drops of dew/fog on the shallow surface soil thanks to the lateral root system. In accordance with the present results, previous studies have demonstrated that *Acacia* has dense roots close to the soil surface which rapidly utilize any precipitation, and hence rapidly "greens up" in response to even small amounts of rain (Barkham and Rainy, 1976; Otieno *et al.*, 2005). There are similarities between the characteristics exhibited by roots located within the shallow soil layers in this study and those described by Cole and Brown (1976) in Botswana, Otieno *et al.* (2005) in Kenya and Deans *et al.* (2005) in northern Senegal. In this study the patterns of fine roots observed corroborate the findings of previous research (Mordelet *et al.*, 1997; Deans *et al.*, 2005; Otieno *et al.*, 2005). The fibrous nature of the *A. tortilis* roots found in the current study are consistent with the findings of Singh (2004) that in the soil layer between 0-30 cm, *A. tortilis* had more fibrous roots in the hot arid regions of Indian deserts.

Another important finding was that the roots of *Acacia tortilis* have a highly contorted form, as shown in Figure 5-23. Some authors have interpreted this as the feature that enables the tree to draw soil moisture from a large area (Cole and Brown, 1976; Canadell *et al.*, 1996). The structure and architecture of roots are important determinants of root distribution (Mordelet *et al.*, 1997), which highlights the need for more studies on root-root and root-water interactions. Such findings may confirm the association between root architecture within the soil profile with an increase in the ability to draw in more water. Previous research in this area has reported that individual

Acacia tortilis trees in Tanzania may use the hydraulic lift process to bring water to an area of more than 300 m^2 each night (Ludwig *et al.*, 2003). In a subsequent paper, Ludwig *et al.* (2004) found that root trenching led to increased soil water content under *A. tortilis* trees. This meant that the trees extracted significant amounts of water from the topsoil.

Generally, rooting depth increases with aridity (Batanouny and Abdel wahab, 1973; Canadell *et al.*, 1996). In this study, it was found that 94% of the sampled trees were found in the range between 20 and 35 metre to the water table level. These results may explain the relatively good correlation between *A. tortilis* tap-rooting and depth to ground water (see Table 5-10). They confirm that the trees should be able to access the water table. This outcome is in agreement with the findings of Do *et al.* (2008) that living root fragments of *A. tortilis* were scouted to the level of the water table in Sahelian Africa. These observed root down to the water table at from 20m to 35m depth match those observed in earlier studies (Cole and Brown, 1976; Ong and Leakey, 1999; Schroth and Lehmann, 2003; Deans *et al.*, 2005; Do *et al.*, 2008).

5.4 Correlation and Multivariate Analysis between the Morphological Characteristics of *Acacia tortilis* and Environmental Variables in the Study Area I.

The Pearson correlation analysis between different *Acacia* tree morphological characteristics and selected soil properties is presented in Table 5-8. Data from this table indicated that there were strong positive correlations between tree height, crown area, crown diameter and diameter at breast height (P <0.01). This means that it is possible to use one of these measures as an index of tree size.

In addition, tree morphological characteristics showed a positive correlation with organic carbon percent, available phosphorus in horizon A & B, soil pH in horizon A & B, volumetric water content in horizon A & B and soil depth. However, negative correlations were obtained with electric conductivity at horizon A & B as well as with gypsum content (%). No significant correlation found between branch number and crown area with gypsum content (%).

All tree parameters found to be strongly positive correlated with organic carbon (%), whilst, available phosphorus in horizon B, volumetric water content in horizon B and soil depth were strongly correlated with tree height, diameter at breast height and crown diameter. This could suggest a causal relationship between any of these soil attributes and the measured *Acacia* morphological characteristics. However, this needs careful and critical consideration, as feedback effects of the trees on soil properties such as organic carbon and available P are likely, and soil water and soil depth will certainly affect tree growth and biomass production.

Available phosphorus in horizon A & B and soil pH in horizon A & B were found to be positively correlated with volumetric water content in horizon in A & B and soil depth. On the other hand, electric conductivity in horizon A & B and gypsum content (%) showed a negative correlation with all measured soil properties. No significant correlation appears between percentage of gypsum content and soil pH in both horizons or with soil depth.

There is a very strong correlation between volumetric water content in horizon B and the soil depth ($r = .818$, $n=222$, $P < 0.01$). Likewise, very strong positive correlation found between VWC in horizon A and VWC in horizon B ($r = .804$, $n=222$, $P < 0.01$). on the other hand, available phosphorus in horizon A & B, soil pH in horizon A & B, VWC in horizon A & B and soil depth showed a negative correlation with the electric conductivity in horizon A & B and gypsum content (%).

Table 5-8: Pearson's Correlation Coefficients between Morphological and Environmental Variables in the Study Area I. [See explanatory notes on next page]

	Branch No.	TH	CA	CD	DBH	OC (%)	Available P$_{A}$	Available P$_{B}$	pH$_{A}$	pH$_{B}$	EC$_{A}$	EC$_{B}$	Gypsum (%)	VWC$_{A}$	VWC$_{B}$
TH	**.825****														
CA	**.816****	**.847****													
CD	**.866****	**.927****	**.948****												
DBH	**.823****	**.950****	**.805****	**.892****											
OC (%)	**.612****	**.712****	**.622****	**.689****	**.651****										
Available P$_{A}$	**.418****	**.525****	.379**	**.478****	**.547****	**.548****									
Available P$_{B}$	**.569****	**.762****	**.546****	**.676****	**.763****	**.648****	**.555****								
pH$_{A}$	.289**	.385**	.309**	.377**	.375**	**.402****	.330**	**.409****							
pH$_{B}$	.172*	.238**	.228**	.220**	.215**	.298**	.216**	.253**	.334**						
EC$_{A}$	**-.426****	**-.555****	**-.429****	**-.510****	**-.549****	**-.596****	**-.512****	**-.638****	**-.632****	**-.435****					
EC$_{B}$	-.387**	**-.481****	-.381**	**-.453****	**-.475****	**-.529****	**-.500****	**-.571****	**-.573****	**-.481****	**.821****				
$^{\Diamond}$Gypsum (%)	-.118	-.147*	-.114	-.137*	-.138*	-.133*	-.174**	-.181**	-.116	-.024	.246**	.213**			
VWC$_{A}$	.312**	**.496****	.349**	**.432****	**.450****	**.412****	**.468****	**.534****	.322**	.337**	**-.562****	**-.570****	-.160*		
VWC$_{B}$	**.554****	**.643****	**.542****	**.602****	**.608****	**.549****	**.479****	**.605****	.353**	**.405****	**-.602****	**-.592****	-.148*	**.804****	
Soil depth	**.531****	**.663****	**.514****	**.675****	**.609****	**.571****	.391**	**.621****	.370**	.320**	**-.548****	**-.546****	-.131	**.658****	**.818****

Notes: *Environmental variables:% Organic carbon, Available phosphorus µg/ml (Horizon A&B), pH (Horizon A&B), Electric conductivity mS/cm (Horizon A&B), %Gypsum, Volumetric water content* m^3 m^{-3} *(Horizon A&B) and Soil depth cm; Morphological variables Branches No., Tree Height m, Crown Area* m^2 $tree^{-1}$*, Crown Diameter m and Diameter at Stem Base cm; * Correlations are significant at* $p < 0.05$ *(two-tailed); **correlations are significant at* $p < 0.01$ *(two-tailed); NS non-significant. [n=222]. ◊ Gypsum soil samples [n= 40] and were excluded from the PCA and regression analysis.*

5.4.1 Principal Components and multiple regression analysis

A principal component analysis was performed on the 11 environmental variables to evaluate the influence of these selected variables on *Acacia* tree morphology under study site I, after checking that the data was suitable for principal component analysis by looking at some assumptions.

A KMO measure of sampling adequacy of 0.899 and a Bartlett's Test of Sphericity that was significant P =0.001 (<0.05) indicating that principal component analysis was suited.

In the PCA, only those components where the eigenvalue was greater than one were considered (Norman and Streiner, 2000). The observed variables, factor loadings, commonalities, derived variables and variance explained for the retained components are presented in Table 5-9. Three components had an eigenvalues greater than 1 and collectively explained 73.95% of the covariation in the original eleven environmental variables. In examining the varimax rotated component matrix, 3 dimensions emerged with 4 variables substantially loaded on component 1, 4 variables substantially loaded on component 2 and 3 variables substantially loaded on component 3. This data analysis shows, the 11 environmental variables and variances explained are *depth to water table level (DWT), available phosphorus in horizon B, organic carbon percent and available phosphorus in horizon A* (56% component 1), *electric conductivity in horizon A&B, soil pH in horizon A&B* (9% component 2) and *volumetric water content in horizon A&B and soil depth* (8.5% component 3).

All eleven environmental variables were included in the three selected PCs as can be seen in Table 5-9. However, only certain variables showed high loadings within each PC, such as the first PC was heavily loaded on DWT, available phosphorus in horizon

B, %OC and available phosphorus in horizon A, and the second PC was heavily loaded with electric conductivity in horizon B, soil pH in horizon A&B and electric conductivity in horizon A. Similarly, PC 3 was loaded heavily with VWC in horizon B&A and soil depth.

Table 5-9: Components with Observed Variables, Factor Loadings, Commonalities, Derived Variables and Variance Explained.

Observed variables statements	Factor loading	Communality	Derived variable	Variance (%)
		Component 1		
DWT	0.854	0.810		
Available P $_B$	0.786	0.796	PC1	56.24
Organic carbon %	0.709	0.657		
Available P $_A$	0.676	0.549		
		Component 2		
EC_B	-0.739	0.812		
pH_A	0.711	0.640	PC2	9.204
pH_B	0.706	0.654		
EC_A	-0.698	0.826		
		Component 3		
VWC_B	0.849	0.904		
VWC_A	0.806	0.786	PC3	8.512
Soil depth	0.777	0.789		

5.4.2 Multiple regression analysis

To ultimately determine the important environmental gradients that influence on the different *Acacia tortilis* morphological parameters; component score coefficients (eigenvectors) were then multiplied to obtain PC score values. The results of the regression analysis are shown in Table 5-10. In regression analysis PC1, PC2, PC3, protection status and topographic positions were found to have significant ($P < 0.001$) linear relationship with all tested *Acacia* tree morphological characteristics (tree height, DSB, crown diameter, branches No. and crown area). The score values, protection status and topographic positions were used as independent variables in the stepwise multiple linear regression analysis to evaluate the influence on *Acacia tortilis* morphological characteristics.

As can be seen in Table 5-10, the three PCs (i.e. PC 1, PC 2 and PC 3), protection status and topographic position could explain 74.7% of the variation in *Acacia tortilis* tree height. All independent variables were significant; however PC 1 and PC 3 were found to be the most significant independent variables in the regression analysis as the standardized beta coefficients values are the highest and the second highest for these two PCs. Both PCs had positive impact on the tree height whilst protection status had a negative impact (Table 5-10). In other words, PC1 and PC3 have a positive relationship with tree height would suggest that as soil nutrient content increases (e.g. available phosphorus and organic carbon), tree height increases. Therefore, a total increase in significant variables of PC1 and PC3, namely DWT, available P_B, organic carbon % and available P_A (PC1) as well as volumetric water content in horizon A & B and soil depth (PC3) would lead to increase in the tree height. On the other hand, the direction and relationships (negative coefficients) would indicate that tree height would influenced by the protection status. The developed model can be written as:

TH = 0.543 + 1.277 (PC1) + 0.478 (PC2) + 0.880 (PC3) – 0.383(Protection status) + 0.575 (Topographic position)

Table 5-10: Multiple Regression Models between *Acacia tortilis* Morphological Parameters (tree Height, Crown Diameter, Diameter at Stem Base, Branches No. and Crown Area), Protection Status, Topographic Positions and Composite Environmental Factors from PCA (df = 5).

Coefficients							
Dependent variable	**Model**	**Unstandardized Coefficients**		**Standardized Coefficients**	**t**	**Sig.**	**R-square**
		B	**Std. Error**	**Beta**			
Tree height	(Constant)	.543	.264		2.058	.041	**74.7%**
	PC1	1.277	.061	**.806**	21.047	.000	
	PC2	.478	.077	.302	6.194	.000	
	PC3	.880	.070	**.556**	12.497	.000	
	Protection Status	-.383	.108	-.121	-3.535	.000	
	Topographic Position	.575	.122	.279	4.709	.000	
Crown diameter	(Constant)	1.201	.444		2.705	.007	**66.5%**
	PC1	1.755	.102	**.759**	17.201	.000	
	PC2	.780	.130	.337	6.012	.000	
	PC3	1.202	.118	**.520**	10.148	.000	
	Protection Status	-1.028	.182	-.223	-5.652	.000	
	Topographic Position	.948	.205	.315	4.619	.000	
DSB	(Constant)	2.159	1.873		1.153	.250	**71.6%**
	PC1	8.736	.431	**.824**	20.285	.000	
	PC2	3.252	.547	.307	5.940	.000	
	PC3	5.309	.500	**.501**	10.623	.000	
	Protection Status	-1.768	.768	-.083	-2.301	.022	
	Topographic Position	4.007	.866	.291	4.625	.000	
Branches No.	(Constant)	52.161	17.522		2.977	.003	**52.6%**
	PC1	50.371	4.029	**.656**	12.503	.000	
	PC2	19.638	5.122	.256	3.834	.000	
	PC3	35.237	4.675	**.459**	7.537	.000	
	Protection Status	-39.636	7.184	-.259	-5.517	.000	
	Topographic Position	25.954	8.104	.260	3.203	.002	
Crown area	(Constant)	7.967	2.896		2.751	.006	**45.6%**
	PC1	6.831	.666	**.576**	10.257	.000	
	PC2	3.222	.847	.272	3.805	.000	
	PC3	5.412	.773	**.457**	7.003	.000	
	Protection Status	-5.654	1.188	-.239	-4.761	.000	
	Topographic Position	3.356	1.340	.218	2.505	.013	

Similarly, the three PCs, protection status and topographic position could explain 71.6% and 66.5% of the variation in *Acacia tortilis* tree diameter at breast height and crown diameter, respectively. PC 1 and PC 3 were also found to be the most significant independent variables in both regression analyses as the standardized beta coefficients values are the highest and the second highest for these two PCs & other independents, respectively. Moreover, both PCs had positive impact on the tree diameter at stem base and crown diameter, respectively.

Meanwhile, the absence of protection had a negative impact on DSB and crown diameter as their coefficient were negative (Table 5-10). The developed model can be written as:

DSB = 2.159 + 8.736 (PC1) + 03.252 (PC2) + 5.309 (PC3) – 1.768 (Protection status) + 4.007 (Topographic position) And

CD = 1.201 + 1.755 (PC1) + 0.780 (PC2) + 1.202 (PC3) – 1.028 (Protection status) + 0.948 (Topographic position)

The branch number and crown area found to have significant ($P < 0.001$) prediction model; however, these models could only explain 52.6 and 45.6 % of the variation in the branches No. and CA, respectively. As previously PC1 and PC3 were also found to be the most significant independent variables in both regression analyses as the standardized beta coefficients values are the highest and the second highest for these two PCs. The effect of protection status had also negatively impact on those two dependant variables (branches number and crown area) as their coefficients were negative (Table 5-10). The developed model can be written as:

Branches No. = 52.16 + 50.371 (PC1) + 19.638 (PC2) + 35.237 (PC3) – 39.636 (Protection status) + 25.954 (Topographic position)

And

CA = 7.967 + 6.831 (PC1) + 3.222 (PC2) + 5.412 (PC3) – 5.654 (Protection status) + 3.356 (Topographic position)

5.4.3 Discussion

The present analysis was designed to evaluate the influence of different environmental gradients on the morphological characteristics of *Acacia tortilis*. The univariate and multivariate statistical modelling techniques did show that attributes such as depth to water table level, available phosphorus, percentage of organic carbon, volumetric water content and soil depth are important factors influencing *Acacia tortilis* morphological characteristics (Tables 5-8 and 5-10). Undoubtedly, soil is a key environmental factor for plant growth and development, which is largely dependent on the combination and concentration of mineral nutrients and water available in the soil (Roca-Pérez *et al.*, 2004). The results indicate that increased phosphorus available in the soil, organic carbon, water content in the top soil and/or groundwater and soil depth all lead to higher tree height, branch number, DSB and crown area and diameter of *Acacia tortilis*. For instance, phosphorus is invariably categorised as one of the macronutrients which is most vital for plant growth and development (Black, 1968; Yuan and Liu, 2008). Through its direct influence in plant metabolism as a carrier of energy, its availability is a major factor limiting plant growth (Black, 1968; Rendig and Taylor, 1989). Generally, it is well known that soil factors such as those mentioned above play key roles in plant growth and development (see Chapter 7).

The present results have also shown a strong effect of protection status and topographic positions influences on *Acacia* tree morphology in study area I (Table 5-10). The multiple regression models reveal that protection status has a negative relationship with the morphological characteristics of *Acacia* trees, which might be due to the absence of protection leading to decreases in the trees morphological parameters and damage to the structure. The findings are consistent with those of Abdallah *et al.* (2012) and Noumi *et al.* (2010) in Tunisia who found that type of management and protection affected the structure and cover of *A. tortilis*.

The growth of *A. tortilis* was found to vary greatly with spatial topographic variations. As shown in Table 5-10, the model detected that tree height, DSB, branch number and crown diameter and area were significantly influenced by topographic position. *Acacia* trees are larger in lower positions such as depressions and smaller in stature higher up on slopes, which is in agreement with an early study of Batanouny (1981). This also accords with the observations earlier reported in section 5.2.1. PC_1 and PC_3, were found to be the most significant independent variables in the regression analysis. A possible explanation for the greater growth at lower positions is the presence of an adequate water supply, access to groundwater resources unrestricted by cemented layer, and soil attributes such as greater available phosphorus, organic carbon and soil depth. This finding corroborates the ideas of Andersen and Krzywinski (2007a), who suggested that the growth of *A. tortilis* seems to vary greatly not only temporally but also spatially, suggesting that the landscape heterogeneity is of much greater importance in harsh desert environments.

In this respect, an intimate relationship exists between *Acacia* growth and the spatial heterogeneity of the geomorphology of the area, through the influence of topography on plant-available soil water and soil attributes (Table 5-10). More specifically, these more moist sites are topographically controlled, being restricted to depressions and footslope microenvironments where runoff water collects and provides sufficient moisture and nutrients for *Acacia* growth. In addition, groundwater is within *Acacia tortilis* potential rooting depths and access is unrestricted by cemented petrogypsic or petrocalcic horizons in these landscape positions. This study has produced results which corroborate the findings of a great deal of the previous work in this field (Kennenni, 1991; Patten and Ellis, 1995; Hegazy *et al.*, 1998; Abd El-Ghani and Amer, 2003; Schaetzl and Anderson, 2005).

