A DESCRIPTION AND CONSERVATION ASSESSMENT OF THE VEGETATION IN THE EASTERN HAJAR MOUNTAINS, OMAN



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ABSTRACT

This thesis describes for the first time the plant communities of the Eastern Hajar Mountains of Oman and reveals the primary environmental variables affecting their composition and distribution. Following very extensive fieldwork, 208 species were described from the above-ground vegetation; a synopsis of the soil seed bank composition was also presented and compared with the above-ground communities. I then used species distribution modelling (SDM) to predict the current distribution of the key species in unsurveyed sites within the Eastern Hajar to provide a full dataset for robust conservation planning decisions. A systematic conservation planning (SCP) exercise was carried out using the predicted SDMs to highlight the priority areas for conservation.

In the first analytical chapter, I describe four well-distinguished plant communities that were identified between an elevation of 1000m and the highest point in the mountains at about 2200m. I identified and quantified the communities using Two-Way Indicator Species Analysis (TWINSPAN) classification, Detrended Correspondence Analysis (DCA) and Canonical Correspondence Analysis (CCA) ordinations. I found annual rainfall, total nitrogen and total calcium to be the most important environmental factors affecting the distribution of plant communities. The sample plots were heavily grazed by livestock, but in contrast to expectations from many studies on the vegetation of arid lands, any grazing effect on plant community distribution appears to be overridden by the other environmental variables.

The vegetation of the Eastern Hajar Mountains is profoundly degraded, and the mountains have been under a prolonged drought for the last 20 years, with more expected dryness in the next 40 years. Also, overgrazing and fast development of the mountains has placed high pressure on their vegetation, which has led to overexploitation of the vegetation and contributed to the lack of regeneration of

many of the principal trees of the mountains. The ability of the vegetation of the mountains to regenerate after severe drought or disturbance is mostly dependent on the soil seed bank. I found species richness and diversity to be very low in the seed bank, with a total of 34 species. Twenty-one species (i.e. that were identified to species level) of a total recorded flora of 208 species were found in both the seed bank and the above-ground vegetation. I explain the relative incongruence by factors comprising disturbance (for instance grazing and development), drought and other biotic and abiotic factors.

Although the landscape of the Eastern Hajar Mountains is mostly gravelly and rocky, and the vegetation is concentrated in the wadis, runnels and cliffs, the mountain range supports a diverse flora representing 31% of the total flora of the country. In 2016 the mountains were proposed as an Important Plant Area (IPA) in the Arabian Peninsula (AP), due to this rich flora and the presence of national and regional endemics, using the newly revised IPA criteria. Although the IPA approach proved to be a powerful tool in identifying sites for plant diversity, they are inefficient compared to other prioritisation methodologies and require more land to conserve less biodiversity.

I, therefore, identified areas with high conservation value in the Eastern Hajar Mountains using a combination of my species distribution modelling results and Zonation prioritisation analysis. I made species distribution models using classification tree analysis (CTA), generalised additive and linear modelling (GAM, GLM), MAXENT and Random Forest (RF) modelling techniques, in addition to ensemble modelling techniques. Ensemble models outperformed all of the other methods with an AUC ≥0.9 for 99% of the species (although the modelling performance was generally good for most of the individual modelling techniques). Although the SDMs returned high AUC values for most of the species, due to the

inherent uncertainty when projecting ranges from small numbers of observations, the models produced in this study, should be further tested with other evaluation methods, and ideally ground-truthed with a new collection of field data. My analysis showed that the existing protected areas had limited overlap with the highest priority conservation areas. Furthermore, and from the five different Zonation analysis scenarios used to identify the priority areas within Eastern Hajar, the top 10% priority conservation areas were identified to be at mid-elevations and outside the existing protected areas. I believe my analysis will, therefore, help to find more representative and efficient conservation areas and guide further conservation activities in the country.

In the last analytical chapter, I compare the results of the IPAs (a criteria-based selection approach) with those of a complementarity- based approach to assess the compatibility of the IPA as an approach to prioritise areas for conservation, using the modelled ranges. I found that the average area overlap between the two approaches was about 85%. I also found that the top 50% of the priority conservation areas selected by Zonation were almost identical with the proposed IPAs, with equal species richness. Integration of the complementarity-based approach and the IPAs will help in locating high priority areas for the plant conservation.

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CHAPTER 1

INTRODUCTION

1 CHAPTER 1: INTRODUCTION

1.1 GENERAL BACKGROUND: OMAN AND THE ARABIAN PENINSULA

The Arabian Peninsula (AP), with Oman being situated at the south-eastern margin, lies between the Red Sea and the Persian Gulf (Arabian Gulf), occupying an area of about 2.7 million km^2, approximately 2% of the world's land surface (Figure 1.1). The Peninsula's constituent countries are Kuwait, Bahrain, Qatar, the United Arab Emirates (UAE), Saudi Arabia, Oman, Jordan, Iraq and Yemen. The Peninsula is characterised by diverse physiography, ranging from large gravel and sandy deserts, wet and dry wadis, upland plateaus, dry mountains, cloud-covered mountains and terraced agriculture (Ghazanfar and Fisher, 1998, Hegazy et al., 2016). The Arabian Desert (Rub' al Khali), the largest sand desert in the world, with an area of about 650,000km^2, forms a large part of the Arabian Peninsula. The mountains of the Peninsula are considered centres of plant richness and diversity, with great floristic and ecological importance for the area. Examples of these mountains are the Asir and Hejaz Mountains in Saudi Arabia, the Hajar Mountains in northern Oman, and the Hadhramaut range in Yemen (Glennie, 1995, Glennie, 2005, Ghazanfar and McDaniel, 2015).

Oman is located between Yemen and the UAE (Figure 1.2.), covering a total area of about 309,500km^2. Physically, Oman is isolated, bordering the Gulf of Oman, the Arabian Sea and the Arabian Desert (i.e. the Empty Quarter, or Rub' al Khali). The vast Empty Quarter forms a barrier between Oman and the Arabian interior. The Hajar Mountains form another barrier by extending from Musandam in the north of the country to the easternmost point of it – the Eastern Hajar Mountains (Hegazy et al., 2016).

1.1.1 Geology and topography

The Arabian Peninsula has its own tectonic plate, the Arabian Plate, which includes Syria and southwest Iran. The Arabian Plate has been moving away from Africa, forming the Red Sea and the Gulf of Aden, towards the Eurasian Plate in the north, forming the Zagros Mountains (Geert et al., 2001, Feulner, 2011), since the late Mesozoic, when the Arabian Plate was part of the ancient supercontinent of Gondwana. The Arabian Plate is still moving away from the African Plate at an average of 2-3cm/year, colliding with the Zagros Mountains in Iran (Hoffmann et al., 2016). The main geographical regions in the Arabian Peninsula are the Tihama Plain, the south and west mountainous region, the northern Oman mountains, the western Najd, the Arabian Platform and the Socotran Archipelago (Miller et al., 1996).