CHAPTER 6: STUDY OF ACACIA TORTILIS REGENERATION

Introduction

The steep population decline of *Acacia tortilis* is becoming pronounced in arid and semi-arid regions such as Qatar as a result of the combination of several environmental and anthropogenic factors (Labidi *et al.*, 2007; Abdelrahman and Krzywinski, 2008; Abd el-wahab *et al.*, 2013); which have been extensively discussed in the literature review of this research. Hence, the natural regeneration of the *Acacia tortilis* has been the focus of several studies since the species holds a preferential place in agroforestry and land afforestation systems due to its high resiliency to drought and grazing (Diouf and Grouzis, 1996; Moustafa and Mansour, 2003; Traoré *et al.*, 2012). Besides the importance of *Acacia tortilis* to ecological conservationism and improving of soil nutrient availability, it also offers other economic values making it an invaluable plant species that warrants protection against extinction (Kennenni and Maarel, 1990; Argaw *et al.*, 1999; Lahav-Ginott *et al.*, 2001; Stave *et al.*, 2001; Noumi *et al.*, 2010). Therefore, this chapter is dedicated to the study of the regeneration of *Acacia tortilis* in the study area which comprises of three sites. As explained in the methodology, the regeneration of *Acacia tortilis* was assessed in site I, which is the main study area comprising of both protected and unprotected areas for comparison purpose. Although site I entails a more comprehensive study of *Acacia tortilis*, the discussion presented in this chapter will be confined only to its regeneration. In addition, northern site II and southern site III were selected exclusively for the study of regeneration of *Acacia tortilis*. In general, the impact of both biotic (i.e. anthropogenic and animal activities) and abiotic environmental factors on the regeneration of *Acacia tortilis* in these sites were assessed. Comparison of the extent of regeneration of *Acacia tortilis* between the protected and unprotected areas of site I will provide insight on the impact of anthropogenic and animals activities on the regeneration this important plant. Though abiotic environmental factors has been found to have a major effect on the distribution and performance of plant species (Traoré *et al.*, 2012), it will be necessary to investigate the influence of these factors on the regeneration of the *Acacia* trees in hyper-arid environment such as Qatar.

6.1.1 Distribution of seedlings/saplings relative to the established canopies of *Acacia tortilis* at study area I.

While no saplings were found under the *Acacia* tree canopies in the protected area, the establishment of *Acacia tortilis* saplings under the mature sampled trees was observed in the unprotected site. In other words, the regeneration of *Acacia tortilis* under mature tree canopies only occurred in the unprotected area of site I. Moreover, topographic variation between positions also shows more saplings in depressions compared with slope positions (Figure 6-1). It is important to emphasize that no mature *Acacia* tree or sapling was found in the summit, so the summit landform is not considered further. Furthermore, the preponderance of zeroes (i.e. indication of absence of saplings) along the various positions of the protected and unprotected areas pose difficulty in presenting the results statistically as exampled in Figure 6-1, which shows the distribution of seedlings/saplings that were established under the *Acacia* tree canopies at the unprotected area.

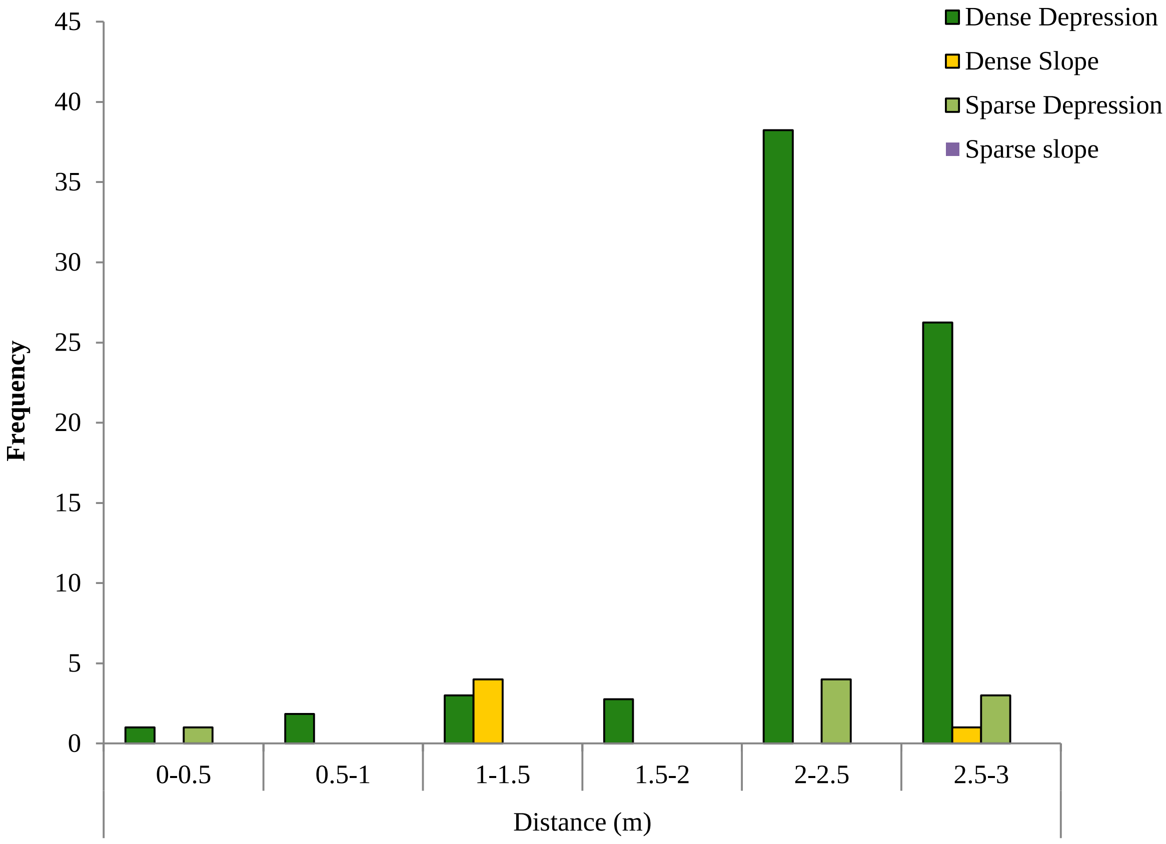


Figure 6-1: Distribution of Seedlings/Saplings Relative to the Established Canopies of *Acacia tortilis*, at the Unprotected Site of the Study Area I. The Distance is Relative to the Position of the Seedling with Respect to the Bole (0m) and Outer Edge of the Canopy (3m).

The results show that depressions with dense acacia cover witnessed a higher frequency of seedlings compare with the sparse depressions. Meanwhile, the seedlings under *Acacia* tree canopies at slope position showed lower establishment, except at dense slope in the distance of 1–1.5 m from the tree bole where the number of saplings in the slope position was slightly higher than for the depression at comparable distances (Figure 6-1). In general, the frequency of seedlings established under canopies of *Acacia tortilis* increases further away from the tree bole position. Obviously, this general trend holds more for the depression position in which the lowest frequency of the established seedlings/saplings occurred at a distance of 0 – 0.5m away from the bole of the *Acacia* tree. Further away from the bole of the *Acacia* tree with the distance of 2 – 2.5m, the highest frequency of the established seedlings/saplings was recorded. As shown in Figure 6-1, the establishment of the seedlings was observed to be declining beyond 2.5m from the bole of the *Acacia* tree. There were no seedlings/saplings on sparse slope position as indicated in Figure 6-1.

6.1.2 The rate of regeneration of *Acacia tortilis*

A multifaceted approach of studying the rate of regeneration of *Acacia tortilis* was undertaken to enable the comparison of this natural process under different environments. As described in the methodology, the assessment of the regeneration rates was based on the area covered by the *Acacia* saplings (or young *Acacia* trees that were less than 60 cm) along the transect sections (20 × 20 m) stratified by the different protection status areas, topographical positions (i.e. depression, slope, summit) and tree densities (dense / sparse). Therefore, the regeneration rate of *Acacia tortilis* has been expressed in percent cover of *Acacia* saplings and categorized as none, below 50%, above 50% and 100% cover of *Acacia* saplings.

The photographs in Figures 6-2A and 6-2B show the difference in the rate of regeneration between the protected and unprotected area. In this case, the regeneration of *Acacia tortilis* sapling in the depression position of the unprotected site can be clearly seen (Figure 6-2A). In contrast, the dried *Acacia* seed pods with no saplings indicate the absence of successful regeneration in the protected area (Figure 6-2B). Nevertheless, it is important to ascertain if the rate of *Acacia* regeneration is significantly different between the protected and unprotected areas of site I. Since the data for the regeneration of *Acacia* seedlings/saplings are ordinal, Chi-Square test has been used to test the significance in differences of the regeneration rate of the *Acacia* seedlings/saplings between the sites (protected/unprotected), topographical positions (depression, slope and summit) and *Acacia* tree density (dense/sparse).

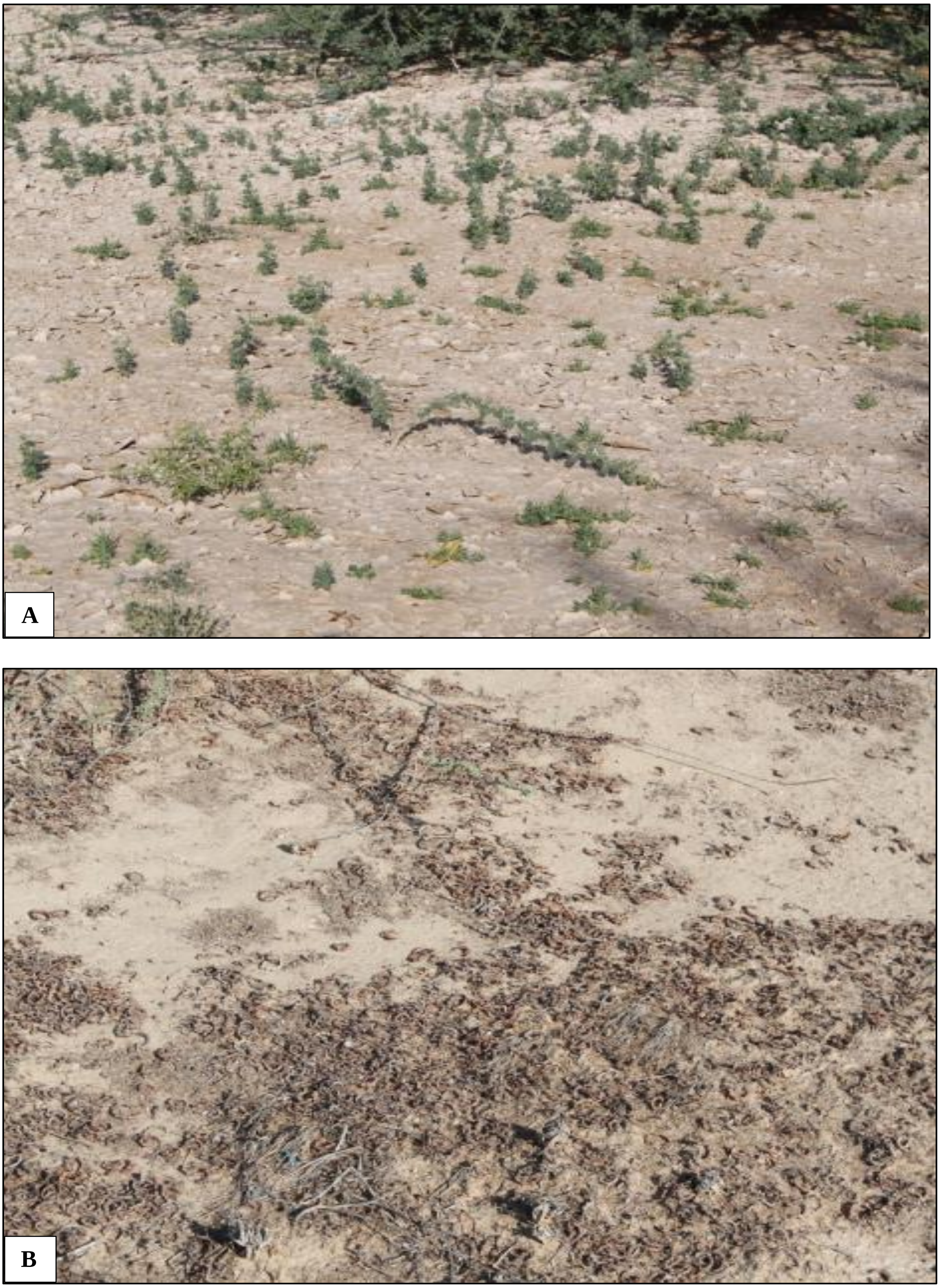


Figure 6-2 A and B: Composite Pictures Show the Comparison in Regeneration Condition between the Protected and Unprotected Sites in the Study Area I. Where Figure 6-2A Clearly Shows *Acacia tortilis* Saplings, in the Unprotected Area and Figure 6-2B Shows the Dried Seed

Pods with no Saplings at the Protected Areas (Both Pictures are Located within the Depression Position).

A strong significant association exists between *Acacia tortilis* regeneration and the protection status (χ^2 =16.147, df = 2, P < 0.001) as shown in Figure 6-3A. According to the results, the number of plots with no saplings was higher than expected in the protected area. In other words, a higher number of transect sections in the protected site did not contain saplings. Moreover, the protected area witnessed a high number of dried seed pods within the depression positions, with no *Acacia* sapling indicating the absence of regeneration (Figure 6-3A). The number of plots having below 50% cover of *Acacia* saplings was lower than expected in the protected area. It is important to emphasize that the rate of *Acacia* regeneration with below 50% cover was observed only twice at the slope position in the protected area. Furthermore, the results confirmed the absence of above 50% cover of *Acacia* saplings in the protected area. In contrast, the numbers of plots having below 50% and above 50% cover of *Acacia* saplings were higher than expected in the unprotected area (Figure 6-3A).

A strong association was found between the regeneration cover of *Acacia tortilis* and the sampling within the different topographical positions (χ^2 = 19.032, df = 2, P < 0.001) as shown in Figure 6-3B. The extent of regeneration of *Acacia* saplings (i.e. below 50% and above 50% cover) was higher than expected in the depressions. While the regeneration of *Acacia* saplings was less supported by the slopes compared to the depressions. It was evidently clear that the slope has a lower number of transect sections with below 50% cover than the depression. Furthermore, there were no sections with above 50% cover on the slope (Figure 6-3B).

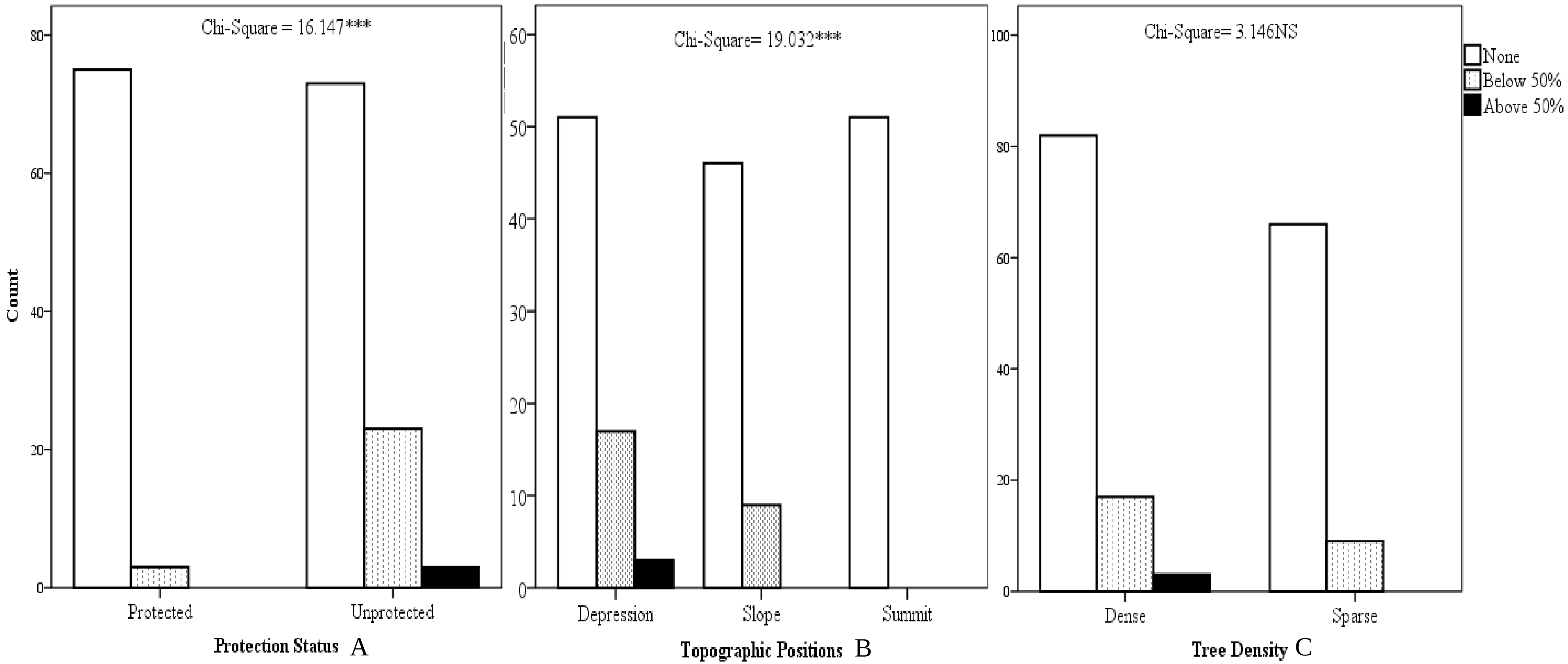


Figure 6-3: Regeneration Rate of The *Acacia tortilis* in the Study Area I; Count Was the Number of Occurrences per 20m^2 Plot: for the Main Effect of Protection Status (A), Topographic Positions (B) and Tree Density (C).

Chi-Square significance at the following confidence level: P < 0.05 (*), P < 0.01(**), P < 0.001 (***) and NS (non-significant).

Finally, the differences in regeneration of *Acacia tortilis* with regards to the mature tree density (dense or sparse) was not significant ($\chi^2 = 3.146$, df = 2, $P < 0.207$) as shown in Figure 6-3C. Despite the dense depressions tending to support the regeneration rate of the *Acacia* saplings more than the sparse depressions, the association between the regeneration of the *Acacia* saplings and tree density was not statistically significant. However, the *Acacia* saplings number of transect sections with below 50% and above 50% cover found in the dense depression was higher than those in the sparse depression.

6.1.3 Regeneration of *Acacia tortilis* in areas II and III

Saplings morphological description

The other two sites exclusively selected for the study of *Acacia tortilis* regeneration were located within a depression landform. A clear difference was observed in the percent cover of *Acacia* saplings/regeneration among these sites. In "northern" site II, the sapling cover was above 50%; while it was below 50% in the "southern" site III. The newly germinated *Acacia* saplings were also greater in number the northern site compared with the southern site. However, bare soil samples were varying in their position between depression and slope.

Table 6-1: Morphological Description of *Acacia tortilis* in the Regeneration Areas

	areas	
Morphological description	**Area II (n=53)**	**Area III (n=17)**
Height (cm)	17.63±1.8a	23.76±3.3a
Branches No.	9.2±0.7 b	13.1±1.4 a
Stem No.	2.33±0.1a	2.71±0.2a

Mean values in the same row which are not followed by the same letter are statistically significant (p < 0.05) as determined by Tukey's HSD-test.

The morphological description of *Acacia tortilis* regeneration indicates that there was no significant difference in the saplings height between the northern and southern sites, but on average they were slightly taller in the southern site (Table 6-1). Furthermore, the number of branches numbers of *Acacia tortilis* saplings was significantly greater in the southern site than in the northern site. Whereas the stem numbers of the *Acacia* saplings were also not significantly different between both sites.

6.1.4 Soil properties

Regeneration areas and soil properties

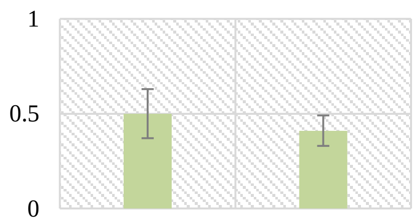
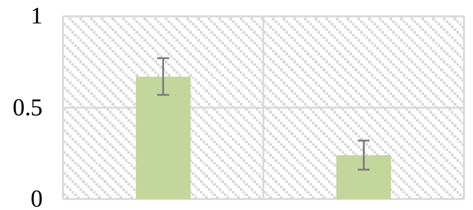
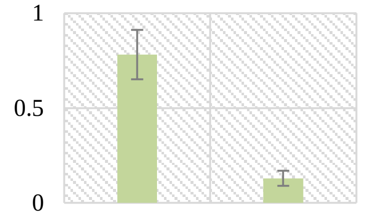
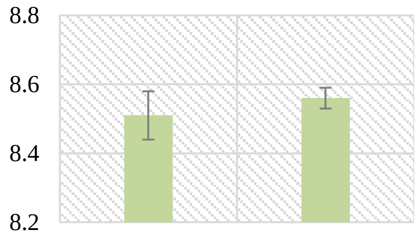
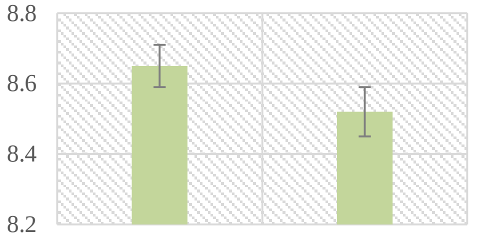
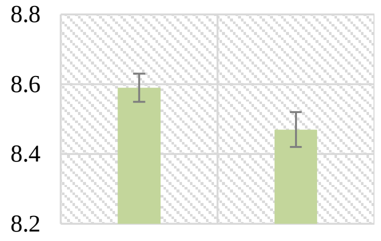
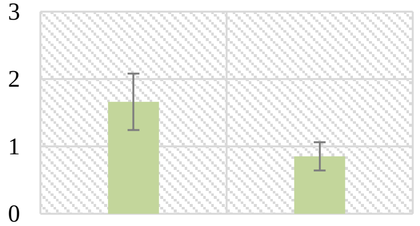
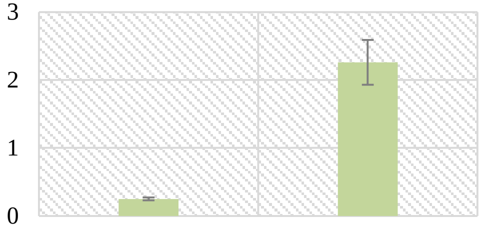
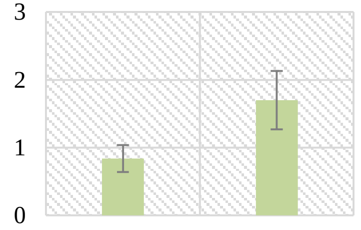
The area has no significant influence on the soil properties measured, except for the gypsum content. In other words, the soil properties determined in both regeneration sites were not significantly different, except for the gypsum content, for which the northern site II significantly out-yielded southern site III (Figure 6-4).

Regeneration status and soil properties

With the exception of soil pH, all the other soil properties varied significantly between *Acacia* sapling and bare sampling positions. The available P, SWC and OC were significantly greater at sapling positions than bare sampling positions; while EC and gypsum content were significantly greater at bare sampling positions than sapling positions (Figure 6-4).

Soil horizons and soil properties

Soil properties were measured in two horizons, A and B, the results indicate that significant difference exist between both horizons for available P and VWC; while no significant difference was observed for soil pH and EC. Soils with higher available P were recorded from horizon A, while VWC was found to be higher in soils from horizon B. Although there was no significant difference between both horizons for soil pH and EC, the soil pH appears to be slightly higher in horizon A than horizon B. Whereas the EC presented a contrary trend of being higher in horizon B than horizon A (Figure 6-4). Since the organic carbon content was determined for soils from horizon A only and gypsum content analysed for soils from horizon B only; it could not be ascertained if there was significant difference between both horizons regarding these soil parameters.

Soil Properties	**Sample Areas**	**Regeneration status**	**Soil Horizon (*n*= 16 each horizon)**
	Area (II) Area (III)	Sapling sample Bare sample	A B
Available P (µg/ml)			
pH			
Electric conductivity (mS/cm)			

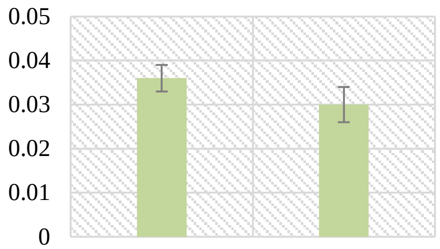
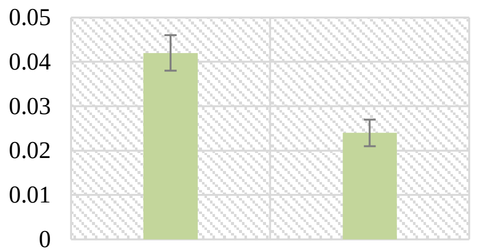
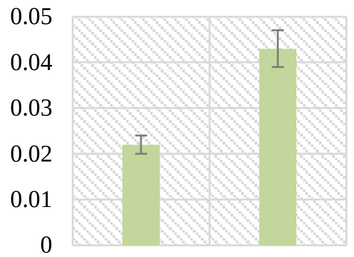
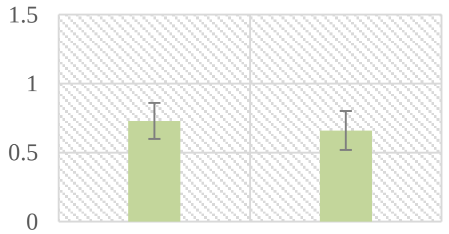
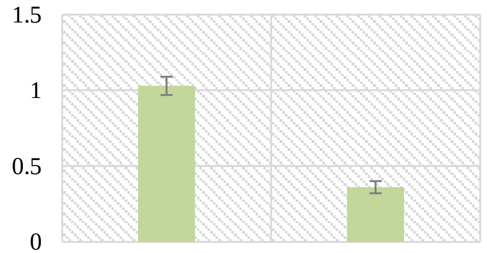
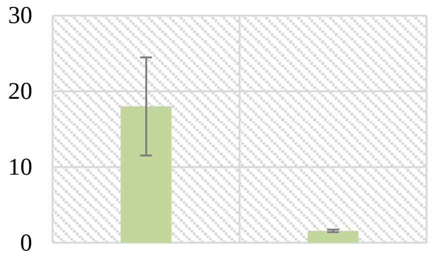
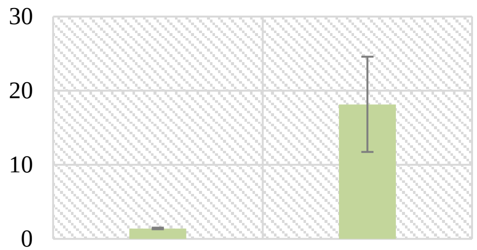
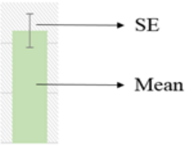
Soil water content(m^3 m^{-3})			
#Organic carbon (%)			– –
***Gypsum content (%)**			– –

Figure 6-4: Differences of the Soil Chemical Indicators between the Regeneration Areas, Sampling Positions and Soil Horizons.



Available phosphorus (P)

The results of soils analysis from both horizons of the regeneration areas are presented in Table 6-2. Soil available phosphorus was significantly lower in bare sample positions of horizon A at the area II; while no significant difference was observed between other sampling positions of area III. However, available P of horizon B at both regeneration sites was so close that they are not measurably different. Higher available P values were always recorded for soils from the sapling sample positions of both sites and horizons. Furthermore, the available P measured in soil horizon A was much higher than that of horizon B within each regeneration site (Table 6-2). Besides the application of Tukey's test (which is a form of Chi-Square test) in assessing the difference between the soil properties from the sampling positions of the soil horizons within each regeneration area, ANOVA was performed on the soil properties to ascertain if significant difference exists between both regeneration areas (area II/area III); sampling positions (sapling/bare); and the interaction of the site and sampling positions (site*sampling) as also presented in Table 6-2. In general, clear significant differences cannot be discerned from the ANOVA results. However, the available P in soils from horizon A was significantly different for the sampling positions; but not for both regeneration areas and the interaction between Area and sampling position as indicated in Table 6-2.While for soils from horizon B, the available P was only significantly different for the interaction between area and sampling positions. The higher available P in the sapling sample position indicates that around areas of a matured *Acacia* tree is richer in available P and possibly other soil nutrients essential for the regeneration of *Acacia tortilis.* Also, the additional P could come from other sources (e.g. bird-dropping or animal dung).

Soil pH

Considering soils taken from horizon A, the mean soil pH values indicate that the bare sample was significantly lower than the sapling sample in the northern regeneration area. The soil pH values of the area III sapling and bare samples were found not to be significantly different (Table 6-2). But for soils from horizon B, the soil pH values of the sapling and bare sampling positions of the two regeneration sites were found to be almost the same without any significant difference. However, the ANOVA results for the soil pH show that only the interaction between area and sampling positions were significantly different for soil horizon A and B, respectively.

Electric conductivity (EC)

For both soil horizons A and B, significantly higher Electric Conductivity (EC) was recorded for the bare soil sampling positions at the northern area. At area III, the results did not show such a clear difference. In this case, the EC of sapling and bare sampling positions were not significantly different for soils taken from horizon A, but significant difference exists between the sapling and bare sampling positions for soils taken from horizon B. The ANOVA results show that the EC was significantly different at 99.9% confidence level for all treatment considered (i.e. site; sampling and site*sampling) for both soil horizons A and B as shown in Table 6-2.

Soil water content (SWC)

Generally, the sapling positions had the higher SWC than the bare sampling positions in both soil horizons. In horizon A, the SWC of the bare soil sampling position was significantly lower compared to sapling sampling position from the regeneration site II. However, in horizon B, the SWC of the bare soil sampling positions were significantly lower than those of the sapling positions of both regeneration sites. According to the ANOVA results, significant difference existsbetween the SWC of the two regeneration sites only for soils from horizon A. Also, the SWC between the two sampling positions were significantly different for both soil horizons (Table 6-2).

Organic carbon (OC)

In horizon A, the organic carbon (OC) expressed in percent was significantly higher in sapling sampling positions than in bare sampling positions of both regeneration sites. It is important to note that %OC was only measured in soil horizon A. Descriptive statistics indicated that %OC values were generally small, particularly, for the bare samples, and ranged between from 0.3 to 1% (Table 6-2). In this case, the %OC was significantly different between the sampling positions only (Table 6-2).

Table 6-2: Statistical Results for Effects on Regeneration Areas, Sampling Positions and Horizons on Soil Properties (*n* = 16 each horizon).

Soil analysis	**Soil horizon**	**Area II**		**Area III**		**ANOVA**		
		Sapling sample	Bare sample	Sapling sample	Bare sample	**Area** (Site II/Site III)	**Sampling** (Sapling/Bare)	**Area*Sampling**
Available P (μg/ml)	Horizon A	1.381 ±0.212a	0.342 ±0.160b	0.802 ±0.303ab	0.598 ±0.168ab	0.474 NS	0.015 *	0.080 NS
	Horizon B	0.255 ±0.109a	0.00±0.00a	0.395 ±0.159a	0.031 ±0.013a	0.399 NS	0.589 NS	0.008 **
pH	Horizon A	8.695 ±0.099a	8.367 ±0.060b	8.612 ±0.083ab	8.687 ±0.044a	0.139 NS	0.118 NS	0.020 *
	Horizon B	8.615 ±0.157a	8.355 ±0.065a	8.643 ±0.031a	8.305 ±0.083a	0.909 NS	0.009 **	0.693 NS
Electric conductivity (mS/cm)	Horizon A	0.250 ±0.050b	2.125 ±0.217a	0.350 ±0.029b	0.625 ±0.149b	0.000 ***	0.000 ***	0.000 ***
	Horizon B	0.175 ±0.048c	4.10 ±0.406a	0.225 ±0.048c	2.200 ±0.147b	0.001 ***	0.000 ***	0.001 ***
Soil water content(m^3 m^{-3})	Horizon A	0.031 ±0.0027a	0.02 ±0.00091ab	0.023 ±0.003ab	0.0147 ±0.001 b	0.040 *	0.004 **	0.666 NS
	Horizon B	0.057 ±0.0042a	0.036 ±0.0030b	0.055 ±0.0025a	0.025 ±0.0018b	0.193 NS	0.000 ***	0.369 NS
Organic carbon content (%)	Horizon A	1.055 ±0.076a	0.406 ±0.059b	1.009 ±0.099a	0.304 ±0.051b	0.336 NS	0.000 ***	0.713 NS
Gypsum content (%)	Horizon B	1.598 ±0.122b	34.37 ±4.09a	1.231 ±0.083b	1.91 ±0.251b	0.005 **	0.000 ***	0.005 **

*Values in the same row followed by the same letter(s) are not significantly different at p < 0.05 according to Tukey's test (P < 0.05). In ANOVA: NS = Not significant, * = Significant (P < 0.05), ** = Significant (P < 0.01) and *** = Significant (P < 0.001).*

Gypsum content

Unlike OC, the gypsum content (also expressed in percent) was only measured in horizon B and exhibited a different pattern. In this case, significantly higher gypsum content was found in thebare soil sampling positions compared to sapling sampling positions of the site II. While no significant difference exist between the gypsum content of the sampling positions in the regeneration site III. It can be clearly seen that the gypsum content in the bare sampling positions was substantially higher in the northern site compared to the southern site. The ANOVA results show that the gypsum differences in the content were significant for all treatments considered (i.e. site; sampling and site*sampling) as shown in Table 6-2.

6.1.5 Discussion

Despite the general concept that soil water availability is essential for the establishment, survival and growth of desert plants like *Acacia tortilis* (Shmida *et al.*, 1986; Otieno *et al.*, 2005; Noumi *et al.*, 2010), little attention has been given to the role of available water content in soils as a factor affecting the topographic distribution of *Acacia tortilis* population. Also the impact of soil properties in sustaining the regeneration of *Acacia tortilis* within the various topographic habitats is rarely considered in most studies. Instead of considering on a wider context the many factors that may affect the regeneration of *Acacia tortilis* in the geomorphological positions of arid and desert ecosystems, most previous studies have narrowly focused on factors such as rainfall (Auld, 1987; Eshete and Ståhl, 1998); grazing (Mwalyosi, 1990; Oba, 1998; Jauffret and Lavorel, 2003); anthropogenic disturbances (Ward and Rohner, 1997; Hadar *et al.*, 1999) and competition among different plant species (Smith and Goodman, 1986; Smith and Shackelton, 1988; Sterner, 1989). Nevertheless, this chapter critically investigates the impact of soil properties (including the available water content), animals and anthropogenic activities on the regeneration of *Acacia tortilis* across the geomorphological positions. Plant regeneration is a complex process which comprises of a series of linked stages (Clark *et al.*, 1999). Previous research into this challenging area has demonstrated that the distribution and regeneration pattern of the *Acacia tortilis* tree are governed by a combination of factors which includes the variations in soil characteristics (Scholes, 1990), herbivory/anthropogenic activities (Miller, 1994a; Miller, 1994b; Rohner and Ward, 1999; Ward et al., 2010; Rodríguez-Pérez et al., 2011), and rainfall (Wilson and Witkowski, 1998; Radford et al., 2001; Stave et al., 2006). More particularly, in arid environment such as Qatar, *Acacia* seeds germination and survival are mainly control by soil moisture (Loth et al., 2005; Stave et al., 2006).

Establishment and regeneration of *Acacia tortilis*

In general, the germination of *Acacia tortilis* under the shade of tree canopy was not optimal in area I. There were no *Acacia* seedling/saplings established under the tree canopy for any sampled trees in the protected site, although a high amount of the seed pods were found (see Figure 6-2B). Moreover, these *Acacia* seeds pods were highly affected by the infestation of bruchid beetles (field observation), which may substantially reduce the probability of the seedling recruitment (Coe and Coe, 1987; Ward and Rohner, 1997; Rohner and Ward, 1999; Fox et al., 2012). In accordance with the present findings, previous studies have demonstrated that between 80–97% of the *Acacia* seeds are usually infested by bruchids in the field (Ward and Rohner, 1997; Ward et al., 2010). Hence, this finding may be explained by the fact that large mammals (herbivores) may indirectly have a positive impact on the recruitment of *Acacia* seedlings in terms of terminating the influence of beetles from destroying/infesting the *Acacia* seeds under the mature trees (Rhoades, 1996; Loth et al., 2005; Noumi et al., 2010). On the other hand, the sampled trees within the unprotected area witnessed relatively higher regeneration number of *Acacia* seedlings/saplings relative to the established canopies (sub canopy) of *Acacia tortilis* in the depression position compared to the slope position (see Figure 6-1 and 6-3). It is also imperative to emphasize that regeneration of *Acacia tortilis* was not restricted to under the canopy area of the *Acacia* trees in the unprotected area; *Acacia* saplings were also seen scattered beyond the periphery of the *Acacia* tree canopy in unprotected area. In fact, about 80% of the *Acacia* saplings were found outside the canopy area of the trees within the 20 × 20 m transects in the depression and sometimes the slope, but not the summit which has no *Acacia* saplings. Herbivores, winds and erosion are instrumental in dispersing the *Acacia* seeds beyond the edge of the canopy area of the trees. These *Acacia* seeds under favourable conditions may eventually develop into *Acacia* saplings.