As a result of the Arabian Plate movement, Oman is currently being pushed slowly northwards. The environment of Oman is very diverse; its coastal margin has been deformed, uplifted, weathered, eroded and subsided under the sea several times through various geological periods (Hoffmann et al., 2016). Thus, Oman displays nearly all the main earth-evolution chapters through its wide variety of topography; a direct consequence of the rich geological history. The Hajar Mountains in the north and the Dhofar Mountains in the south are the two prominent mountain chains in Oman. The Hajar Mountains extend about 700km from Musandam in the north to Ras Al Had. The mountains are mainly composed of limestone units that date to the Mesozoic on the tips of Musandam. There was a great upheaval in the earth's crust during the Cretaceous (90 million years ago) period and further upheaval during the Oligocene (23-34 million years ago) period. Samail Ophiolite is the most-exposed oceanic plate material in the world and is located within the Hajar Mountains (Hoffmann et al., 2016).

In the northeast of Oman is the Batinah coastal plain, which is composed of sand and gravel eroded from the Hajar Mountains, with many wadis cutting through it. Most of Oman's landscape is formed from desert plains that are covered by wadi gravel in the north and south of Oman. Alluvial fans originate from Oman's mountains and reach as far as the central desert. Umm as Samim (translated as the 'Mother of all Poison') *sabkha* or *playa* is the largest in Oman. The salt in this area forms crust of polygonal-ridges several metres thick as the water evaporates from flowing wadis. Bar Al Hikman Peninsula, with its tidal lagoons, is another large salt pan in the central desert of Oman. Wahiba and Sharqiyah sands are the two main dune deserts in the country. Most of the dunes were formed more than 14,000 years ago by the then strong south-western monsoon that used to deflate the exposed seafloor during ice ages. The Rub al Khali (or Empty Quarter) forms the south-western area of Oman.

1.1.2 Climate

Several climate zones are found within the Arabian Peninsula, ranging from a subtropical climate in the north to a tropical (monsoon) climate in the south. Generally, the climate in the Peninsula is semi-arid (250–500 mm rainfall) to arid (100–250 mm rainfall), and, locally, even hyper-arid (<100 mm rainfall), with hot, dry summers and mild winters (Glennie and Singhvi, 2002, Kwarteng et al., 2009). The rainfall is irregular and varies considerably across the region and between countries (Almazroui et al., 2012, AlSarmi and Washington, 2014). The annual rainfall in the Arabian Peninsula ranges between 50 and 200 mm, with some local exceptions, such as the southwest escarpment mountains, where the annual rainfall is higher than 300mm, and more than 1500mm in the Ibb region of Yemen (Miller et al., 1996). Convective rainstorms, tropical cyclones, cold frontal troughs and the south-westerly monsoon are the main mechanisms responsible for the rainfall in the Arabian Peninsula, including Oman (Al-Maskari, 2006, Al-Maskari, 2012). These

four meteorological conditions originate from the Mediterranean, Central Asia, the tropical maritime regime of the Indian Ocean, and tropical Africa (Kwarteng et al., 2009). Parts of Yemen and the Dhofar region in southern Oman are the two areas where the monsoon is crucial.

Two air masses also influence the climate system of the Arabian Peninsula. These air masses are the Polar Continental, which occurs from December to February, and the Tropical Continental, which occurs in the summer, from June to September. Both systems are affected by minor incursions of the Polar Maritime and the Tropical Maritime (Fisher and Membery, 1998). These meteorological conditions and their interactions with the local topography affect the pattern of rainfall in Oman (Kwarteng et al., 2009).

Although Oman is characterised by its arid climate (Charabi, 2009), the coastal position of the country on the south-eastern side of the Arabian Peninsula, in addition to the high Hajar Mountain ranges in the north, helps bring significant annual mean rainfall in a few areas (Al-Maskari, 2006). The average annual rainfall of the country varies from a low of about 76.6mm in the hot, dry desert, to a high of 184.6mm in the Dhofar Mountains, with an overall country annual average of about 117.4mm (Figure 1.3B). From November/December (winter season) to April, northern and central Oman receives the most rainfall, accounting for 58–83% of the average annual rainfall. Here, the mountains of Oman act as a natural barrier and cause an orographic effect, resulting in convective rainfall; whereas, the rainfall on the Salalah Plain (the largest city in the region of Dhofar) and the Dhofar Mountains accounts for 73% and 55%, respectively, of the annual rainfall, which occurs during monsoon season, mainly in June and July. The annual average number of rainy days for the entire country is 12.4, with an average of 8 days in the northeast coast, and 46 days in the Dhofar Mountains (Kwarteng et al., 2009).

Oman is subject to infrequent tropical cyclone influence. The most recent cyclone events recorded were Cyclone *Gonu* in 2007, Cyclone *Phet* in 2010 and Cyclone *Chapala* in 2015 (Hoffmann and Reicherter, 2014). The total rainfall exceeded the average annual rainfall ten times during Cyclone Gonu, which was the most intense cyclone recorded in the Arabian Sea.

The average summer (from May to September) temperature in Oman ranges between 32^{o}C and 48^{o}C, with local maximum temperature exceeding 50^{o}C. The temperature is considerably lower in the winter months, from October to April (26^{o}C and 36^{o}C) (Figure 1.3A) (Kwarteng et al., 2009). More than 90% of humidity is recorded in the coastal regions of Oman during the summer months. In the highlands and southern Dhofar regions, the temperatures are moderate throughout the year. A study of the climate change trends in the Arabian Peninsula (AP) found that the mean temperature warmed at about 0.27°C, overland; while the maximum temperature is increasing in a rate of 0.032°C/decade. The overall warming of the maximum temperature in the AP was important and ranged between 1.5 to 3^{o}C and the minimum temperature is increasing faster than the maximum temperature. Generally, important warming of the mean annual temperature was recorded mainly over the eastern/south-eastern areas of the AP over the period 1980 to 2008 (AlSarmi and Washington, 2011). Mean temperatures warming at more than 1.5–3.5 times the global rate was reported from some site-specific stations in the AP, with minimum temperature increases reached approximately 3–6°C, over the period 1980 to 2008. (AlSarmi and Washington, 2011, Almazroui et al., 2012, AlSarmi and Washington, 2014). The variable rainfall and temperature help to shape the abundance and distribution of vegetation in the country.

1.1.3 Flora and vegetation

The variations in the environment and the ecological habitats of the Peninsula are reflected in its rich flora. Different vegetation types have been recorded, ranging from dense evergreen woodlands, xeromorphic shrubland and wadi communities to sparse gravel and sand desert vegetation (Ghazanfar and Fisher, 1998). Phytogeographically, and using the system proposed for Africa by White in 1983 (based on regional centres of endemism separated by regional transition zones: phytochorion), and from the phytochoria extension by White and Leonard (1991) in South-West Asia, as cited in Miller and Cope (1996), Arabia is subdivided into three main phytogeographical areas: the Saharo-Sindian zone (including an Arabian regional subzone and a Nubo-Sindian local centre of endemism); the Somalia-Masai regional centre of endemism; and the Afromontane archipelago-like regional centre of endemism (Ghazanfar and Fisher, 1998) (Figure 1.4). These vegetation types and their dominant taxa indicate the strong influence and relationships between, for example, Arabia and Africa, which are evident in the Afromontane vegetation in the high mountains, as well as the presence of some taxa of Mediterranean and Irano-Turanian origin (Zohary, 1973, Ghazanfar and Fisher, 1998) in the north and southeast of the Peninsula.