The regeneration of *Acacia* seedlings/saplings in the unprotected area was found to be a combination of below 50% and above 50% cover and most of the saplings were newly grown (between < 1 – 40 cm in height). It is encouraging to compare this figure with the ideas by Kennenni and Maarel, (1990) who suggested that *Acacia tortilis* saplings are those of less than 0.6 meters in height and seedlings are those grown in current season. Several possible explanations have been proposed for these observations of individuals established in the current season, but the availability of soil water content has been identified as a key factor for the regeneration of *Acacia tortilis* (Mahamane and Mahamane, 2005) and the main source of water in most semi-arid region is the rainfall pattern. Some studies have shown that only rain higher than 10 mm are adequate and beneficial to vegetation in arid areas (Floret and Pontanier, 1982). While other studies have demonstrated that frequent, but not necessarily high rainfall appears to be essential for germination and seedling of *Acacia tortilis* over the first 7 weeks (Wilson and Witkowski, 1998). Stave et al. (2006) added that regeneration seems to be less dependent on the average rainfall than the frequency and regularity of rainfall event. Moreover, Franz et al. (2010) examined the interactions between climate, soil and plants using a quantitative ecohydrological framework for predicting the distribution pattern of *Acacia tortilis* in central Kenya. They reported that changes in growing season of *Acacia tortilis* are comparable to rainfall variability changes and precipitation season. They emphasized that the modest increase in relative water used by *Acacia tortilis* when rainfall is low is sufficient to allow it to remain the dominant species under reduced rainfall scenarios. However, Rohner and Ward (1997) reported that no germination of the *Acacia* tree was found in areas where rainfall was low, a finding not supported by the current study. Nevertheless, the average monthly rainfall of the main study area ranged from 0.6 to 16 mm since September and throughout the fieldwork period of November and December 2013 as shown in Figure 6-5 .Therefore, it would have facilitated the recruitment of *Acacia* seedlings in both protected and unprotected areas as the rainfall was not expected to be significantly different in the two areas. However, the inability of the protected area to support the regeneration of *Acacia tortilis* could be attributed to reasons other than rainfall.

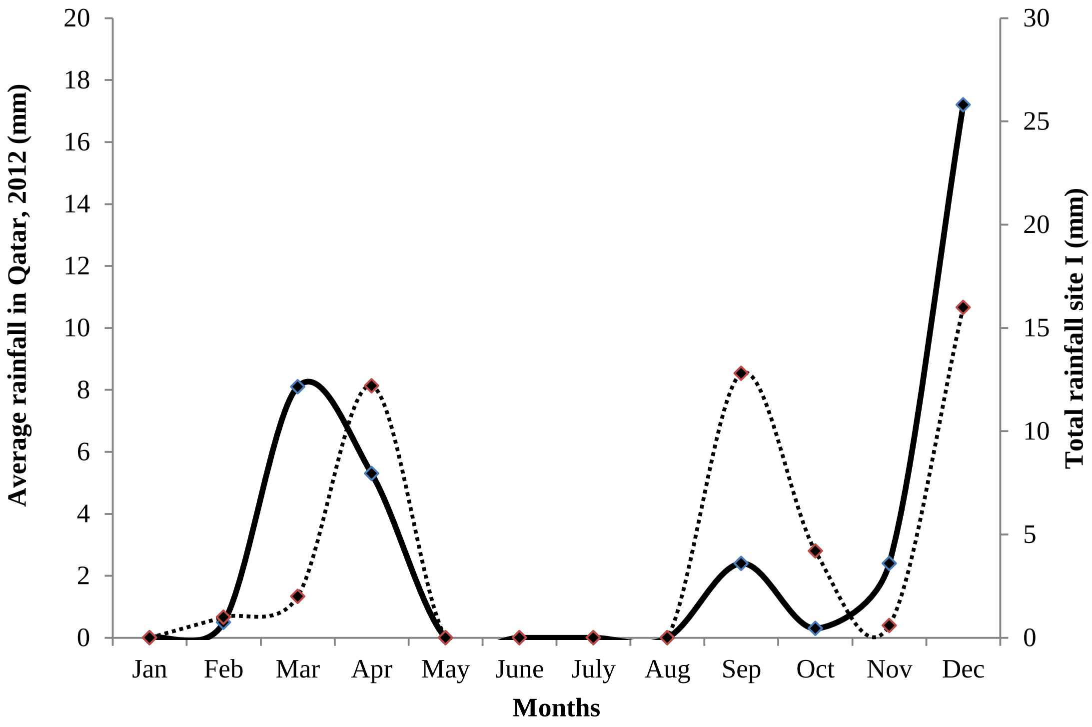


Figure 6-5: Total Amount of Rainfall (mm) in the Study Area (dotted line) and for Whole Qatar (solid line) in the Period (Jan-Dec 2012).

Data Collected from the Weather Station Located near the Study Area I, and for Whole Country of Which the Mean of 34 Weather Stations was Used.

As previously explained, the occurrence of torrential showers causes lateral runoff and erosion particularly on the sloping topography which in turn lead to 'phenomena' that play a vital role in Qatari hydrology and hydro-geology. Moreover, the depressions soon after rainfall acting as a pool that gathered water of rainfall from the surrounding elevated areas. For example, a significantly higher VWC was recorded in the saplings sampled plots compared with bare soil in regeneration. This is particularly true for horizon A (i.e. the surface soil) as indicated in Table 6-2.This may explain the higher water content (SWC) in these positions

It is important to noted that the regeneration results of this study did show that the unprotected area had the higher germination or regeneration of *Acacia* seedlings/saplings compared to the protected area which almost did not have any *Acacia* seedling/sapling (except three observations plots within a slope position in protected site) as illustrated in Figure 6-3A. Possible explanation for the difference between the protected and unprotected areas in supporting the regeneration of *Acacia tortilis* could be attributed to the absence of animal (e.g. browsing/grazing) and anthropogenic activities (cutting, soil tilling etc.) that may have hamper the recruitment of *Acacia* seedlings (Noumi *et al.*, 2010). Several studies have demonstrated that the absence of animal and anthropogenic activities in protected areas could lead to the development of surface crust in the soil (i.e. surface sealing or crusts) which inhibits the germination of seeds, reduces water infiltration in the soil and enhances surface runoff of water (Rockström et al., 1998; Noumi et al., 2010; Biazin Birhanu et al., 2011). Consequently, the soil water content available to support seed germination and for the uptake by the roots of plants such as *Acacia tortilis* will be reduced. For these reasons, the protected areas are usually less inclined to regeneration of *Acacia tortilis.* In fact, the findings of the protected area in this research are consistent with those obtained by Noumi et al. (2010).

Another possible explanation for our results may be due to the absence of adequate large herbivores/ungulates which had no access to the protected area for several years. Herbivores (e.g. goats and carmels) facilitate the dispersal of *Acacia* seedlings and improving its germination by scarification of the seed coat and killing of bruchid beetles (Hauser, 1994; Rohner and Ward, 1999; Or and Ward, 2003). These seeds are subsequently deposited with faeces that could contribute to the soil organic content. The viable seeds are then mixed with disturbed soil with the potential of germinating into saplings. Several other studies have also acknowledged that ungulates and bruchid beetles had potentially the largest impact on *Acacia tortilis* population and regeneration dynamics (Miller, 1994b; Reid and Ellis, 1995; Rohner and Ward, 1999; Oba *et al.*, 2002; Rodríguez-Pérez *et al.*, 2011). These studies found that an improvement in the seed germination and seedling recruitment in the presence of livestock (e.g. herbivory) which positively decrease bruchid beetle infection via seed consumption as well as help in the seed dispersal around the grazing sites. The dispersed seedlings are subsequently sustained by the availability of soil water content. However, the protected area does not allow access to animals thereby making it unfavourable for the regeneration of *Acacia tortilis*.

Regeneration of *Acacia tortilis* in the unprotected area

Since *Acacia* saplings were predominantly found in the unprotected area, it is important to consider its regeneration in this area in more detail. As earlier stated, the regeneration and distribution of *Acacia* saplings were not confined under the mature sampled trees but scattered throughout the transects in depressions and slopes of the unprotected area, as shown in Figure 6-1 and 6-3. This can be attributed to the availability of water and other soil nutrients sufficient to sustain the *Acacia* saplings in the unprotected area. It is generally acknowledged that available water content in soil is a treasure in extremely arid ecosystems. Hence, the growth and survival of woody seedlings such as *Acacia tortilis* in arid and semi-arid environments is partly determined by the ability of their roots to maintain contact with available water content of the soil (Stave *et al.*, 2005). In other words, soil moisture is essential for seed germination and seedling establishment. However the success of seedling establishment is challenged by the ability of their roots to make contact with soils sufficient with available water content. Otieno *et al.*, (2005) has shown that leaf growth and shoot elongation depended on soil water availability (SWC) and plant tissue water status. According to Otieno et al. (2005) the success of *Acacia tortilis* in a drought environment of the arid and semi-arid regions could be attributed to its deep rooting system and efficient root water uptake and transport. The presence of plants with shallow rooting system (e.g. *Acacia* saplings) either among or under the canopies of mature *Acacia* trees in the xeric environment was as a result of a modified soil environment caused by the enhanced soil water content, probably through hydraulic lift by *Acacia tortilis* (Ludwig *et al.*, 2003; Ludwig *et al.*, 2004). Despite the fact that the seedlings are more common further away from mature trees in this study which would suggest water status under canopies is not the most important factor of regeneration. However, this improvement of water status in the upper layer of soils within the vicinity of matured *Acacia tortilis* facilitates water access to shallow rooted plants like *Acacia* saplings. Consequently, the availability of soil water content to germinating *Acacia* seedlings/saplings is indispensable to the regeneration of *Acacia tortilis*. Besides the availability of water content in the surface soil under the canopied area, these areas have also been shown to be rich in soil nutrients that will sustain young *Acacia* saplings that may not be able penetrate very deep into the soil. Moustafa and Mansour, (2003) have shown that soil enriched with nutrients (e.g. organic matter) supports the regeneration *Acacia tortilis* as indicated by increased vitality and improved vegetation cover of the plant.

Acacia seedlings/saplings are rarely seen near the base of the mother tree (Figure 6-1). Saplings were predominantly distributed at the periphery of the adult trees on flat ground of the depression position. However, for a sloping surface the saplings tend to be concentrated down-slope at some distance from the adult tree. In general, the frequency of seedlings established under canopies of *Acacia tortilis* increases further away from tree bole position, which is a more conspicuous trend in the depression position. This trend may be caused by the dispersal of the seeds by winds which are blown away from the tree bole. Argaw *et al.*, (1999) also emphasized that the *Acacia tortilis* seeds could be dispersed by wind and deposited under the canopy of the parent plant. The dispersal of *Acacia* seeds by animals (endozoochory) is likely to result in a more patchy distribution and often over longer distances compared to wind dispersal. Again, the grazing or browsing of the matured *A. tortilis* by animals usually takes place at the edge of the canopy. While these animals grazed the edge of the canopy, they are likely to disperse seeds further away from the tree bole. Furthermore, these animals also disperse the seeds beyond the periphery of the tree canopy to other areas while moving about in the unprotected area.

Topographical positions represent contrasting run-off regimes with the depression being characterized by higher amounts of water availability and more intense floods than the summits (Lahav-Ginott *et al.*, 2001). Therefore, the topographical variation within the habitats of plants usually has profound influence on their distribution which may explain the regeneration pattern of the *Acacia tortilis* in Qatar. In particular, the depression followed by slope seems to be the preferred environment that support and enhanced seed germination. These findings could be attributed to higher soil moisture (SWC) within these positions which were significantly higher in depression, followed by the slope. The summit has the least available water content among the topographical positions. Besides the relationship between the topographical positions and the available water content, other soil properties could also impact on the distribution and regeneration of *Acacia tortilis.* For example, the available P and OC were found to be higher in the depression than the slope and least in the summit. In contrast, the EC and gypsum content were least in the depression followed by the slope and highest in the summit. This trend in the soil properties which has been extensively discussed in chapter five and previous sections is very important in explaining the regeneration and distribution of *Acacia* sapling along the topographical gradients. Since the SWC, available P and OC are essential for the regeneration and distribution of the *Acacia* saplings and were found to be highest in the depression, the *Acacia* saplings were predominantly found in this topographical position. This was followed by the slope position which comes next in term of these essential soil properties. However, there were no *Acacia* saplings on the summit due to the high salinity (EC) and gypsum content that were unfavourable for the regeneration and distribution of most plants including *Acacia tortilis*. The presence of high gypsum content in the summit makes it very difficult for dispersed and germinating *Acacia* seedlings in this summit position to penetrate the soil, hence these seedlings will neither be unable to attain stability (i.e. fixed to the soil) nor absorb nutrient. As a result, seeds will be either be washed/blown away to other positions by run-off water/wind or seedlings will soon die for lack of the required nutrients. The depression has been known to be the most fertile among the topographical positions since it has the largest number of mature *Acacia* trees compared to the other positions (i.e. slope and summit) and considering the role depression plays in improving soil fertility (Abdallah *et al.*, 2012). *Acacia tortilis* has been known to improve soil fertility. This is especially reflected in the enrichment of soil nutrients the under the canopy areas of *Acacia* trees (see section 5.1.2). The soil under the canopy areas of *Acacia tortilis* are often characterized with a higher organic matter content, available nitrogen content for plant uptake and a better cation exchange capacity (Kellman, 1979). In addition, these soils have good physical structure (or texture) and better water infiltration potential that supports the germination, survival and development of seedlings or plants (Vetaas, 1992; Smit and Swart, 1994). The improvement of soil under the canopy areas of *Acacia tortilis* have been attributed to several factors which includes the litter of herbs and dead parts of the *Acacia* trees (Amiotti *et al.*, 2000) and faeces of animals that seek shelter under the trees (Belsky *et al.*, 1989). Furthermore, additional factors could influence the distribution and regeneration of *Acacia* tortilis along the various topographical gradients. For example, the absence or low density of matured trees to produce enough seeds for regeneration, or a poor seed dispersal strategy of the species (Argaw *et al.*, 1999).

The regeneration rates of *Acacia tortilis* in the dense depression comprised of both below 50% and above 50% cover *Acacia* saplings (Figure 6-3C). In contrast, only below 50% cover of *Acacia* saplings was found in the sparse depression (Figure 6-3C). It has been emphasized that the amount of seeds of a species in/on the soil surface is a function of plant density (Louda, 1989). For the fact that the dense depression has more matured trees, there is greater tendency that more *Acacia* seeds will be dispersed here by the several dispersal agents (e.g. erosion, wind, animals etc.) which have already been elaborated upon in the previous sections. For the same reason, the sparse depression which has less matured *Acacia* trees will have a less *Acacia* seeds dispersed. Since the depression (both dense and sparse) has the necessary soil nutrients (i.e. more of SWC, available P and OC; less of EC and gypsum content) that supports regeneration and distribution of *Acacia* seedlings, most of these seeds will eventually germinate into saplings that are proportional to the dispersed seeds in both the dense and sparse depression positions. The presence of more *Acacia* trees in the dense depression has the potential of improving the fertility of soil in this position for reasons already presented in previous sections. Furthermore, the dense depression experience more grazing activities due to the presence of more trees in this position compared to the sparse depression. Besides these animals facilitating the dispersal of the seedlings, they also disturb the soil that provides favourable conditions for the germinating *Acacia* seedlings present in the dense depression compared to those in the sparse depression. Therefore, the dense depression will eventually have more regenerated *Acacia* saplings than the sparse depression as shown in Figure 6-3C.

As mentioned in the results of the previous chapter (chapter 5) that SWC was significantly lower in sparse depression sites. So this could also be a limiting factor to regeneration, as well as seed availability / dispersal. Hence, it’s hard to tell if the dry conditions cause the lack of trees or the lack of trees causes dry conditions, but in either case this would influence regeneration.

Regeneration of *Acacia tortilis* in areas II and III

Regeneration was also exclusively studied in the northern and southern areas II and III. The relationship between the regeneration sites and soil properties were assessed. In general, both regeneration sites were not significantly different, except for the gypsum content. In this case, the gypsum content in the northern area II was significantly higher than that obtained for the southern area III. In the current study high gypsum content in the northern area may have interfered with the regeneration or growth of the plant as shown in Table 6-1. Also, assessment of the regeneration status based on the soil properties was undertaken. The results revealed that with the exception of soil pH, all the other soil properties varied significantly between *Acacia* sapling and bare sampling positions. Although there was no clear differences in the variation of these soil parameters in sampling sites, the available P, SWC and OC were significantly greater at sapling positions than bare sampling positions in both sites; while EC and gypsum content were significantly greater at bare sampling positions than sapling positions (Figure 6-4 and Table 6-2). In addition, the soil properties were assessed between two horizons to ascertain if they are significantly different. In this case, significant difference exists between both horizons for available P and SWC; while no significant difference was observed between them for soil pH and EC. These preliminary assessments of the relationship of the regeneration sites, regeneration status and soil horizon with regards to the soil properties provide insight on the most important environmental variables (e.g. SWC, P, and OC) that could impact on the distribution and regeneration of the *Acacia tortilis* in both regeneration sites and paved way for a more detailed analysis.

Another possible reason for a better regeneration rate of *Acacia tortilis* is the improved soil fertility (i.e. organic carbon and available phosphorus), which were significantly higher in depression and slope areas compared with summit of the both regeneration sites. It is important to emphasize that some of the reasons for the distribution and regeneration of the *Acacia* saplings have already been presented in the previous chapters indicating that the influence of soil properties on regeneration was independent of the modifying influence of mature tree canopies. However, these soil properties were generally found to be significantly higher in saplings sampled compared with bare soil sampled positions. These findings are in agreement with those of Moleele et al., (2005) that investigated *Acacia tortilis* seed weight/quality patterns across Botswana in relation to soil nutrient status, altitude, latitude and slope angle. They found that seed weights of *A. tortilis* were primarily determined by rainfall and soil organic carbon. The organic carbon (OC) content was not significantly different between regeneration sites or (Table 6-2). However, a significant difference exists between the sampling positions. For both sites, the sapling sampling position was significantly higher than the bare sampling positions. Hence, the regeneration rates appear to be higher in the sapling position compared to the bare position for both sites. The better fertility of the sapling position has also been extensively explained in previous sections. Furthermore, the presence of higher OC in the surface soil (i.e. horizon A) is also relevant to the regeneration of the *Acacia* sapling as they can easily reach this vital soil nutrient with their nascent and fragile roots.

The soil pH value of the bare sample was significantly lower than the sapling sample in the northern regeneration site. While the soil pH values of the southern sapling and bare samples were found not to be significantly different (Table 6-2). But for soils from horizon B, the soil pH values of the sapling and bare sampling positions of the two regeneration sites were found to be almost the same without any significant difference. The impact of soil pH on the regeneration of *Acacia* saplings is less pronounced in both sites. This can be attributed to the fact that the soil pH values of both sites, sampling positions and the horizons falls within the pH range (8.3 – 8.7) that is appropriate to support the growth of most plants including *Acacia tortilis.*

In general, the Electric Conductivity (EC) of the regeneration areas, sampling positions were significantly different as shown in Figure 6-4. Although the significant difference exists between these parameters (i.e. area II/area III; sampling positions; and sites*sampling), but these differences were not conspicuous visually as reflected at a lower confidence level (95%) using Tukey methods (Table 6-2). However, the EC is usually low in the depression which supports regeneration of *Acacia tortilis* and high in soil (e.g. in the summit) that are hostile to regeneration or plant growth. In area II, the sapling position was significantly lower than the bare position for both horizons indicating that the regeneration in the sapling position was much greater than those in the bare position for reasons already advanced in previous sections. While not so defined in area III as there was no significant difference between the sapling and bare positions in horizon A; but significantly different in horizon B. Consequently, the difference between the regeneration rates the sapling and bare positions were not so pronounced in area III. It seems possible that higher amount of these soil properties do affects regeneration of the *Acacia* negatively. In the present study, the slightly higher EC and gypsum content was found in those areas with lesser regeneration such as the bare position. This findings are consistent with those of Mehari *et al.* (2005) who found that effect of salinity with 150 and 300 mm NaCl on seedlings growth, biomass production and water status of *Acacia tortilis* under greenhouse experiment were sensitive to increased NaCl salinity.

As already stated, the gypsum content was only measured in horizon B which revealed significant difference for all treatments considered (i.e. area I/area II; sampling positions; and site*sampling) as indicated in Table 6-2. In general, the gypsum contents of the soils were less than the threshold of 2%, except for the bare sampling position of the area II (Table 6-2). Consequently, the adverse effects of the gypsum contents could be ignored except for the bare sampling position of area II. Regarding the sites, despite of that the gypsum content was significantly higher in the bare soil areas of study area II than the area III, but this study found that there was no significant difference in saplings height and stem numbers. Therefore, the implication of this results being that the area II is more disposed to support the regeneration of *Acacia tortilis* than the site III. In term of the sampling positions, the gypsum content was found to be significantly higher in the bare soil sampling positions (34.4%) compared to sapling sampling positions (1.6%) of the regeneration area II. As can be seen the gypsum content in the bare sampling position was much higher than the threshold of 2% highlighted above. Consequently, the *Acacia* saplings not found in the bare sampling position of area II as those in the sapling position of the same area II or both sampling positions (i.e. sapling and bare sampling positions) of the areas III since these sampling positions are well below the threshold limit of 2% that could impact adversely on the growth of the *Acacia* plant. While no significant difference exists between the gypsum content of the sampling positions in the regeneration area III (Table 6-2). However, the gypsum contents of the sapling and bare sampling positions were below the threshold value of 2%. Hence, the adverse effects of high gypsum content in soils do not apply in this case.

The rainfall in both regeneration areas II and III followed the same trend as area I as shown in Figure 6-5. Consequently, rainfall may not have accounted for their difference in their regeneration rates. Generally, the sapling positions had the higher SWC than the bare sampling position in both soil horizons. In horizon A, the SWC of the bare soil sampling position was significantly lower compared to sapling sampling position in the northern site. However, in horizon B, the SWC of the bare soil sampling positions were significantly lower than those of the sapling positions of both regeneration sites. This is consistent with the explanation already presented in the previous sections. The sapling sample position is in the areas which have the potential of hydraulically lift soil water content to the surface soil to support seedlings and saplings. In contrast, the bare sample positions are far away from the trees; therefore, it is expected to be lower than that of the sapling sampled position. Although the difference in the available water content between both regeneration areas are insignificant for the fact that both sites are exposed to the similar amount of rainfall and are not protected.

Conclusion

Although plant regeneration is a complex process involves series of linked stages; it is of enormous importance because of its role in salvaging plants that are on the verge of extinction. Hence, the regeneration of such plant could be used for the restoration of plant that threatened stability of the ecosystem. *Acacia tortilis* is a typical example of such plant that requires regeneration in most arid and semi-arid environments in the Middle East and North African countries. Several environmental and anthropogenic factors have been identified to influence the process of regeneration. Among these factors, soil water availability has been generally accepted to be a key factor for the regeneration and distribution of *Acacia tortilis* due to its importance in the establishment, survival and growth of most desert plants like *Acacia tortilis.* Nevertheless, little attention has been given to the role of available water content in soils as a factor affecting the topographic distribution of *Acacia tortilis* population. This study has extensively investigated the impact of several abiotic and biotic factors on the regeneration of *Acacia tortilis* in Qatar. The abiotic factors include several environmental factors (including soil water availability); the biotic factors considered in this study include animal and anthropogenic activities that will not only create disturbance in the study area but also help in the dispersal of the *Acacia* seedlings in the study area. The study area selected for this research consists of three sites.

It was found that the germination of *Acacia tortilis* under the shade of tree canopy was not optimal in area I. There was no *Acacia* seedling/saplings established under the tree canopy for all sampled trees in the protected site. However, a high amount of the *Acacia* seeds pods were highly affected by the infestation of bruchid beetles which have the potential of reducing the probability of the seedling recruitment. The importance of large mammals (herbivores) on the recruitment of *Acacia* seedlings in the unprotected area was also observed. In general, there was no regeneration in the protected area of area I (with the exception of two *Acacia* sapling identified in the slope position); while the unprotected area witnessed regeneration, particularly in the depression and slope position.

In the protected area, the regeneration was not confined within the canopy area of the matured tree; instead the saplings were scattered under the canopy area of the matured trees and extend beyond its periphery. Considering the regeneration and distribution of *Acacia* saplings under the canopied area, the number of *Acacia* saplings increases away from the bole and climax towards the edge of the canopy area. Grazing animals and winds could be major contributing factors in dispersing the *Acacia* seedlings away from the tree bole. Nevertheless, about 60% of the *Acacia* seedlings/saplings were scattered beyond the edge of the tree canopy. In this case, herbivores, winds and erosion were the major dispersing agents. Topographically, the regeneration and distribution of *Acacia* seedlings/saplings were predominantly in the depression, and then followed by the slope of the unprotected area. There was no regeneration of *Acacia tortilis* in the summit. In other words, the summit was found to be unfavourable for regeneration as no sapling was found there. The reason for having the greater amount of *Acacia* sapling in the depression was attributed to the presence of greater amount of SWC, available P, OC. These soil properties support regeneration of *Acacia tortilis*. While the depression has the least amount of EC and gypsum content; these soil properties does not support the regeneration of the plant. However, the slope position has lesser amount of the favourable soil properties compared to the depression; hence the slope could support the regeneration process to a lesser extent compared to the depression. The impact of soil properties on the northern and southern sites exclusively selected for the regeneration study also confirmed the importance of SWC, available P and OC in the regeneration and distribution of *Acacia tortilis.* These soil properties were found to be higher in the areas of higher regeneration of *Acacia tortilis* such as the sapling position compared to the bare position. While the EC and gypsum content was found in those areas with lesser regeneration such as the bare position. The adverse effect of gypsiferous soils, which depends on the amount of gypsum present in the soil and the depth at which it occurs was also highlighted in this study. Nevertheless, the adverse effect of gypsum content could be ignored in soils having less than 2%, which is the threshold most plants can tolerate.

CHAPTER 7: GENERAL DISCUSSION AND CONCLUSIONS

7.1 Distribution of *Acacia tortilis* in Qatar Using Field Survey, Remote Sensing and GIS at National Scale

7.1.1 Multitemporal derived vegetation index dynamics

This study aimed to determine the distribution of *Acacia* tree species and to investigate changes between 1998 and 2010 using vegetation indices derived from remote sensing data acquired by Landsat satellite. On the question of to what extent do vegetation indices derived from the free Landsat archive enable us to detect *Acacia* and other tree species in Qatar. These tested indices did not show any potential discrimination for estimating tree cover and species composition of the three tree classes in Qatar (or characteristics that differentiate the vegetation groups) from the Landsat data examined. Likewise, as the *Acacia* species is the main concern in this study, the image analysis indicated that it is not possible to use NDVI and SAVI at the resolution tested here to detect its presence since the *Acacia tortilis* cannot be distinguished from bare soil. A possible explanation for these results are the sparse distribution of *Acacia tortilis* and the morphological or physiological adaptation of such trees to the surrounding arid environments which, in turn, result in different spectral responses in terms of both pigment concentration and/or leaf structure (mostly lack of leaves). The present findings seem to be consistent with those of other research which has found that the type of plants has significant importance in the overall production of greenness signals in arid environments where higher plants are sparse (Karnieli *et al.*, 2002). In accordance with the present results SAVI did not improve NDVI test. Similar findings have also demonstrated that soil-adjusted SAVI (soil-adjusted vegetation index) and other modified soil-adjusted vegetation indices was not able to enhance the estimation accuracy of the normalized difference vegetation index (NDVI) (Ren and Feng, 2014). Their work concluded that the soil-adjusted vegetation indices is not appropriate to use to define green vegetation information in arid and semi-arid areas with low green vegetation cover (<30%).

The second question posed in this research is if it possible to assess the expansion or decrease in of *Acacia* between 1998 and 2010 in an arid country, as well as to monitor factors that affecting its distribution. It is interesting to note that the mean values of acquired NDVI for the three vegetation types in 1998 were higher than those for 2010. It seems possible that these results are due to level of greenness, indicating photosynthetic activity changing from 1998 to 2010. The observed changes in NDVI could be attributed to dramatic changes in climatic variations and human activities over the last few years, which in turn have increased anthropogenic impacts such as overgrazing and overcutting on the Qatari vegetation by 2010. This may have led to general decreases in the volumes of tree structures and total biomass. It is encouraging to compare this conclusion with that of Hadeel *et al.* (2011), who highlighted the environmental changes between 1990 and 2003 in Iraq according to the normalized difference vegetation index computed and obtained from Landsat TM and Landsat ETM+ satellite images. The authors concluded that, from the analysis of NDVI, a high decrease in vegetative cover in most of the studied areas was observed, and they also revealed that vegetation degradation, which is mainly due to overgrazing and human activities, was a major component of the land degradation problem. Secondly, the observed increase in the NDVI values for the 1998 satellite images was probably due to the influence of climatic variations. In fact, water availability in arid and semiarid areas is the primary determinant of varying levels in productivity and the classical discussions of this relation have emphasized the ability of the vegetation to respond to sporadic pulses of precipitation (Noy-Meir, 1973; Rodríguez-Moreno and Bullock, 2014). Therefore, the high rainfall in 1998 clearly corresponds to maximum NDVI values. Likewise, this research founds that the October-December rains in 2010 (14.6mm) are more reliable as manifested in the amount of rainfall and the greenness of the vegetation compared to the October-December rainfall season in 1998 (1.9mm). Correlations of precipitation with NDVI variation have been reported in several others studies too (Volcani and Karnieli, 2002; Maselli, 2004; Aguilar *et al.*, 2012).

Despite the sparse distribution of tree vegetation and the morphological structure of Qatari desert plants, the analysis of the satellite imagery and spectral measurements, is evidently a useful tool for detecting phenological changes. The comparison of temporal analysis based on vegetation measures (NDVI) shows a consistent phenological pattern for the different vegetation classes, characterized by higher NDVI values during the spring and early summer period (see chapter four; part one). The present findings seem to be consistent with those of other studies which have confirmed the capability of NDVI to capture seasonal and monthly phenological variations among vegetation types (Geerken *et al.*, 2005; Pettorelli *et al.*, 2005; Wagenseil and Samimi, 2006; Martínez and Gilabert, 2009; Gasparri *et al.*, 2010). Also, the present research has found that NDVI values helped in characterizing the unique reflectance patterns from trees other than acacia species (in the no-acacia plots) compared with those of the *Acacia* and the mixed class plots. This may be explained in terms of the morphological variations in species such as *Prosopis* and *Ziziphus* which are characterised by higher canopy cover and leaf area size, which in turn produce different spectral responses from these species.

7.1.2 Patterns of *Acacia tortilis* distribution related to environmental gradients at a national scale

Very little was found in the literature on the question of the influence of environmental gradients on the distribution of the *Acacia tortilis* at a national scale in Qatar. Therefore, it was hypothesized that the gradients studied may be important factors affecting *A. tortilis* distribution. The current investigation considers how elevation, distance to coastline, depth to water table level, soil type, disturbance, TDS (groundwater) and topography predictors acting independently affect vegetation type classified as Acacia, Mixed, No Acacia and Bare Soil. Among those seven main environmental parameters, a very strong positive relationship was found between topographic position and the four vegetation type plots evaluated across Qatar. The plots with Acacia trees were confined to depression and slope positions only, whereas this important tree was never present in summit positions. This is also consistent with several previous research findings that the distribution of desert plants is related to topography and landforms in arid regions (Orshan, 1986; Hegazy *et al.*, 1998; Shaltout *et al.*, 2010; Alatar *et al.*, 2012).

The correlation analysis revealed a strong relationship between soil type and vegetation type (see section 4.2.1). The study of soil type showed that *Acacia* and mixed plots were distributed in areas with an absence of gypsiferous soils. Meanwhile, areas with *Acacia* trees were characterised by soils of the haplocalcic type. This result may be explained by the fact that gypsum in soil has significant negative effects or constraints on the distribution of some plants. Castillejo *et al.* (2011) reported that gypsum in soil plays a significant role in determining the composition of plant communities. In accordance with the present results, previous studies have demonstrated that soil type and characteristics play a major role in the distribution of plant species (FAO, 1990 ; Escudero *et al.*, 1999; Rubio and Escudero, 2000; Chigani *et al.*, 2012; Pascual *et al.*, 2012).

At national scale, the depth to underground water study did not detect any evidence for depth to water table as a limit factor for *Acacia tortilis* to growth in Qatar. Due to the fact that groundwater table are in range of depths that the *A. tortilis* capable to extract (see chapter 4).

As mentioned in chapter one, Qatar is witnessing tremendous levels of anthropogenic activities such as urban sprawl, agricultural practices and overgrazing. Hence, the study of the disturbance index as an indicator of human activity revealed a strong relationship between vegetation type and disturbance index (r = 0.537). It was shown that areas with *Acacia* plots were located close to human activity (0.32 km) followed by areas with mixed plots (0.51 km). As expected, areas with bare soil plots were the least affected by human disturbance (0.91 km) followed by the no-acacia plots (0.83 km). In general, due to the fact that Qatar is such a small country these results imply that the Qatari natural habitat is in serious danger from such activity as well as this tree is more disturbed. Action needs to be taken to maintain and restore the depressions in particular, as one of the key habitats in Qatar. The findings concerning the effect of disturbance on *Acacia tortilis* habitats in this study agree with those of previous studies (Batanouny, 1981; Donohue, 1995; Abd el-wahab *et al.*, 2013; Seleem *et al.*, 2013). It is encouraging to compare this finding with that of Darkoh (1998) that the human causes and consequences of desertification are usually confined to densely populated settlement areas.

To predict the vegetation type *Acacia*, mixed, no-acacia and bare soil in Qatar, three logistic regressions were used. Ranking these models overall according to the value of R^2, the multinomial regression using all seven variables accounts for 79% of the variation in vegetation types followed by the multinomial regression using PCs which represented 61.5% of variation. Meanwhile the ordinal regression accounts for 45% of this variation of vegetation types (Table 4-16 and 7-1).

Table 7-1: Comparison between the Three Logistic Regressions Models, Criteria for Assessment and Accuracy of Prediction of the Four Individual Vegetation Types.

Models	**Predicted Response Category**				**Criteria for Assessment**		
	Acacia	**Mixed**	**No Acacia**	**Bare soil**	**R^2 Adjusted**	**AIC**	**OCC%**
(1) Multinomial	78.4%	66.7%	95.2%	99.3%	**79%**	**232.1**	**85%**
(2) Multinomial using PCs	47.1%	62.2%	64.3%	97.1%	**61.5%**	**281.5**	**68%**
(3) Ordinal	76.5%	17.8%	28.6%	92.0%	**45%**	-	**54%**

Bare soil is always very well predicted with 92, 97.1 and 99.3% accuracy; whereas the no-acacia type had the largest variation in prediction compared with acacia and mixed vegetation types. Mixed plots showed a reasonable prediction of 62.2% and 66.7% in models one and two. However, the prediction was poor in the third model for this vegetation types. For the acacia plots, good predictions resulted from models one and three (76-78%) whereas it was only moderate for model two.

In this research three models have been developed to determine the major vegetation and environmental variables associated with *Acacia* abundance, and these could potentially be used to predict its distribution. Therefore, it is necessary to decide which of these models is superior. Three criteria have been used to make this assessment, namely the Akaike Information Criteria, R-squared and the overall percentage correct prediction. Table 7-1 shows the performance of the three models for each criterion. The results show that the multinomial logistic regression model has a superior ability to predict *Acacia* distribution, as it gives the lowest AIC, the highest R-squared and the highest overall percentage correct prediction of vegetation type. The statistical modelling for the prediction of species distribution has produced results which corroborate the ideas of Scott *et al.* (2002) and Austin (2002) who suggested that statistical approaches with logistic regression appear to be increasingly popular for detecting relationships between species distribution and the environment.

Understanding patterns of species occurrence and abundance is a central theme of ecology (Nielsen *et al.*, 2005). This work has shown that multinomial logistic regression is a suitable method in the prediction of the occurrence of different vegetation types in Qatar. In this method, it is not necessary to use quantitative attributes such as canopy cover, density and frequency (Zare Chahoukia and Zare Chahoukia, 2010). Thus, based on the prediction models, it is possible to estimate the probability of the presence or absence and the accuracy of prediction of plant species in response to environmental factors. In accordance with the present results, previous studies have demonstrated that logistic regression is a frequently used regression method for modelling species distributions (Guisan and Zimmermann, 2000; Rushton *et al.*, 2004). Concerning plant-environment relationships, Franklin *et al.* (2000) have provided a useful geographical perspective on issues associated with the choice of model for vegetation prediction.

For a comprehensive understanding of *Acacia* ecology in Qatar, a multifactorial approach was used based on field investigation to study the environmental factors that govern the distribution of this key species.