Little is known about the vegetation composition and distribution in Oman. Ghazanfar (1992b) describes four phytochoria in Oman. These are the Somalia-Masai regional centre of endemism (including southern Yemen and Dhofar); the Saharan regional subzone to the north; the Arabian regional subzone; and the Nubo-Sindian local centre of endemism. Patzelt (2015c) provides a more detailed and updated overview of the flora and the main vegetation types in Oman. Four main vegetation types can be recognised in Oman: the coastal vegetation, the deserts (including sand and gravel deserts, and *Sabkhas*), the Hajar Mountains and the Dhofar Mountains (Figure 1.5.). A total of 1407 species have been recorded in

Oman thanks to continuous research in the past three decades (Miller et al., 1996, Ghazanfar, 2003, Ghazanfar, 2007, Patzelt, 2014, Patzelt et al., 2014). Southern Oman, northern Oman and the central desert are the most species-rich areas, with 58%, 51% and 18%, respectively, of the country's total flora. Poaceae, Fabaceae and Asteraceae are the three most abundant families in Oman (Patzelt, 2015a, Patzelt, 2015c).

A total of 15.8% of the Oman flora comprises range-restricted (endemic, near-endemic and regional endemic) species (Patzelt et al., 2014, Patzelt, 2015a). Most of the range-restricted species are contained in the Asteraceae, Apocynaceae and Lamiaceae families. Although these range-restricted species are found throughout the country, and in different vegetation types, they are concentrated in three main areas that are recognised as a centre of endemism. These areas are the southern mountains (mainly the Al Qamar and Al Qara Mountains and Samhan Mountain), the central desert (mainly Jiddat Al Harasis, Jiddat Al Arkad/Sahil Al Jazir), and the northern mountains (Ghazanfar, 1992b, Patzelt, 2015c). The Dhofar Mountains in the south are influenced by monsoon summer rains and have been identified, in addition to central Oman, as global, key biodiversity hotspots due to the considerable plant diversity with a high level of endemism.

1.2 STUDY SITE: THE EASTERN HAJAR MOUNTAINS

1.2.1 Location

The Hajar Mountains consist of three ranges: the Western Hajar (reaching 3009m), the Eastern Hajar (reaching 2230m) and the Musandam Mountains (reaching 1087m) (Figure 1.6.) (Miller et al., 1996). The ranges run from Musandam in the north, head south along the coast for 700km, and vary in width from 30 to 70 km

(Ghazanfar and Fisher, 1998). Jabal Shams, with an elevation of ca. 3009m, is the highest point in the Western Hajar Mountains and the highest in eastern Arabia.

1.2.2 Climate

The Hajar Mountains (of which the Eastern Hajar forms a large portion) is a hyper-arid area; the climate in the mountains is considerably cooler than lower elevations, with an annual average air temperature of 18.1°C (a minimum of 3.6°C and a maximum of about 36°C) (Fisher & Membery, 1998). The coolest and hottest months are January and June, respectively. The Western Hajar Mountains receive about 300-350mm rainfall above 1800m, mainly in winter and spring. No climatic data are available for the Eastern Hajar, and the nearest weather station for the Musandam Mountains is about 30km away, and, thus, not accurate. However, according to the recent national report prepared by the Ministry of Environment and Climate Affairs (MECA), the annual mean temperature for the Eastern Hajar Mountains is about 12.7°C, with a predicted increase of about 1.5°C (Ministry of Environment and Climate Affairs (MECA), 2015). The annual rainfall for the mountains is 120mm, with a general slight predicted dryness for all the Hajar Mountain ranges. Generally, in the Arabian Peninsula, the analysis of the climate data for the period from 1970 to 2008 indicates an increase in the number of warm days and nights, as well as an increase in the annual mean of the maximum and minimum temperature, with no evidence of change in the precipitation (AlSarmi and Washington, 2014).

1.2.3 Geology

The Hajar Mountains are comprised predominantly of Cretaceous limestone. There are also metamorphic and igneous rocks, including the distinctive grey-brown ophiolites formed in the earth's lower crust and upper mantle and thrust to the surface to form jagged hills and mountains. The mountains are mostly steep, with

bare rock outcrops and very shallow soils on the slopes (Ghazanfar & Fisher, 1998). Gravel soils predominate in the valleys and alluvial fans. The terrain is crossed by dry river valleys (*wadis*) formed by flowing water during the rainy season, remaining dry until the next rains fall.

1.2.4 Flora and vegetation

The Hajar Mountains fall into the Nubo-Sindian local centre of plant endemism. The species distribution in these mountains reveals that the floras are closely related to the flora of southwest Iran, Afghanistan and southwest Pakistan (Figure 1.4.). The Hajar Mountains comprise about 60% of the total flora, of which 22, 28 and 94 species are range-restricted to the Western Hajar, Eastern Hajar and Musandam Mountains, respectively (Ghazanfar, 1991, Patzelt, 2015a, Patzelt, 2015c). The flora of the Hajar Mountains displays strong links with the flora of Iran, Afghanistan and Baluchistan communities (Ghazanfar, 1992b). The Hajar Mountains are considered a local centre for plant endemism (Miller and Nyberg, 1990; Ghazanfar 2003) and belong to the WWF's (World Wildlife Fund) Global 200 eco-region 'Arabian Highland Woodlands and Shrublands'.

There are very few studies available on the phytogeography and vegetation structure of the Hajar Mountains. Ghazanfar (1991) describes the vegetation structure and phytogeography of Jabal Shams using multivariate analysis. In the study, 30x30m quadrants were set out at about 100m intervals from about 600m elevation to the summit of the mountain (3000m). The density of the plant species was recorded. Using Two Way Indicator Species Analysis (TWINSPAN) software, Ghazanfar describes four vegetation zones: the *Acacia tortilis-Rhazya-Fagonia* zone (elevation 650-1130m); the *Euphorbia larica* zone (1130-1480m); the *Sideroxylon-Olea-Dodonaea* zone (1480-2050m); and the *Juniperus-Ephedra-Teucrium* zone (2050-2820m). The results of the study indicate that the plant composition is

influenced by elevation and that plant diversity was highest at mid-elevation (1000-1480m), and lowest at a higher elevation (2500-2820m).