7.2 Multifactorial Approach of Studying *Acacia tortilis* Distribution at Local Scale

7.2.1 Effect of protection status

An initial objective of the project was to compare the condition and distribution of *Acacia tortilis* trees in representative protected and unprotected areas, as well as determine the anthropogenic factors affecting this tree in Qatar. It is interesting to note that protection status had both negative and positive effects on the *Acacia tortilis* condition and distribution. The results presented show significantly superior conditions of the trees based on all measured morphological characteristics assessed in the protected area compared with those in the unprotected one. These differences are attributed to the absence of grazing livestock and cutting practices, which in turn have led to enhanced growth and foliage condition. There are similarities between the positive impact of protected areas on the *Acacia tortilis* morphological characteristics in this study and those described by Wahbi *et al.* (2013) and Noumi *et al.* (2010) in Tunisia and Dangerfield *et al.* (1996) in Botswana.

Importantly, this research shows that *Acacia tortilis* trees in most of the unprotected site at the study area I, are suffering from intense anthropogenic activities. Table 5-7 shows that browsing and cutting are highly correlated, and are resulting in over utilisation, i.e. the tree that has been subjected to such intense animal browsing and/or cutting by pastoralists that there has not been enough time for regrowth. From a land management point of view, trees subjected to cutting should not be allowed to be browsed simultaneously. These findings are consistent with those of Abd el-wahab *et al.*(2013) in South Sinai, Egypt, who also found that *Acacia* populations were subject to intense anthropogenic disturbances resulting from overgrazing, cutting and urbanization. Similar results were also reported by Mwalyosi (1990) in Tanzania and Noumi *et al.* (2010). Other negative human-induced impacts on *Acacia tortilis* distributions detected in the present study relate to the regeneration process and will be discussed in further detailed in section (7.2.5).

7.2.2 Effect of topographic positions

The aridity conditions prevailing in the Qatari desert correspond very well to Noy-Meir's (1973) definition of the desert ecosystem as a "water controlled ecosystem with infrequent, discrete, and largely unpredictable water input". Therefore, in such conditions adequate water supply is a prerequisite for plant life and droughtiness the principal limiting factor of this harsh environment. The present findings demonstrate that *Acacia tortilis* trees are largely confined to the moister sites in study area I. More specifically, these moister sites are topographically controlled, being restricted to depressions and footslope microenvironments where runoff water collects and provides sufficient moisture for *Acacia* growth. These depressions receive water from more extensive elevated areas, so that soil water resources available for plant growth may be greater than the actual rainfall suggests. In this respect, an intimate relationship exists between *Acacia* growth and the spatial heterogeneity of the geomorphology of the area through the influence of topography on plant-available soil water and soil depth. These findings are consistent with the hypothesis that the heterogeneity of local topography and soil properties are important local determinants of the distribution of plant species in arid regions i.e. Hegazy *et al.,* (1998) in Saudi Arabia, Abd el-ghani and Amer, (2003) and El-bana *et al.*, (2007) in Sinai, Egypt and El-Bana and Al-Mathnani, (2009) in Libyan Sahara.

The study of soil properties confirms that soil water content and soil depth increase significantly in depressions and to a lesser extent in midslope positions, supporting the hypothesis that topography controls the transfer of water and eroded soil materials to low points in the landscape. Organic carbon and available phosphorus also increase significantly in the depressions, whilst impeding cemented petrogypsic horizons were consistently absent. These are considered to be additional key edaphic factors in determining *Acacia tortilis* distribution and tree health. It can therefore be argued that the deepest, most fertile soils with the most favourable moisture conditions for *Acacia* tree growth are located in topographic depressions and that effort for conservation and restoration of the species should be concentrated in such areas. In contrast, soil properties of high gypsum content, shallow soils with impeding cemented petrogypsic horizons and/or hard bedrock and unfavourable moisture conditions and slightly higher B horizon (n.b. although still only indicating slight salinity) electrical conductivity values were significantly related to the upper positions in the landscape, especially in extensive summit areas where *Acacia tortilis* trees were absent, or were present as scattered individuals of poor stature and growth.

It is interesting to note that the presence of gypsum in the soil (B horizons) is much greater in the upper topographic positions (50.7%), than in the depressions (1.31%). The presence of gypsum is always associated with the rocky outcrops (field observation). It is encouraging to compare this study observation with that reported by Kianian (2014) who found that physicochemical properties including gypsum are highly depenent on the upland geological characteristics in Iran.

Both the small and/or local scale approaches used in the current study has demonstrated the variation of gypsum content between topographic positions. These variations had not been reported in the study by Scheibert *et al.* (2005), however, they did recognize the depression soils "Rawda" as the main productive soils in Qatar for farming and thus, by implication are suggesting that such depressional soils are more favourable for plant growth. The measured higher gypsum content in the upper positions may explain the absences of *Acacia* trees. The common presence of cemented petrogypsic horizons in such topographic positions prevents root penetration and, therefore, limits access to both soil profile water and groundwater supplies. Failed plant growth and less productive soils has been linked to an increase in the soil gypsum (Poch *et al.*, 1998; Escudero *et al.*, 1999; Eftekhari and Asadi, 2001; Chigani *et al.*, 2012; Pascual *et al.*, 2012), so the absence of the *Acacia* trees in the upper positions is not surprising.

7.2.3 The regeneration of *Acacia tortilis*

This study has investigated the impact of several abiotic and biotic factors on the regeneration of *Acacia tortilis* in Qatar. The abiotic factors include several environmental factors (including soil water availability); the biotic factors considered in this study include animal and anthropogenic activities that will not only create disturbance in the study area, but also help in the dispersal of the *Acacia* seedlings. It was found that the germination of *Acacia tortilis* under the shade of the tree canopy was not optimal in area I. However, a high amount of the *Acacia* seeds pods were highly affected by the infestation of bruchid beetles, which have the potential of reducing the probability of the seedling recruitment (field observation).

An initial objective of the research was to compare the condition and distribution of *Acacia* trees in representative protected and unprotected areas. One of the most interesting findings was that the protected area had a negative effect on the *A. tortilis* regeneration process. This finding is also consistent with those of Noumi *et al.* (2010) who found that *Acacia tortilis* regeneration in protected areas was very poor, with only two seedlings observed among three hundred studied adult trees. In the current research, the importance of large mammals (herbivores) on the recruitment of *Acacia* seedlings in the unprotected area was also observed. In other words, large mammals (herbivores) may indirectly have a positive impact on the recruitment of *Acacia* seedlings (Miller, 1994b; Rhoades, 1996; Loth *et al.*, 2005; Goheen *et al.*, 2010; Rodríguez-Pérez *et al.*, 2011). Therefore, it was hypothesized in this thesis (see Chapter 3) that unprotected areas will favour regeneration due to the browsing of large mammalian herbivores contributes positively to the seed germination due to the breakage of seed dormancy (through feeding, digestion and excretion), as well as to increased dispersion. Thus, the unprotected area witnessed successful seeds germination, particularly in the depression and backslope positions where soil and water conditions are more favourable.

As mentioned in the research hypothesis, time and frequency of rainfall is considered to be an essential factor controlling germination and seedling establishment of the *Acacia tortilis* tree (Floret and Pontanier, 1982; Wilson and Witkowski, 1998; Rohner and Ward, 1999; Stave *et al.*, 2006). Although this data represents one year of good rainfall, observation in the current study indicates that rainfall time from September to December and frequency of rainfall events is critical and emphasizes the importance of rainfall on *Acacia* seedling establishment in the current season 2012/2013. The hypothesised correlation between time/frequency of rain and regeneration as essential factors for germination of the *Acacia* might be explained in three stages. Firstly, after the flowering season of the *A. tortilis* in Qatar which arises in May-June (Norton *et al.*, 2009), the seeds and/or pods of *Acacia* trees are eaten by mammalian herbivores (e.g. camels, goats or sheep) during summer season. Then, this eaten *Acacia* seeds/pods can potentially facilitate the dispersal of *Acacia* seedlings and improve germination by scarification of the seed coat and protecting from infestation by bruchid beetles (Miller, 1994b; Rohner and Ward, 1999). Thirdly, seeds therefore may be potentially advantageous to germinate once receiving an adequate water resource through early rainfall which might be the only water resource for the seeds in this arid country.

The regeneration and distribution of *Acacia* seedlings/saplings were topographically related, being predominantly in the depressions, and with more limited evidence of regeneration on the sloping sites (backslopes) of the unprotected area. There was no regeneration of *Acacia tortilis* on the summit positions in the study area I which were unfavourable for regeneration. The reason for having the greater amount of *Acacia* saplings in the depression is attributed to the presence of greater amounts of soil water content, greater soil depth, available P, and organic carbon (see chapter 5). It is important to acknowledge that an increase in the soil organic matter influences other soil properties by improving soil structure, moisture holding capacity, nutrient availability and enhanced microbial activity (Alexandra and Jose, 2005). In the present study, the presence of seedlings or recruitments in lower positions in the soil landscape is more likely due to indirect positive relationships between organic carbon and plant growth. The positive influences of high levels of organic matter on plant growth includes: encourages plant root development and penetration (Price *et al.*, 2009; Assogbadjo *et al.*, 2011), supplies nutrients such as phosphorus (Polglase and Attiwill, 1992) and a great influence on improves the soil's ability to store water from thus aiding seed germination (Hudson, 1994; Gutterman, 2001). These soil properties mentioned above follow the same trend on the study area II and III which exclusively selected for the regeneration study. They also confirmed the importance of soil water content, greater soil depth, available phosphorus and organic carbon in the regeneration and distribution of *Acacia tortilis* (see chapter 6). These soil properties were found to be higher in the areas of higher regeneration of *Acacia tortilis* such as the sapling position compared to the bare position.

The absence of elevated soil salinity, as judged by EC measurements and very small gypsum contents in soils of depressions suggests that higher amount of these soil properties may affect regeneration of the *Acacia* negatively. In the present study, much greater gypsum content and slightly higher subsoil EC values were found in those areas with less regeneration, such as the bare position (see section 5.1.2 and Table 6-2). In accordance with the present results, previous studies by Mehari *et al.* (2005) have demonstrated an effect of salinity (150 and 300 mM NaCl) on seedling growth, biomass production and water status of *Acacia tortilis* under greenhouse experiments were sensitive to increased salinity. They added all seedlings treated with salt solution exhibited leaf abscission. Although, the *Acacia tortilis* was reported as salt tolerant (Jaouadi *et al.*, 2010; Abari *et al.*, 2011; Jaouadi *et al.*, 2013), the negative effects of higher salt concentration on growth parameters of *Acacia tortilis* seedlings were reported by several authors (Al-Shaharani and Shetta, 2011; Kebbas *et al.*, 2013).

The adverse effect of gypsiferous soils, which depends on the amount of gypsum present in the soil and the depth at which it occurs, was also highlighted in this study (see section 7.2.2 and chapter 5). The gypsum content of less than 2% in the soils of depressions is not limiting to plant growth or regeneration according to (Van Alphen and de los Rios Romero, 1971; FAO, 1990) and is the threshold most plants can tolerate. In contrast to this, the presence of large quantities of gypsum and cemented gypsic horizons are likely to hinder regeneration on backslope and summit sites. In accordance with the present results, previous studies have, in addition, demonstrated that increased levels of gypsum (cemented petrogypsic horizon) have led to prevention of the penetration of roots and water into soil (Poch *et al.*, 1998; Chigani *et al.*, 2012).

It is concluded that the development of a surface soil crust in the soils of depressions at the protected site is related to fewer disturbances by large herbivores and that this could lower and inhibit the penetration and germination of seeds and reduce water infiltration. This limitation was not observed at the unprotected site (see section 5.1.9). These finding suggests that soil crusting may be an additional factor that explains the relative absence of the seedlings in the protection site. This also accords with earlier observations in the research literature, which show that the presence of a soil crust can lower and inhibit the penetration of seeds and reduce water infiltration (Van Bremen and Kinyanjui, 1992; Deines *et al.*, 2007).

7.2.4 Underground water

In reviewing the literature, *Acacia tortilis* has a well-developed root architecture, which enables it to draw on groundwater and to utilize constant moisture sources (Cole and Brown, 1976; Mordelet *et al.*, 1997; Ludwig *et al.*, 2003; Ludwig *et al.*, 2004; Do *et al.*, 2008). Therefore, it was hypothesized in this thesis (see Chapter 3) that depth to ground water is one of the factors controlling this tree’s survival in Qatar. The results presented in Chapter five show that for 94% of the sampled *Acacia* trees in study area I, the depth to the groundwater table was estimated to be between 20-25 m and 30-35m (see section 5.5). As the findings of a great deal of the previous work have shown that *A. tortilis* trees explored the soil profile to depths of up to 35 m to reach water (Ong and Leakey, 1999; Schroth and Lehmann, 2003; Deans *et al.*, 2005), it is concluded that mature trees in the present study could also tap groundwater supplies where there is no impeding layer, i.e. in the depressions. It is noteworthy to point out that measured depth to ground water in this research is calculated from isolated national well measurements (see methods chapter).

7.3 Conclusion

This thesis has given an account of and explanations for the environmental determinants for the distribution of *Acacia tortilis* under arid conditions in Qatar. The investigation has shown that the distinctive topography of Qatar has clearly resulted in a heterogeneous soil landscape with varying amounts and forms of edaphic factors, either chemical or physical within and between depressions and upland positions. The results of this study fulfil the stated objectives to investigate the significance of protection status and topographic positions on the morphological characteristics and spatial distribution of *Acacia tortilis*, and support the hypotheses that depressional land forms are the more suitable for the *Acacia* tree growth than the surrounding uplands. This is attributed to the superior soil water content, soil depth, organic carbon and available phosphorus contents. Conversely, the absence of *Acacia* trees in summit areas is mainly due to negligible soil water content and shallow soil depth (impeding or cemented horizons), as well as the potential of high content of gypsum, or $CaCO_3$ in soils leading to less productive and more stressful edaphic conditions for plant growth and survival.

This research confirms the importance of soil moisture and unimpeded access to groundwater supplies for *Acacia tortilis* growth. It provides additional evidence with respect to the difference between soil profile available water necessary for seedlings establishment and young tree growth in particular, and the importance of more permanent access to ground water sources for mature tree survival.

It was hypothesized that the effect of soil attributes are essential for explaining the differences in tree morphological characteristics. Multiple regression analysis revealed that the tree’s morphological characteristics such as the height, crown diameter and diameter at stem base of the *Acacia tortilis* was significantly correlated and affected by depth to water table, available phosphorus in B horizon, organic carbon and available phosphorus in A horizon, as well as volumetric water content in horizon A & B, and soil depth (section 5.8).

The complex and interrelated factors that were found to govern *Acacia tortilis* distribution in this research project are summarised in Figure 7-1. Topographic position at a local scale, in particular the existence of depressions is the most important environmental factor controlling the distribution of this tree in Qatar because it influences those soil and water conditions that more directly control the tree's growth and survival. Water is the key limiting factor in arid areas. Runoff of rain water from summit areas transports soil materials, nutrients and plant debris towards lower positions in the landscape and leads to higher soil moisture, available phosphorus and organic carbon in depressions. It is also hypothesized that the permeability of soils and sediments found within the depression positions, and the observed periodic ponding of water in such low-lying topographic sites, leads to preferential leaching of soluble salts and calcium sulphate during rainfall events. This has resulted in lower electrical conductivity values and smaller gypsum contents than on summits and backslopes, and hence to lower concentrations of these growth-limiting soil properties. In terms of the mature trees, the ability of the *Acacia tortilis* to draw on groundwater is essential for supplying water during dry periods. The absence of *Acacia tortilis* in summit positions is attributed by the present author mainly to the presence of cemented or impeding petrogypsic or petrocalcic soil horizons that prevent rooting and access to groundwater, and reduces profile available water. Near-surface bedrock present in some sampled transects has a similar effect.

In terms of the anthropogenic factors, both positive and negative impacts were observed. The negative impact on the mature trees was either through cutting by local people or by livestock grazing, which in turn, led to a direct effect on the tree's morphological characteristics such as the tree height, crown area, crown diameters and branch numbers tree seedlings were also heavily grazed upon so that sapling survival was minimal. Whereas the poor regeneration observed in the protected area is attributed to a lack of the positive impacts of ingestion by large and small mammalian herbivores that increase the germination rate, as well as protect the seeds from insect predators, such as the Bruchid Beetle. Moreover, seed ingestion also causes dispersal by mammalian herbivores move between the depression areas.

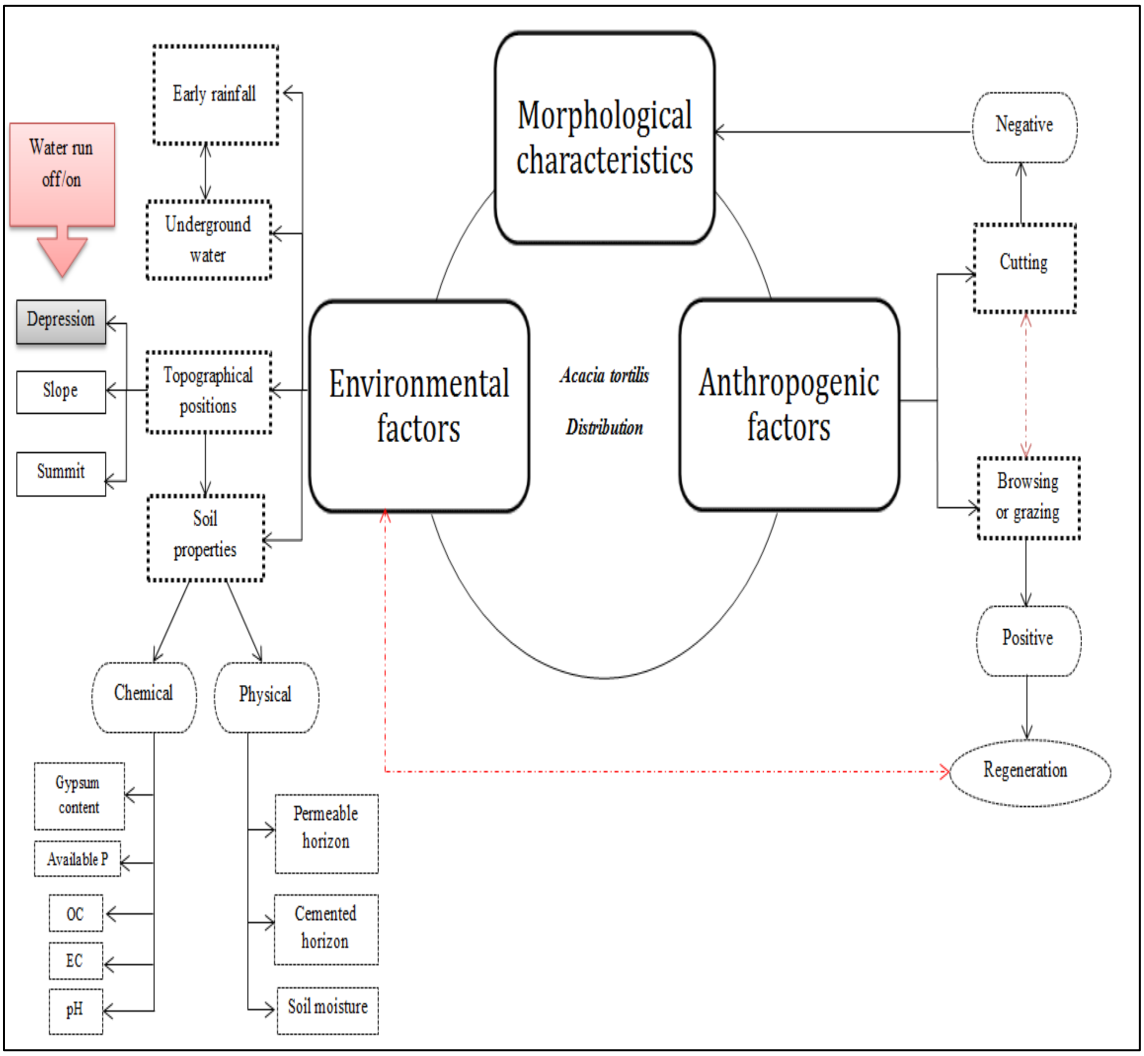


Figure 7-1: Relationships of the Distribution Determinants of *Acacia tortilis* in Qatar

Although the present study clearly suggests that the effects of soil development and human activity on the distribution of *A. tortilis* is complex and interrelated, it provides a useful starting point for future research that should be focused on gaining a better understanding of the tree dynamics. This includes more experimentally-based investigations of the restrictions imposed by petrogypsic and petrocalcic soils, the impact of intensive grazing and cutting of trees, and the factors leading to successful regeneration (e.g. the germination requirements of seeds under laboratory conditions and the field) of the *Acacia tortilis* trees in these sites, and in similar depression systems in other arid environments.