Brinkmann et al. (2011) used the Classification Tree Analysis (CTA) method to model the presence and absence of seven plant communities in central Jabal Al Akhdar (Western Hajar Mountains) based on different environmental predictors. The result was a vegetation map (400km^2) that identifies 25% of the study area as a priority conservation site, including mainly the *Teucrio-Juniperetum* plant community. These conservation areas were identified by, 1) the total number of species (species richness); 2) the relative occurrence of rare and endemic species; 3) the maximum number of the vulnerable and endangered species for each plant community; and 4) grazing intensity for each plant community. The list of endemic and threatened species was obtained from the Oman Red Data Book based on the International Union for Conservation of Nature (IUCN)Red List categories (IUCN 2001).

The Western Hajar Mountains are the most botanically studied areas within the northern mountains range. Mandeville's (1977) study describing the phytogeography of Jabal Al Aswad is the only study carried out in the Eastern Hajar Mountains. Detailed studies defining plant communities, the determinants of plant distribution, and vegetation ecology are lacking, and the effects of grazing and rapid development on plant species and communities are poorly understood in the Eastern Hajar Mountains. Without a comprehensive understanding of these factors, effective conservation of the area will be ineffectual. My doctoral research aims to fill some of the significant gaps in botanical knowledge and provide a solid basis for meaningful conservation efforts.

The Eastern Hajar Mountains were thought to support a diverse and rich flora of about 324 plant species, which represents 23% of the total flora of the country

(Ghazanfar, 1992a, Miller et al., 1996, Patzelt, 2015c). This thesis increases that number to 433 species, representing about 31% of the total flora of the country (see Chapter 7). An overview of the vegetation units of the Eastern Hajar Mountains identified four main plant communities that are not found in any other area of the country (Patzelt, 2015c). These communities are the Colline and sub-montane zone: *Commiphora wightii-Grewia erythraea* shrubland; the Montane zone: transitional shrubland with *Searsia aucheri*; the High-montane zone: *Prunus arabica-Ceratonia oreothauma* steppe woodland community; and the High-montane zone: *Helianthemum kahiricum-Convolvulus acanthocladus* desert steppe community (Figure 1.7.) (Patzelt, 2015c). The current study systematically classifies the vegetation of the Eastern Hajar into plant communities (see details in Chapter 4).

The vegetation of the Eastern Hajar Mountains differs from the vegetation of the Western Hajar in several ways. Juniper woodlands are absent from the Eastern Hajar, and the *Olea europea* woodlands are sparse and poorly developed (Miller and Knees, 2014). The Eastern Hajar Mountains contain unique plant species of local and regional importance. The elegant tree *Ceratonia oreothauma* is a relict species found only in the Eastern Hajar Mountains, southern Iran, southwest Pakistan and Yemen. Also, 28 range-restricted species are listed in the Oman Plant Red Data Book. Ten species are endemic to Oman, five species are near endemic, 16 species are regional endemic, and eight are rare and threatened species (Patzelt, 2015a).

The vegetation of the Eastern Hajar Mountains is very poorly researched. Detailed studies defining plant communities, the determinants of plant distribution, and vegetation ecology are lacking. Species distribution modelling is necessary to estimate the full range of species that are only occasionally sampled. Grazing and development are seriously threatening the fragile mountain ecosystem. Therefore, a

more systematic approach is needed for a better selection of conservation areas. The use of important plant areas (IPAs) and strategic conservation planning (SCP) is essential and requires, with another set of procedures, the mapping, identifying and prioritising of the conservation areas in the Eastern Hajar Mountains.

1.2.5 Land-use history in the Eastern Hajar Mountains

Gathering information about the land-use history of the Eastern Hajar Mountains (Clarke and Warwick, 2001, Cowling et al., 2003, Damme and Banfield, 2013) is a difficult task because not much is published about the area. What is known about the area is what has been published through archaeological studies, in addition to the discoveries of some of the wild crop relative plant species. From a general overview of the literature, the land-use history of the Eastern Hajar Mountains stretches back as far as 5000 BC. The first settlement indication of the mountains was found by archaeological studies in the area, which began in the early 1970s. The land-use history can be divided into three major areas: trade, grazing and, to a lesser extent, oasis agriculture. Other recent uses have been identified and documented during the term of this study.

The Eastern Hajar Mountains contain sites of archaeological, geological and cultural interest. Several Hafit (3100-2700 BC) and Umm an-Nar (2700-2000 BC) tower tombs have been discovered in these mountains (Yule and Weisgerber, 1998, Siebert et al., 2005). These tower tombs are the only indication of old pastoral land-use in Maqta, and there is no indication of any settlement older than this. Maqta, with its oasis agriculture terraces, has been the largest agro-pastoral village in the Eastern Hajar Mountains since about 1000 AD. The site currently holds about 200 semi-nomadic inhabitants, about 900 sheep and goats and 22 small springs for watering the terraces (Siebert et al., 2005). The main crops are the date palm and local wheat landraces.

The presence of ancient trade routes between inland and the coast, passing through Maqta and other locations within the Eastern Hajar Mountains, is an indication of the key role in the trade that Oman played long ago. These trade routes contributed to the thriving civilisations in the region five thousand years ago. These civilisations were begun by autochthonous populations; then, in the third millennium BC by the Sumerian civilisation, with the Persian colonisation later contributing to the changes in the economy and cultural life in the region (Kechichian, 1995, Hakim, 2013, Benkari, 2017). Trade relationships with Africa, China and India were established in the Persian era (Kechichian, 1995, Benkari, 2017). The new wheat varieties from Maqta are evidence of the ancient trade route between Oman and Mesopotamia and Asia (Al-Maskri et al., 2003, Buerkert and Schlecht, 2010). The mountains contain numerous ancient footpaths that connect many of the villages scattered in the mountains and are used by the locals for personal visits (Siebert et al., 2005).

Conclusive studies linking human activity and ecosystem change require comprehensive analyses of land-use history and long-term vegetation records, which are lacking for the Eastern Hajar Mountains. To help understand the relationships between vegetation, environment and the development of human settlements in this area, a high-resolution palaeoecological study was conducted near Maqta village (Urban and Buerkert, 2009). In the study, the sediment profile was analysed for its physicochemical properties, pollen and spores. The study helps to understand the previous environmental and climatic changes in the Hajar Mountains during the Last Glacial Maximum (LGM), the Late Glacial (LG) and the Holocene period. An Early Holocene increase of rainfall was found by the analysis, followed by dryer conditions at about eight ka *("ka" means "kilo-annum" Before present)*, and short, humid period at about 5.7, 5 and 4.4 ka. The link with increased settlement activities during the Umm al-Nar period throughout Oman was recognised in the analysis by the identification of 4300-year-old pollen in the

sediment. The major conclusion from the study is that the vegetation was slightly affected by the changes in the local rainfall and human activity over the past four millennia (Urban and Buerkert, 2009), which indicates that the vegetation 4000 years ago was almost the same as it is today.

Nevertheless, during the past 50 years, Oman has undergone enormous socioeconomic changes due to the exploitation and export of oil and natural gas. One of the major changes is the rapid and continuous urbanisation of the country, which has grown from 30% in 1970 to about 80% today. The increase of the road network in the mountains is unquantified, but there has been a rapid increase in the number of roads in less than five years that was noticed during the field work of the current study. These roads link the inland and coastal areas, which are separated by the Eastern Hajar Mountains. This urbanisation has led to the migration of many rural households to urban areas, seeking employment for better income and an improved lifestyle. This type of migration was reported in the Jabal Al Akhdar in the Western Hajar Mountains (Oasis book) and documented through personal conversations with the local people of the Eastern Hajar Mountains. These socioeconomic changes have affected livestock husbandry due to the change from the ancient traditional semi-nomadic past to a more sedentary practice (Birks, 1976). This change is due to the availability of supplementary feed and the lack of labour, which made livestock husbandry less dependent on the natural vegetation of the mountains.

1.2.6 Threats to the vegetation of the Eastern Hajar Mountains

Many reports and publications have raised concerns over the adverse impacts on vegetation due to development (road building, new houses, and other construction), an increase in the number of animals, and overgrazing in many critical vegetation areas, as well as the potential effect of climate change (Gardner and Fisher, 1996,

Fisher, 1997, Patzelt, 2015c). A recent survey of the Eastern Hajar vegetation describes the mountains as 'heavily degraded with little or no regeneration of the principal trees like *Ceratonia oreothauma*, *Prunus arabica*, *Olea europaea* subsp. *cuspidata* and *Sideroxylon mascatense'* (Miller and Knees, 2014). Many of the habitats of Oman form parts of fragile ecosystems and are highly sensitive to disturbance and very slow to regenerate (Patzelt, 2015b). Extended areas of the unique vegetation of the country have today been over-exploited and destroyed or are suffering from habitat degradation. Overgrazing (Figure 1.8) and development (e.g. road construction) are the most pervasive and overriding threats to the plants of Oman. Overgrazing affects 82% of all the threatened plant species and development, while development affects 72% of all plant species; together, more than 97% of the threatened species in Oman are affected (Patzelt, 2014). These are the main factors contributing to the lack of regeneration of many important tree species (e.g. *Ceratonia oreothauma*) (Patzelt, 2015a, 2015b). One other notable threat is the felling of trees for fuelwood and construction (Figure 1.9).

In addition to the above threats, the Eastern Hajar Mountains, as discussed previously, is an important recreational, archaeological, geological and cultural area. The tower tombs monuments and other recreational and geological sites, such as the 'Majlis al jen' cave (translates to 'the meeting room of spirits'), are among the top 10 caves in the world (with the second largest chamber in the world) and the largest in the region (Hoffmann et al., 2016). In recent years, and due to much-increased accessibility to the mountains, climbing and hiking, in addition to the above attractions, have increased in popularity. The scenic, dramatic landscape and the challenges that these mountains offer to these different types of tourists are very attractive. It is highly likely that the diverse landscapes of the Eastern Hajar Mountains will attract more local and foreign tourists, which will place more pressure on this fragile mountain ecosystem.

Nature reserves such as Wadi As Sareen, which encompass a wide variety of elevations and habitat types and a limited amount of human activity, are crucial to ensure that these rare and range-restricted plant species are protected. Unfortunately, many important plant locations within the mountain range are unprotected. Moreover, as the mountains are becoming more accessible due to the continuous road building, this will lead to more people visiting the mountains and more animal grazing in the area. The introduction of camels in recent years, in addition to the increase in the numbers of goats, sheep, and donkeys, will result in the increased destruction of vegetation in the future. Although the Government provided houses for the villagers at lower elevations in the mountains, the people prefer to remain in their old houses. Consequently, there are many existing and potential threats to conservation. One of the added challenges is the remote and sporadic distribution of the villages, which will make selecting sites for protection difficult due to the vast areas over which these villages are found.

1.2.7 Existing protected areas within the Eastern Hajar Mountains

Wadi As Sareen National Park (established in 1976) and Ras Al-Shajar Nature Reserve (founded in 1985) lie in the Eastern Hajar Mountains (Figure 1.10). Wadi As Sareen Nature Reserve was recently reviewed by the Office for the Conservation of the Environment (OCE), and its status was upgraded to a National Park. The park includes Jabal Aswad National Nature Reserve, the Jabal Abyadh National Scenic Reserve and a section of the Jabal Tayyin National Resource Reserve, as proposed by the IUCN in 1985/86. The park has a total area of 780 km^2 and a boundary of 161.92 km. The park encompasses one of the largest populations of Arabian Tahr (*Arabitragus jayakari*), and it is the only reserve for these animals in the world. In addition to the fauna, the park includes a diverse flora of national, regional and global importance.

A detailed management plan was developed by an environmental consultancy firm (Five Oceans Environmental Services (5OCS)) in collaboration with the OCE management responsible for the protected area, local communities, Earthwatch and government departments, including the Ministry of Housing (MoH) and the Ministry of Agriculture and Fisheries (MAF) (Five Oceans Environmental Services, 2015). The plan was prepared from data collected over the past 30 years by the park rangers and OCE. The main goals of the park are the protection of the natural biodiversity, ecological structure, and supporting environmental processes. These goals are planned to lead to a gradual introduction of low-intensity tourism to promote educational and recreational objectives (Five Oceans Environmental Services, 2015).

The Ras Al-Shajar Reserve is also located in the Eastern Hajar Mountains range between Wilayat Qurayyat in Muscat Governorate and Wilayat Sur in AlSharqiya Governorate. Covering a total area of 93.7 km2, the Reserve is characterised by an abundance of *Acacia tortilis* (simr) trees; hence, its name. The Reserve is rich with a diverse range of fauna and flora and geological components. Red Fox, Caracal, Arabian Gazelle and Arabian Tahr are found in the reserve. Water basins were created to mimic natural oases to aid the survival of fauna in the reserve (Five Oceans Environmental Services, 2015).

1.3 THE IMPORTANCE AND AIMS OF THE STUDY FOR THE REGION

Detailed studies defining plant communities, the determinants of plant distribution, and vegetation ecology are lacking for most of the areas in Oman. This study is the first systematic vegetation analysis in the Eastern Hajar Mountains based on a comprehensive field-data collection. Species distribution modelling is necessary to estimate the full range of species that are only occasionally sampled. Grazing and development are seriously threatening the fragile mountain ecosystem. Therefore, a

more systematic approach is needed for a better selection of conservation areas. The use of IPAs and the SCP is essential and requires, with another set of procedures, the mapping, identifying and prioritising of the conservation areas in the Eastern Hajar Mountains. Using the IPA approach, in this study, is important at this stage, as Oman is developing its national spatial strategy for the first time and the IPA's approach is being adopted by the experts involved in developing this strategy for identifying the plant priority conservation areas. Therefore, the IPA approach will be used in this current study in order to be compatible with this strategy. This study contributes significantly to flora and vegetation knowledge and forms a basis for further ecological and phytological studies in the country. The main aims of the study are as follows:

- Classify the vegetation of the Eastern Hajar Mountains into plant communities and relate the distribution of these communities to a set of environmental variables, such as climate and soil type.
- Quantify the soil seed bank and compare it with the above-ground vegetation.
- Predict the current distribution of the perennial plant species of the Eastern Hajar Mountains.
- Assess the conservation status of the mountains using an IPAs approach and spatial conservation prioritisation to inform and guide the conservation planning and activities within the mountains.