With regards to the effects of the environment, plant management and anthropogenic activities on the growth forms, the main conclusions are that factors including protection status, topographic position and its effects on soil depth, topsoil fertility and water availability, and human utilization (animal browsing or cutting), are the major factors underlying the various growth forms of the *A. tortilis* under arid conditions in Qatar. Combinations of these factors are sufficient to explain the distribution and morphological characteristics of *A. tortilis* in the studied areas.

Several limitations to this study need to be acknowledged. Although, the use of satellite data proved to be a useful tool to provide information needed to review and detect changes in vegetation cover, it could not fully replace field work as a tool for understanding the ecology and distribution of *Acacia* trees at the species level. The resolution of the data available and issues in arid areas with low green biomass are the main limits. Secondly, the most important limitation lies in the fact that further experimental approaches were not taken to examine the tolerances of *Acacia tortilis* seedling survival and young tree performance in relation to soil properties. This is mainly due to limited time available.

7.4 Recommendations for Further Research Work

Although there is a clear correlation between the environmental factors studied in Qatar and *Acacia* distribution, the results of this study did not explain the cause and effect, in relation to the occurrence of *Acacia tortilis* at lower or slope positions, or its absence from summits. Therefore, this needs to be established through further experimental investigations. To develop a more complete picture of whether these factors, such as chemical properties (i.e. available phosphorus and/or organic carbon) and physical properties (i.e. soil structure/ aggregation and soil-water content) are causing the existence of *Acacia* in certain positions or vice versa, additional studies will be required.

This research has thrown up many questions which are in need of further investigation. Firstly, experimental approaches (investigated experimentally) to assess how variation in water and nutrient availability such as available phosphorus content, organic carbon and soil moisture availability affects the recruitment, survival and performance of *Acacia tortilis* seedlings. On the other hand, contrasting responses to some factors that have been observed in this research such as gypsum content need to be studied on different regeneration processes (e.g. seedling growth or survival). From these experimental approaches seedling height, root length and survival percentage data need to be examined, in order to answer the following two questions: 1- how does *Acacia* genotype in Qatar differ in their respective growth rates? 2- What will be the percentage survival of the tree under proposed study over a period of a year?

Secondly, if the debate is to be moved forward, a better understanding of social factors involved needs to be developed. Such research should involve targeted people, e.g. livestock owners (or farmers), villagers etc. Government sector or policy makers and university specialists may also be involved at various stages for advice. It would then be interesting to evaluate the awareness of Qatari society concerning the importance of *Acacia* trees to their environment and livelihoods. Initially, techniques commonly used for participatory rural appraisal should be adopted (Oudwater and Martin, 2003; Payton *et al.*, 2003) to collect local knowledge about the land use practices, constraints and opportunities. The following questions could be explored via semi-structured informal interviews and the results refined by focus group discussions (Payton *et al.*, 2003):- Does the implementation of the environmental policies (see chapter one), aid in protecting the natural habitats on the ground? Does any further legislation or mitigation need be added to prevent the cutting or destruction of the habitats of these trees during developmental projects, the settlement of herds and farm expansions? With regards to the acacia tree, is the *Acacia tortilis* tree population decreasing or increasing? What is responsibility of local people towards the environment? Do local inhabitants undertaking a picnic or camping trip prefer to cut part of, or the entire, *Acacia* tree and for what reasons? A key policy priority should be to plan for the long-term care of the habitats of the trees? How aware are herders that soil and water conditions in depressions favour Acacia growth and need to be protected? Do they realize the level of browsing intensity that leads to damage? What would be the reaction to a restriction of livestock numbers so as to allow active regeneration and healthy growth?. This approach to gathering the data has a great deal of flexibility and it allows the researcher to interact directly with the views of several participants either individually, or in groups. Moreover, it allows participants to use their own words and swap their views, which gives deep meaning and understanding (Oudwater and Martin, 2003; Payton *et al.*, 2003; Wilkinson, 2004; Coleman, 2012).

Another possible area of future research would be to investigate how predators and mammalian herbivores affect the germination and recruitment of *Acacia* distribution. This can be applied through semi protecting areas, which temporarily eliminate grazing by fencing selected depressions with *Acacia* populations. To avoid any impact of pseudo-replication on conclusion relating to protected area I, replicate samples should be dispersed in space in a manner appropriate to the specific hypothesis being tested. Then, allow access to these selected areas at favourable times, preferably during the end of the flowering season in June and July to study the impact of the herbivores on seed dispersal and protection from predators. It is also suggested that to enhance germination phosphorus and/or manure should be added to depressions as a source of fertilizer, because available P and organic carbon have been established to be key soil chemical properties for the regeneration of the *Acacia* tree by the research reported in this thesis.

In spite of the limitations of the tested vegetation indices, the approach could be improved either by using high-resolution imagery in certain areas where the *Acacia tortilis* populates occur, or by using ground-based spectral sensors to help detect changes to the natural tree vegetation. Furthermore, it is worth mentioning that the capability of GIS to manage and integrate multiple datasets is helpful for the conservation planning of *A. tortilis* in Qatar, through detecting areas with a high degree of disturbance and stress, and establishing a sustainable use strategy and effective conservation program. Finally, based on the research findings, the following recommendations on management options are put forward:

In severely degraded areas

A reasonable approach to tackling this issue could be to use artificial regeneration by direct sowing at favourable micro-sites such as in depression positions. This can be achieved by seed collection and dispersal by hand at the most favourable times, preferably at the beginning of the rainy season in September and October.

In unprotected areas

Use rotational grazing, whereby grazing is allowed on some occasions and prevented at others, so as to enhance seedling recruitment. Reduce the number of grazing animals to minimize browsing pressure during critical life cycle stages, such as the saplings stages or through the early development of the seedlings. It is important to completely avoid (if possible) the removal of trees through enforcement of protection laws, or by securing tenure and using rights.

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APPENDICES

APPENDIX 1

Table 1: Geographic coordinates of each depressions (Dense/Sparse) in the study area I.

Site	**Replicate**	**Tree Density**	**QND Y-coordinate (meters)**	**QND X-coordinate (meters)**
Protected	1	Dense	393175.2	201272.1
		Sparse	393616.0	201278.6
	2	Dense	393175.1	201258.4
		Sparse	393627.5	201290.2
	3	Dense	392984.6	199520.2
		Sparse	393063.9	199702.7
Unprotected	1	Dense	397310.6	201763.3
		Sparse	395166.3	198179.4
	2	Dense	394549.0	202371.2
		Sparse	392435.1	201129.0
	3	Dense	393956.5	198075.7
		Sparse	394492.2	196865.2

APPENDIX 2: RANDOM TABLES FOR THE STUDY AREA I.

Table 1: Random orientations (in degrees from N) for transects:

1st transect	2nd transect
354	212
109	315
253	51
240	4
195	2
252	69
240	351
65	261
47	177
360	48
62	257
12	147
203	345
318	90
241	19
69	308
133	40
166	28
354	28
57	252

Table 1a: Random directions for paired samples on transects (1=right, 2=left)

2	2	1	2	1	2	1	1	2	2	2	1	1	1	1	2	2	1	2	1
1	1	2	1	2	1	1	1	2	2	2	2	2	2	2	2	2	1	2	1
2	1	1	2	2	1	1	2	2	2	1	1	1	2	2	2	1	1	2	1
1	2	2	1	1	2	1	2	1	2	1	1	2	1	1	2	1	1	2	2
2	2	2	2	2	2	2	2	2	1	2	1	2	2	2	1	1	1	1	1
1	2	1	1	1	1	2	1	2	2	2	1	2	2	1	1	1	1	2	2
1	1	2	1	2	1	2	1	2	1	2	1	2	1	2	2	1	1	1	1
1	1	1	2	1	1	2	2	2	1	1	1	1	1	2	2	2	1	1	1
1	1	1	2	2	1	1	1	1	2	2	1	1	1	1	2	1	2	2	1
1	1	2	1	1	1	2	2	2	2	1	2	2	2	1	1	1	2	2	1
2	1	2	2	2	1	2	2	1	2	1	1	2	2	1	2	1	2	1	2
2	2	2	2	2	1	1	1	1	1	1	1	2	1	1	2	1	1	1	2
2	1	2	2	1	1	2	2	2	2	2	2	2	2	1	1	1	1	2	2
1	1	1	1	2	1	2	2	2	2	1	2	2	2	2	2	1	1	2	2
2	2	2	1	1	2	2	2	2	1	1	2	2	2	2	2	1	2	2	1

2	2	1	2	1	1	2	2	1	1	1	2	1	2	2	1	1	1	2	1
2	1	2	1	2	2	1	2	2	1	1	2	1	1	2	2	1	1	1	1
1	1	2	1	1	1	1	2	1	2	2	2	1	1	1	2	1	1	2	1
1	1	2	2	2	1	2	2	2	1	2	2	2	2	2	1	1	1	1	1
2	1	1	2	1	1	1	2	2	2	1	1	2	1	1	2	1	1	2	2
2	2	2	2	2	2	2	1	2	2	1	1	2	1	2	2	2	2	1	2
1	2	2	2	2	2	2	1	1	1	2	1	2	1	1	2	1	1	2	2
1	2	1	1	2	2	2	2	1	1	2	1	1	2	2	2	2	2	2	1
2	1	2	1	1	2	1	2	1	2	2	2	2	1	1	1	1	2	1	1
1	1	2	1	2	2	1	1	2	2	2	1	2	2	2	1	1	1	1	2

Table 1b: Random distances for paired samples on transect (between 3 and 20m)

8	17	6	7	10	8	6	19	5	18	4	4	15	18	16	8	17	16	12	4
12	7	12	6	5	10	19	12	12	4	5	8	13	9	16	12	8	13	7	14
4	11	14	13	3	11	4	4	11	9	17	16	6	15	16	10	17	6	7	19
5	19	3	14	19	16	7	17	19	9	8	15	6	8	16	10	17	20	11	9
5	13	14	10	8	17	3	9	17	15	13	5	4	12	4	6	18	7	7	10
15	18	9	6	8	4	10	8	16	13	20	5	19	17	15	7	12	19	17	20
11	16	3	20	8	6	3	16	3	17	10	4	15	13	11	3	14	7	20	20
6	13	11	4	11	9	19	3	4	9	15	3	13	9	6	19	20	9	3	15
11	7	6	4	14	4	6	3	4	6	16	10	8	8	4	14	10	4	12	20
5	14	5	5	3	12	4	15	17	4	10	14	5	11	17	19	4	14	4	16
3	4	6	5	18	9	8	13	19	16	14	16	14	10	6	5	18	6	17	9
18	14	5	14	13	6	11	12	15	6	4	12	20	9	5	19	14	3	20	14
13	14	6	13	18	6	4	16	5	9	19	4	6	13	14	17	9	16	4	7
19	16	3	3	9	19	20	15	16	12	6	14	7	16	19	13	20	9	19	8
15	19	14	19	11	15	8	17	4	7	7	5	10	10	12	10	7	14	3	15
13	20	8	16	3	11	8	8	5	14	17	5	4	10	15	7	14	9	15	12
17	16	12	16	6	19	4	15	14	11	11	4	15	5	5	16	13	14	17	10
18	13	15	4	14	4	8	13	8	5	16	5	10	3	20	7	9	3	12	13
20	19	11	18	8	16	3	10	14	17	10	6	20	8	12	4	5	19	18	16
3	13	12	19	19	16	12	4	16	4	7	6	10	8	15	16	3	17	19	13
18	3	11	20	5	13	16	17	13	8	3	8	14	14	3	15	10	16	14	12
14	5	5	18	20	6	14	9	16	7	15	8	5	20	17	15	6	17	5	13
20	18	11	17	12	13	4	13	7	12	10	6	9	19	16	14	16	9	6	12
12	11	18	12	15	8	4	16	16	4	11	7	5	11	5	10	9	14	6	4
11	18	18	6	20	5	16	4	20	10	13	19	16	7	12	10	18	13	3	15

Table 1c: Random locations for trees, distance (m) into transect section (along transect): Selecting trees in transect sections: Locate position by distance into section (from depression end), direction from transect and distance from transect. Then select nearest tree over 60cm tall.

76	5	43	25	27	13	26	52	54	46	12	72	47	83	18	23	35	100	83	96
77	45	9	86	52	67	76	100	71	82	0	58	86	15	9	53	62	35	29	57
58	58	62	92	98	57	100	86	1	90	73	43	4	46	32	5	80	4	40	85
75	69	1	70	71	17	18	97	80	43	35	89	69	62	77	76	75	21	87	27
65	72	57	73	31	14	78	68	14	33	78	39	98	94	23	60	12	40	62	62
12	65	79	23	29	48	19	40	48	60	44	18	28	84	74	86	83	33	100	59
50	73	23	58	85	91	100	94	25	91	44	63	13	90	69	99	2	23	20	97
35	37	45	81	92	55	81	48	37	70	4	63	69	58	83	93	41	94	83	8
9	58	57	40	64	3	42	23	66	38	5	33	91	58	83	41	73	69	68	50
14	11	6	99	25	5	73	40	17	74	9	81	61	86	29	0	78	97	25	52
20	5	50	9	8	81	50	71	28	96	59	100	90	3	31	54	37	44	48	9
67	98	64	32	84	45	81	56	20	54	24	99	19	89	52	20	75	94	40	91
43	28	22	51	59	38	36	76	19	54	84	12	76	41	32	22	90	0	60	89
70	60	84	6	95	79	7	100	33	31	86	23	34	3	84	32	24	61	80	44
25	97	98	73	6	36	59	97	88	7	97	2	42	75	81	9	13	80	10	78
0	18	85	56	59	53	91	54	47	18	49	61	15	15	56	75	22	23	82	14
53	19	51	53	28	71	19	97	40	9	22	11	82	14	26	75	35	94	84	62
28	34	28	83	83	88	43	11	18	46	22	41	63	61	68	54	28	77	35	26
95	94	75	86	19	33	75	5	97	0	54	89	74	25	23	34	93	83	43	45
91	39	23	79	44	65	3	30	41	92	76	55	81	32	46	84	5	57	57	85
39	27	96	32	39	98	95	58	85	64	35	37	6	40	38	55	59	80	70	19
2	15	62	45	83	7	77	53	62	0	46	21	96	41	54	96	16	33	74	30
67	40	60	75	68	59	56	91	38	3	64	44	50	39	100	90	84	22	76	48
84	37	17	11	20	41	18	54	88	21	92	96	76	61	76	36	16	31	39	34
98	13	9	11	32	31	50	43	79	45	16	12	74	16	99	55	50	59	43	80

Table 1c-1: Direction from transect (1 = right, 2 = left)

2	2	1	2	1	1	1	2	2	1	2	1	1	2	2	1	2	1	1	1
1	1	2	2	2	2	1	1	1	2	2	2	1	1	1	1	2	1	1	2
1	1	1	2	1	2	2	1	2	1	1	1	1	2	1	1	2	1	2	2
2	2	2	1	1	2	2	1	2	2	2	1	2	1	1	2	1	1	1	2
1	2	2	1	1	1	2	2	1	2	1	1	1	2	2	1	1	1	2	2
2	2	2	1	2	1	2	1	1	1	2	1	1	1	2	2	2	2	1	1
2	2	1	2	1	2	1	1	1	1	2	2	2	1	1	1	2	2	1	1
2	2	2	2	2	2	2	2	2	2	2	2	1	2	2	2	2	1	1	1
2	2	2	1	2	2	1	1	1	2	1	1	2	1	2	2	2	1	1	1
1	1	1	1	2	1	1	2	1	2	1	2	2	2	2	1	1	2	1	2
2	2	1	1	2	1	1	2	1	1	2	1	2	2	2	2	2	1	1	2
2	2	1	2	1	2	1	2	1	2	2	2	2	1	2	1	2	1	2	1

2	1	2	2	2	2	2	1	2	1	2	2	1	1	1	2	2	2	1	1
2	2	1	1	2	1	1	2	2	2	2	2	1	2	1	2	2	2	2	2
2	2	2	1	2	1	2	1	2	2	1	1	2	1	1	1	1	1	2	1
1	1	2	1	1	1	2	2	2	1	1	2	2	1	1	1	2	2	2	1
2	2	2	2	2	2	2	1	2	1	1	1	1	1	2	2	1	2	2	2
2	1	1	1	2	2	1	2	1	2	1	1	2	1	1	2	2	1	1	1
1	1	1	2	2	2	2	1	2	1	1	2	2	1	1	1	2	1	1	2
1	1	2	1	1	2	2	2	1	1	1	2	2	2	1	1	2	2	2	1
2	1	1	2	1	1	2	2	1	2	2	1	2	1	2	2	2	1	2	1
1	1	1	2	1	2	1	1	1	1	1	2	2	1	1	1	2	1	2	2
2	2	1	2	2	2	2	1	2	2	1	2	2	1	1	2	2	1	1	2
2	1	1	2	2	1	1	1	2	2	1	1	1	2	2	2	1	2	1	2
2	1	2	2	2	1	1	2	1	2	1	2	1	1	2	1	1	2	2	2

Table 1c-2: Distance from transect centre (m)