1.4 THESIS STRUCTURE

This final thesis of the project consists of the following chapters. Each chapter contains an introduction, methodology, results and discussion section.

This thesis begins with an overall introduction (Chapter 1), followed by a review of relevant existing literature (Chapter 2). Chapter 3 provides a detailed description of

the fieldwork and data collection, followed by four empirical chapters. The four chapters are entitled as follows:

Chapter 4: Classification and ordination of the main plant communities of high-elevation mountains in Oman

Chapter 5: The soil seed bank in the Eastern Hajar Mountains

Chapter 6: Species distribution modelling for floristic conservation planning in the Eastern Hajar Mountains, Oman

Chapter 7: Conservation assessment and prioritisation using Important Plant Areas: the Eastern Hajar Mountains, Oman.

There is a final chapter (Chapter 8) discussing the overall outcomes of the project and offers concluding remarks and general recommendations for further research required in the area.

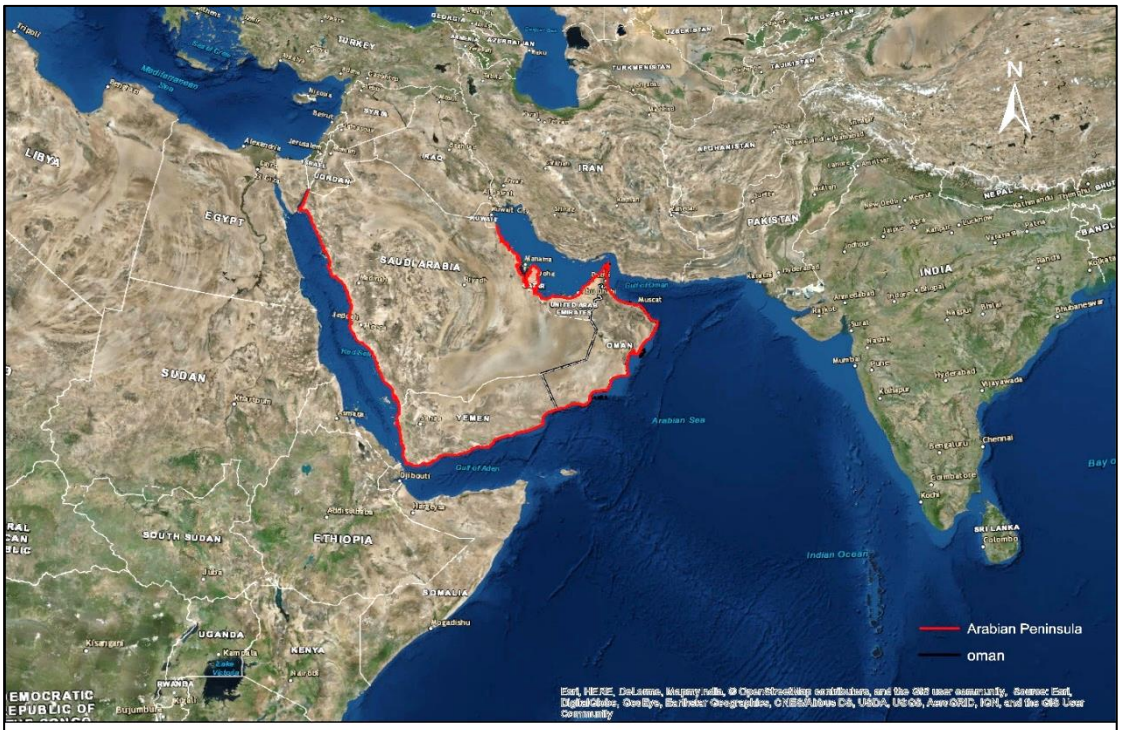


Figure 1.1. Location of the Arabian Peninsula and Oman.



Figure 1.2. Map showing the location of Oman.

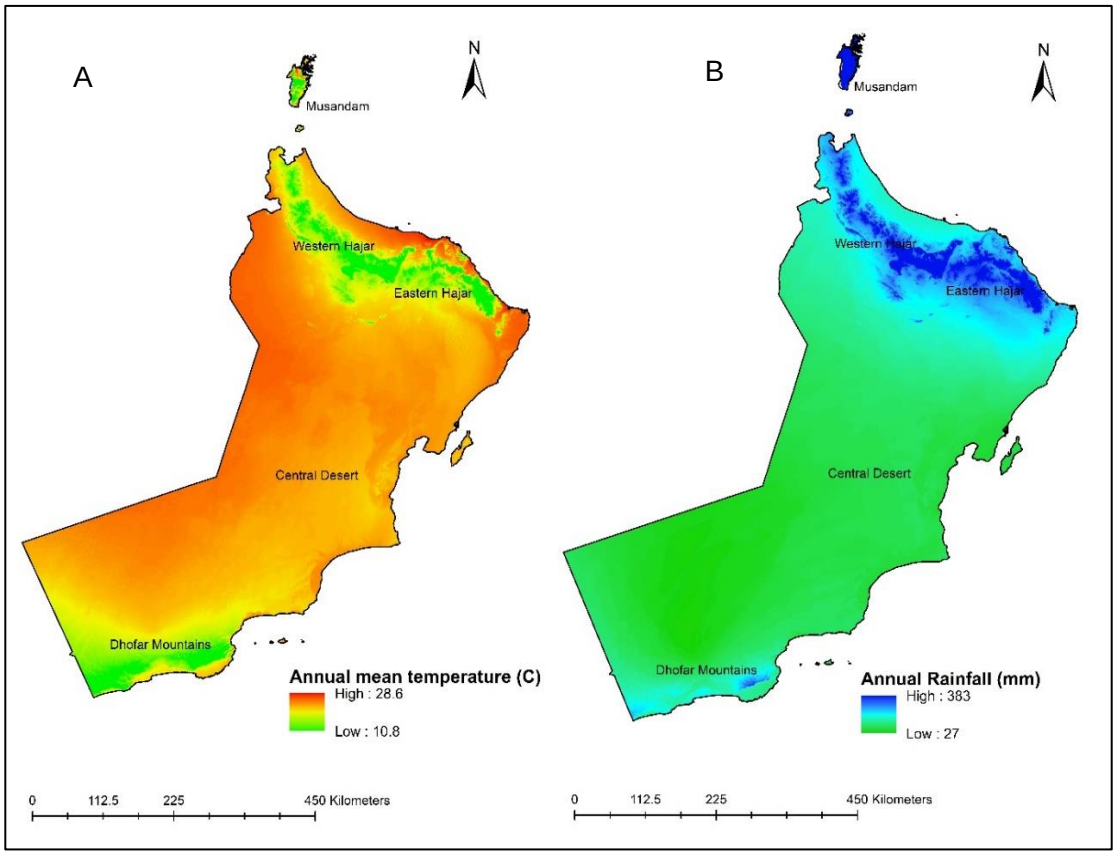


Figure 1.3. Oman current climate: A: Annual mean temperature; B: Annual Rainfall. Source: MECA, 2015.