4	6	3	8	8	9	4	5	9	5	7	0	0	6	8	5	6	1	4	1
1	3	6	6	6	9	5	3	5	7	0	7	4	1	6	1	10	9	6	4
8	2	4	10	10	2	9	0	1	8	4	6	9	9	0	6	5	5	6	7
2	9	1	0	9	5	8	0	0	3	10	2	7	7	10	2	10	6	7	1
7	4	0	2	10	9	0	0	7	0	6	4	4	1	0	5	2	5	4	4
9	8	5	10	7	1	3	4	3	9	5	6	6	6	5	3	4	0	0	7
0	1	3	8	4	9	4	1	7	4	5	6	2	10	1	3	7	9	5	9
10	9	3	5	5	9	9	4	7	8	3	1	6	8	4	7	0	3	0	3
0	0	3	7	10	2	4	9	5	1	10	1	10	7	8	5	8	2	8	4
9	9	1	4	0	0	2	3	7	1	10	0	9	5	2	8	4	6	0	9
9	9	4	4	1	5	6	1	5	9	5	4	3	2	9	2	8	5	10	7
0	5	7	2	5	9	5	6	5	9	10	5	7	6	7	7	4	4	8	2
6	1	2	4	5	5	9	9	5	10	5	1	3	2	4	0	3	7	10	8
10	1	7	0	0	4	10	3	10	9	4	7	10	3	2	8	10	10	5	3
3	7	4	5	7	5	8	0	4	0	2	0	0	10	2	7	7	6	2	3
8	9	4	3	9	1	7	1	1	5	2	1	2	9	8	10	4	3	2	0
6	0	1	10	1	1	8	0	2	10	9	10	8	8	0	1	1	2	8	4
8	8	2	6	4	9	9	8	7	5	7	10	0	10	7	9	8	4	10	4
8	10	6	9	3	6	0	5	9	9	5	0	5	1	6	5	7	0	3	3
0	3	2	4	10	2	3	7	10	0	9	5	8	5	8	6	0	9	8	3
3	7	6	5	6	9	0	7	2	10	5	9	8	6	10	3	1	6	1	2
7	3	10	9	2	0	9	6	8	10	6	2	1	10	4	0	10	2	6	10
5	2	7	10	1	5	5	6	6	6	2	9	4	7	2	9	5	5	4	9
10	8	7	5	5	7	4	9	4	4	6	8	3	4	9	1	0	0	8	4
8	7	10	10	9	3	2	7	5	3	1	6	5	8	8	4	0	9	2	5

APPENDIX 3: SOIL DESCRIPTION FORM

Project: Al Safran PhD Qatar______ **Site / Profile No.** _______ **Map/GPS Ref:** ________________________

Location: ____________________________ **Described by:** M. Al Safran__ **Date:** _ _________________

Soil Classification Subgroup:_______________________________________ **Soil Series:** _______________

Elevation (m O.D.): _____ **Slope (°):** ___ **Slope form:** _______ **Slope Shape:** **Slope Position:**_______

Relief/Landscape Position: ______________________________________ **Aspect:**________

Parent Material: ____________________ **Land Use/Vegetation:** ___________________ __________________

Soil Surface/ Humus Form: ____________________ **Erosion/Deposition:** ________ __________________

Depth to slowly permeable horizon (cm): ____ **Depth to $CaCO_3$** _______ **Rock Outcrops:** _______ **Soil Drainage Class:** ________

Soil Samples Collected:

____

Give sample numbers, horizons and depths

Profile Description (*describe each soil horizon recognized*)

▶Horizon 1: _______ **Depth (cm):** _______ **Moisture:** _______ **Decomp. (O, F, H only)**

Soil Matrix Colour: ___________ **Mottle Colour: 1.**__________2.__________ **Frequency:** _________________

Texture_____________________ **Stone Abun/Size:** ____________ **Stone Type:** __ _________________

Structure Shape: _____________ **Structure Size:** ______________ **Structure Degree:** __________________

Consistence (dry or moist): _________________ **Stickiness & Plasticity (wet):** __________ __________________

Root Abundance: _________ **Root Size:** _______________ **Root Nature:**

Pedogenetic features: ______________________________________ **Humose ? (A only):** ______________

$CaCO_3$ (HCl test): ___________________ Soil pH:___________ Boundary: ___
____

▶**Horizon 2:** ________**Depth (cm):** ________ **Moisture:** ________ **Decomp.** (O, H only)
____

Soil Matrix Colour: ______________ **Mottle Colour: 1.**__________2.__________ **Frequency:**
____

Texture: ________________________ **Stone Abun/Size:** ________________ **Stone/Rock Type:**
____

Structure Shape: _____________ **Structure Size:** ____________ **Structure Degree:**
____

Consistence (dry or moist): ________________ **Stickiness & Plasticity (wet):** ____________
____

Root Abundance: ______________ **Root Size:** ________________ **Root Nature:** _
____

Pedogenetic features: ____ **Humose ?** (A only):
____

$CaCO_3$ (HCl test): ___________________ **Soil pH:** ____________ **Boundary:** ___
____

▶**Horizon 3:** _______ **Depth (cm):** ________ **Moisture:** ________ **Decomp.** (O only)

Soil Matrix Colour: ______________ **Mottle Colour: 1.**_________**Frequency:** ___________
____

Texture: ________________________ **Stone Abun/Size:** _______________ **Stone/Rock Type:**
____

Structure Shape: _______________ **Structure Size:** ____________ **Structure Degree:**
____

Consistence (dry or moist): ________________ **Stickiness & Plasticity (wet):** ____________
____

Root Abundance: _______________ **Root Size:** ________________ **Root Nature:** _
____

Pedogenetic features: ____ **Humose ?** (A only):
____

$CaCO_3$ (HCl test): ___________________ **Soil pH:** ____________ **Boundary:** ___
____

APPENDIX 4: *Acacia* Description Form

Project: AlSafran PhD Qatar __ Site / Profile No. ________ Map/GPS Ref: ___________________________

Location (STRIP NO.): ___________________Described by: _M. Al Safran__ Date: ________

Relief/Landscape Position: ____

Section length: ___________________ Section Width: 20m

Tree Description

▶**Tree 1:** ___________ **Height (m):** _______________________________

stem Numbers:___________________

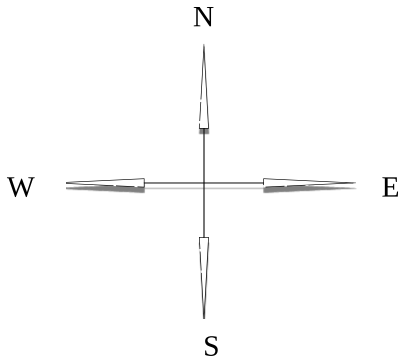
DBH (or if multi stems) :

Crown area:____________________

Branches No. (For multi stems per stem):

1-………………….
2-………………….
3-………………….
4-………………….

Crown direction



Proportion of branches:

- Browsing

No browse	Some browse	Completely browse

- Cutting

No cutting	Some cutting	Whole branch

- Leaves

No leaf	Partial coverage	Fully coverage

Seedling establishment within 3m

Numbers:
Distance from the tree stem:

APPENDIX 5: Transect Description Form

Project: **Al Safran PhD Qatar** **Site / Profile No. _______** **Map/GPS Ref:**
____

Location (transect NO.): _________________ **Date: _____________Compass reading:_______**

Slop angle:___________ **Slope Length:____________**

GPS Ref Start:_____________________ **GPS Ref End:________________________**

GPS elevation start:___________________ **GPS elevation end:**
____

Section length: 20m **Section Width: 20m** **Starting point:** from the central point of each sampling depression

Regeneration: 1 = (none) 2= (below 50%) 3 = (more than 50%) 4 = (100%), per plot

Plot	Tree name and number				Regeneration				Location			Notes
	At	Ae	Zi	Le	1	2	3	4	Dep	Slope	Sum	
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												

11												
12												
13												
14												
15												
16												
17												
18												
19												
20												
21												
22												
23												

APPENDIX 6: Regeneration Description Form (Study area II & III)

Project: Al Safran PhD Qatar   Site / Profile No. ________   Map/GPS Ref: ___________________________

Location (quadrat NO.): ___________Date: _____________Compass reading:_______

Slop angle:___________   Quadrate: 5m residue

Seedlings will be selected for less than 60 cm height (Kennenni and Maarel, 1990).

Regeneration: 1 (none)   2 (below 50%)   3 (more than 50%) 4 (100%), per plot

(Sheet for each plot)

▶ **Height (m):** ________________________________**stem numbers:**________________

DBH (or if multi stems) : ____________________________

Branches No. (For multi stems per stem):
1-………………….
2-………………….
3-………………….
4-………………….

▶ **Height (m):** ________________________________**stem numbers:**________________

DBH (or if multi stems) : ____________________________

Branches No. (For multi stems per stem):
1-………………….
2-………………….
3-………………….
4-………………….

▶ **Height (m):** ________________________________**stem numbers:**________________

DBH (or if multi stems) : ____________________________

Branches No. (For multi stems per stem):
1-………………….
2-………………….
3-………………….
4-………………….

▶ **Height (m):** ________________________________**stem numbers:**________________

DBH (or if multi stems) : ____________________________

Branches No. (For multi stems per stem):
1-………………….
2-………………….
3-………………….
4-………………….

Table 1: Regeneration survey, direction of paired samples (degrees from North).

210	321	42	185	223	311	118	153	38	99	168	55	66	2	292	218	15	332	68	171
104	310	316	300	244	62	217	221	253	313	8	179	60	196	308	341	336	232	175	129
131	76	229	326	217	65	131	356	143	202	291	292	54	311	144	177	350	38	302	172
261	144	36	261	125	88	49	80	31	168	65	228	73	328	42	158	130	97	51	242
309	320	328	138	132	271	329	128	78	155	60	248	344	305	29	279	232	275	264	346
126	93	13	108	62	72	231	96	90	279	66	231	6	317	130	268	25	290	249	33
347	349	15	250	287	354	238	105	82	236	249	263	345	269	299	160	75	38	13	288
344	223	356	317	178	256	244	68	254	237	77	310	10	43	78	20	15	170	176	213
75	60	248	333	128	64	269	9	272	58	108	226	350	184	285	32	169	79	350	329
277	298	136	30	280	309	304	162	198	156	277	66	108	61	236	288	55	333	41	37
222	237	182	174	86	328	186	88	200	182	181	207	190	300	10	237	357	116	268	106
331	197	275	47	305	347	55	313	228	136	328	59	311	335	283	12	154	309	230	19
217	91	18	92	294	206	138	191	355	173	21	327	323	62	333	201	344	94	214	182
253	15	262	319	305	203	296	330	229	124	158	28	69	319	178	260	261	317	180	277
268	85	253	71	134	64	62	351	217	280	207	122	238	140	301	40	210	68	205	102
139	131	166	44	138	185	119	211	328	139	204	210	339	138	48	78	195	274	154	82
91	229	210	196	311	198	348	43	206	257	297	172	352	98	274	292	254	12	28	120
14	355	123	114	168	60	291	334	121	174	46	290	39	313	334	50	2	232	105	164
170	75	62	138	206	178	80	214	345	263	109	192	65	267	300	318	282	205	203	266
233	273	144	285	251	193	360	319	159	338	1	82	269	162	94	333	334	136	229	184
101	320	332	303	346	72	23	153	217	187	343	256	18	256	77	5	3	77	336	138
187	171	82	245	197	225	154	219	260	326	276	54	26	340	189	136	297	286	352	326
89	58	130	151	230	10	146	26	245	79	271	237	177	63	144	61	277	53	34	348
108	292	117	232	206	115	145	333	77	315	50	229	306	89	173	195	359	177	239	227
235	172	31	78	334	192	41	232	30	30	126	83	359	231	358	37	82	5	217	48

Appendix 7

Table 1: Monthly Mean NDVI Values of Acacia, Mixed, No Acacia and Bare Soil in 1998 and 2010.

Vegetation Type	1998				
	May	Jun	Aug	Nov	Dec
Acacia	0.100 **c**	0.096 **c**	0.094 **c**	0.096 **c**	0.095 **c**
Bare soil	0.099 **c**	0.095 **c**	0.093 **c**	0.096 **c**	0.093 **c**
Mixed	0.110 **b**	0.106 **b**	0.101 **b**	0.108 **b**	0.106 **b**
No acacia	0.147 **a**	0.139 **a**	0.130 **a**	0.128 **a**	0.121 **a**
Vegetation Type	**2010**				
	April	**May**	**Jun**	**July**	**Dec**
Acacia	0.096 **b**	0.087 **b**	0.088 **b**	0.080 **b**	0.087 **b**
Bare soil	0.097 **b**	0.088 **b**	0.087 **b**	0.082 **b**	0.088 **b**
Mixed	0.098 **b**	0.089 **b**	0.087 **b**	0.082 **b**	0.089 **b**
No acacia	0.120 **a**	0.107 **a**	0.101 **a**	0.099 **a**	0.127 **a**

Means that do not share a letter within each column are significantly different according to Tuky's test (P<0.05)

Table 2: Monthly Mean of SAVI Values of Acacia, Mixed, No Acacia and Bare Soil in 1998 and 2010.

Vegetation Type	1998				
	May	Jun	Aug	Nov	Dec
Acacia	0.086 **c**	0.082 **b c**	0.080 **b c**	0.078 **c**	0.078 **c**
Bare soil	0.084 **c**	0.080 **c**	0.078 **c**	0.077 **c**	0.076 **c**
Mixed	0.091 **b**	0.087 **b**	0.084 **b**	0.084 **b**	0.083 **b**
No acacia	0.114 **a**	0.107 **a**	0.099 **a**	0.094 **a**	0.088 **a**
Vegetation Type	**2010**				
	April	**May**	**Jun**	**July**	**Dec**
Acacia	0.085 **b**	0.076 **b**	0.073 **b**	0.070 **b**	0.077 **b**
Bare soil	0.084 **b**	0.077 **b**	0.072 **b**	0.071 **b**	0.077 **b**
Mixed	0.086 **b**	0.077 **b**	0.072 **b**	0.071 **b**	0.077 **b**
No Acacia	0.098 **a**	0.089 **a**	0.078 **a**	0.081 **a**	0.100 **a**

Means that do not share a letter within each column are significantly different according to Tuky's test (P<0.05)

Appendix 8

Table 1: Effect of Protection status, Topography, Tree Density, Sampling and Horizon on Soil Properties in the Study Area I (*n*= 222 Each Horizon); ±SEM.

Variable	Protection status		Topography			Tree density		Sampling		Horizon	
	Protected	Unprotected	Depression	Slope	Summit	Dense	Sparse	Under tree	Bare Soil	A	B
Soil pH	8.37 [a] ± 0.03	8.37 [a] ± 0.03	8.58[a] ± 0.03	8.31[b] ± 0.03	8.07[c] ± 0.04	8.39[a] ±0.03	8.34[a] ± 0.03	8.57[a] ±0.02	8.26[b] ±0.03	8.36 [a] ±0.03	8.38 [a] ±.03
EC (mS/cm)	1.85 [a] ±0.11	1.61[a] ±0.10	0.6[c] ± 0.04	1.9 [b] ±0.10	3.7[a] ± 0.15	1.75 [a] ±0.10	1.79[a] ±0.12	0.65[b] ± 0.03	2.37[a] ±0.10	1.47 [b] ±0.07	2.05[a] ± 0.13
Available P (µg/ml)	0.57 [a] ± 0.06	0.53 [a] ± 0.05	0.79[a] ± 0.06	0.529[b] ±0.06	0.14[c] ± 0.03	0.57 [a] ±0.05	0.53[a] ± 0.05	0.99 [a] ±0.08	0.32 [b] ±0.03	0.96 [a] ±0.06	0.14 [b] ± 0.01
Gypsum %	19.96[a] ± 5.70	14.16[a] ± 4.51	1.31[c] ± 0.07	15.96[b] ± 4.87	50.7[a] ± 5.47	16.03[a] ±4.71	18.08[a] ±5.61	1.39 [b] ±0.09	27.50[a] ±0.01	---------	--------
Organic Carbon %	0.49 [a] ±0.03	0.29 [b] ±0.03	0.59[a] ± 0.04	0.35[b] ± 0.04	0.08[c] ± 0.01	0.41[a] ±0.03	0.36 [a] ± 0.03	0.74[a] ±0.04	0.20[b] ±0.02	---------	--------
Soil Water (θ m^3 m^{-3})	0.04[a] ± 0.002	0.04[a] ±0.002	0.06[a] ± 0.003	0.03[b] ± 0.001	0.01[c] ±0.001	0.04[a] ±0.003	0.03[b] ±0.002	0.06[a] ±0.004	0.03 [b] ± .001	0.02[b] ±0.001	0.05[a] ±0.003
Soil depth	30.65[a] ±1.77	34.14[a] ±1.62	46.46[a] ± 2.08	23.87[b] ±0.73	20.19[b] ±0.80	35.7 [a] ± 2.03	28.65[b] ±1.13	45.62[a] ±2.51	25.14[b] ±0.79	--------	-------

Means across a row for each treatment followed by the same letter are not significantly different at $p < 0.05$ by Tukey's test

Appendix 9

Table 2: Differences of the Soil Chemical Indicators between the Regeneration Areas (II and III), Sampling Positions and Soil Horizons

Soil Properties	Areas		Regeneration status		Soil Horizon(n= 16 each horizon)	
	Area (II)	Area (III)	Sapling sample	Bare sample	A	B
Available P (µg/ml)	0.50 ±0.13*a*	0.41 ±0.08*a*	0.67 ±0.10**a**	0.24 ±0.08**b**	0.781 ±0.13**a**	0.13 ±0.04**b**
pH	8.51 ±0.07*a*	8.56 ±0.03*a*	8.65 ±0.06**a**	8.52 ±0.07**a**	8.59 ±0.04**a**	8.47 ±0.05**a**
Electric conductivity (mS/cm)	1.66 ±0.42 *a*	0.85 ±0.21 *a*	0.25 ±0.02**b**	2.26 ±0.33**a**	0.84 ±0.20**a**	1.7 ±0.43**a**
Soil water content(m^3 m^{-3})	0.036 ±0.003*a*	0.03 ±0.004*a*	0.42 ±0.004**a**	0.024 ±0.003**b**	0.022 ±0.002**b**	0.043 ±0.004**a**
#Organic carbon (%)	0.73 ±0.13*a*	0.66 ±0.14*a*	1.03 ±0.06**a**	0.36 ±0.04**b**	–	–
***Gypsum content (%)**	17.99 ±6.48*a*	1.57 ±0.18*b*	1.41 ±0.1**b**	18.14 ±6.42**a**	–	–

Mean values in the same row which are not followed by the same letter are statistically significant ($p < 0.05$) as determined by Tukey's HSD-test.

*#Organic carbon was analysed for horizon A only; *Gypsum content was analysed for horizon B onl*