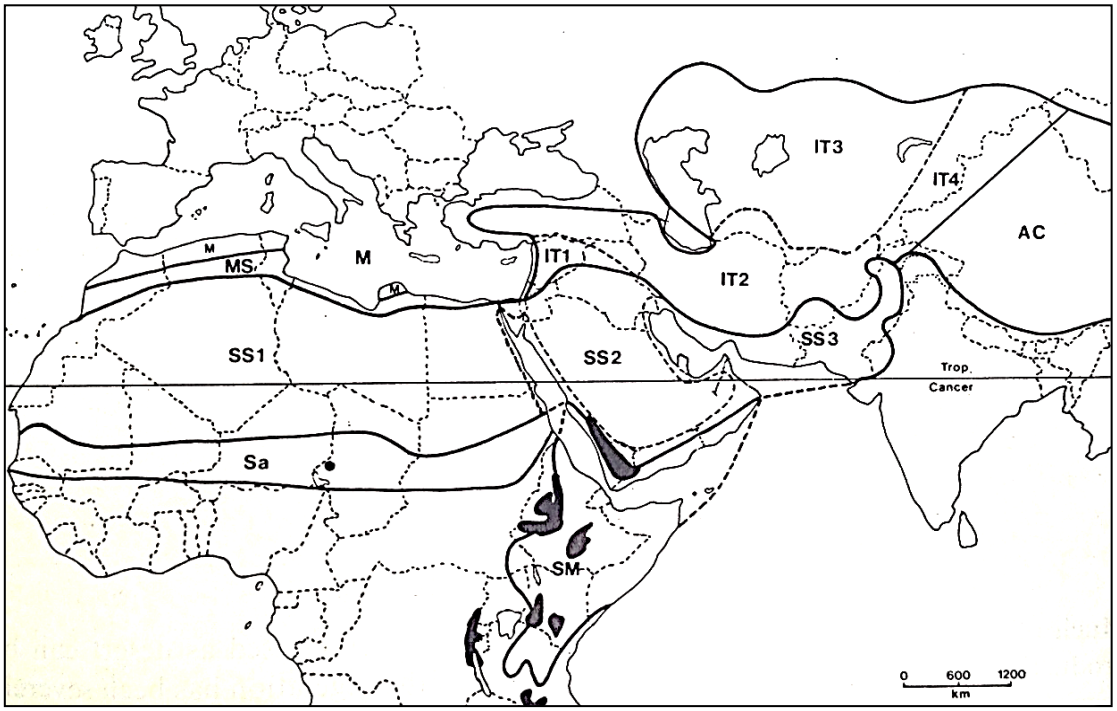


Figure 1.4. Main phytogeographical region of Africa and Asia. AC, Central Asiatic region; IT, Irano- Turanian regional centre of endemism; M, Mediterranean regional centre of endemism; MS, Mediterranean-Sahara regional transition zone; SS, Saharo-Sidian regional (Ghazanfar and Fisher, 1998).

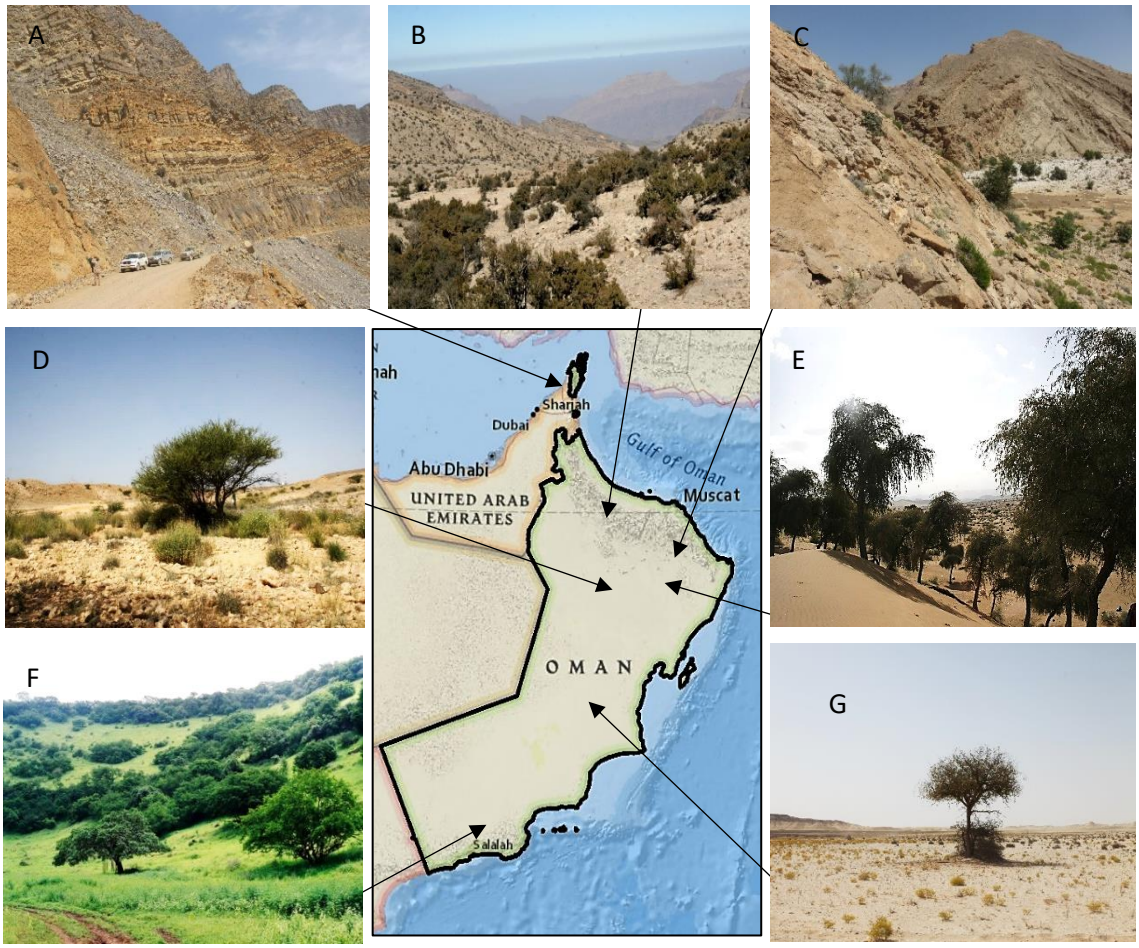


Figure 1.5. Main vegetation types found in Oman: The Hajar Mountains: Musandam (A), Western Hajar (B) and Eastern Hajar (C); Deserts: Gravel desert (D), Sand desert (E) and Central desert (G), and the Southern Mountains (F).

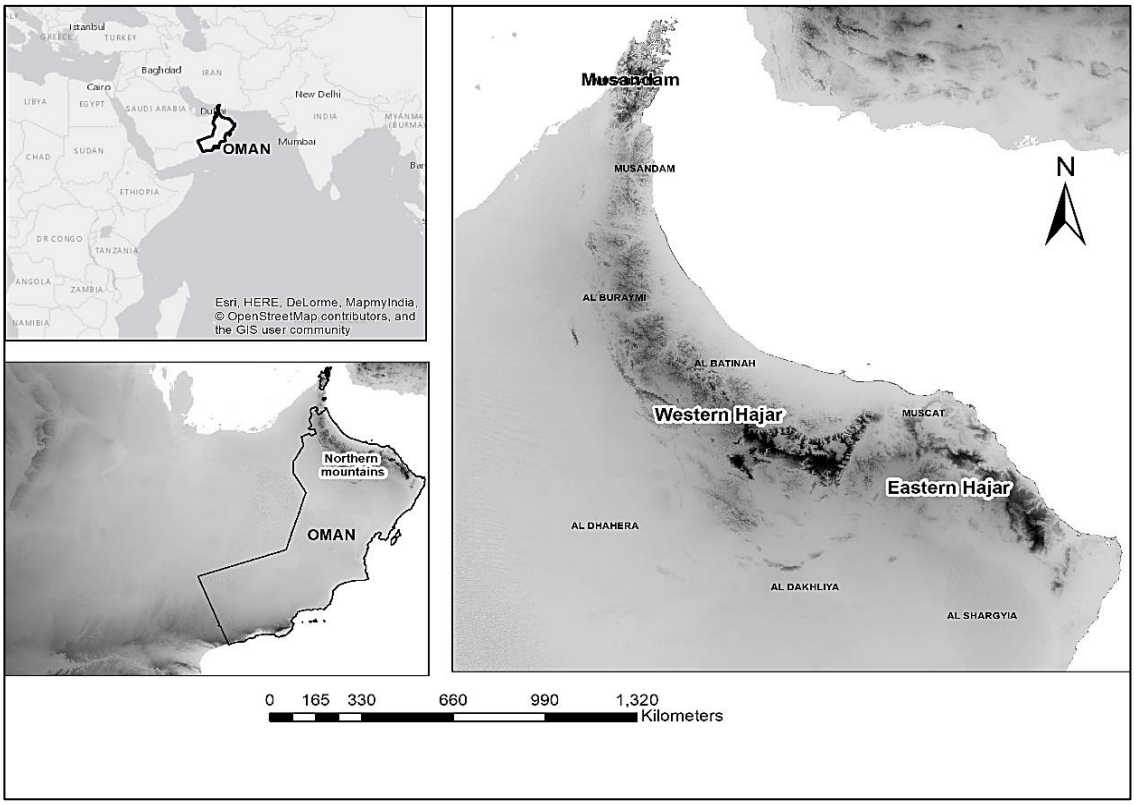


Figure 1.6. The three ranges of the Hajar Mountains in northern Oman: Eastern Hajar, Western Hajar and Musandam. Map sources: top left: Esri, DeLorme, HERE, MapmyIndia; bottom left and right : Digital Elevation Model (Oman National Survey (ONS)).

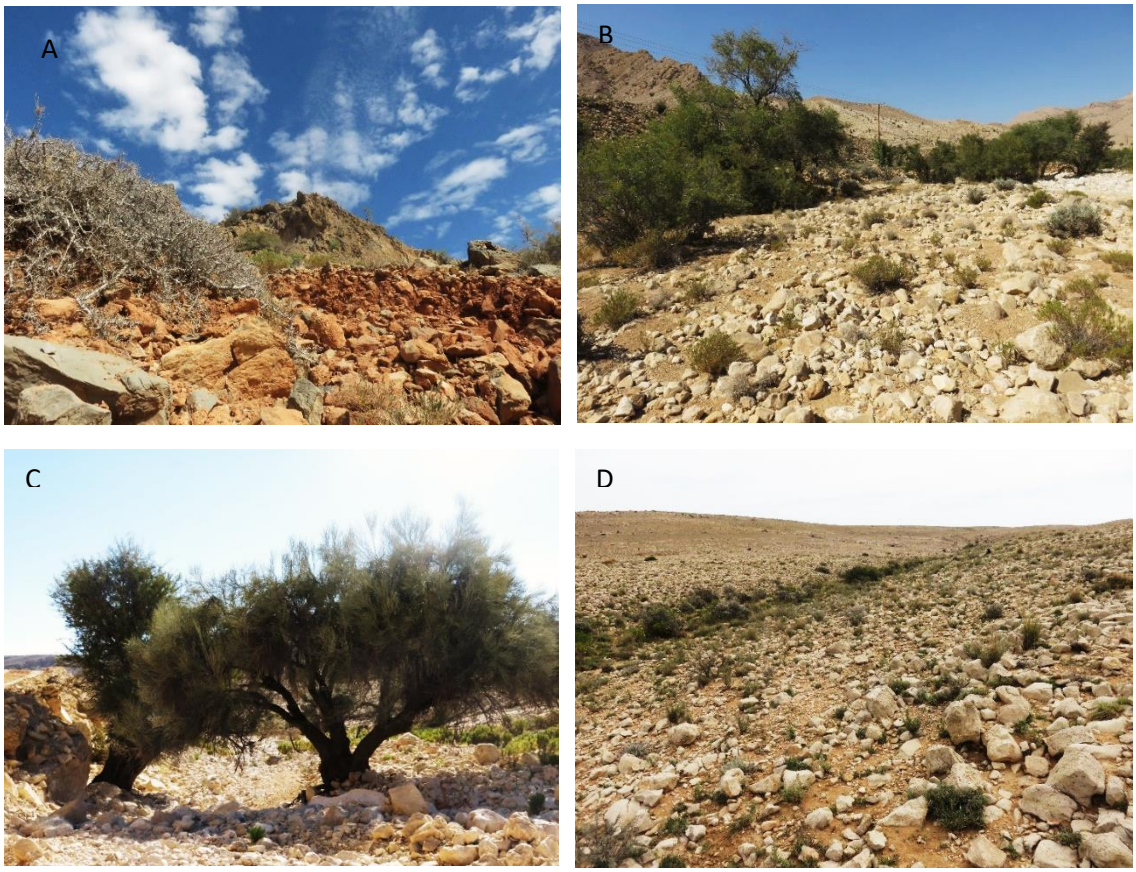


Figure 1.7. The four plant communities identified in the Eastern Hajar Mountains: A: Colline and sub-montane zone: *Commiphora wightii-Grewia erythraea* shrubland; B: Montane zone: transitional shrubland with *Searsia aucheri*; C: High-montane zone*: Prunus arabica-Ceratonia oreothauma* steppe wood-land community; D: High-montane Zone: *Helianthemum kahiricum-Convolvulus acanthocladus* desert steppe community (described by Patzelt, 2015).

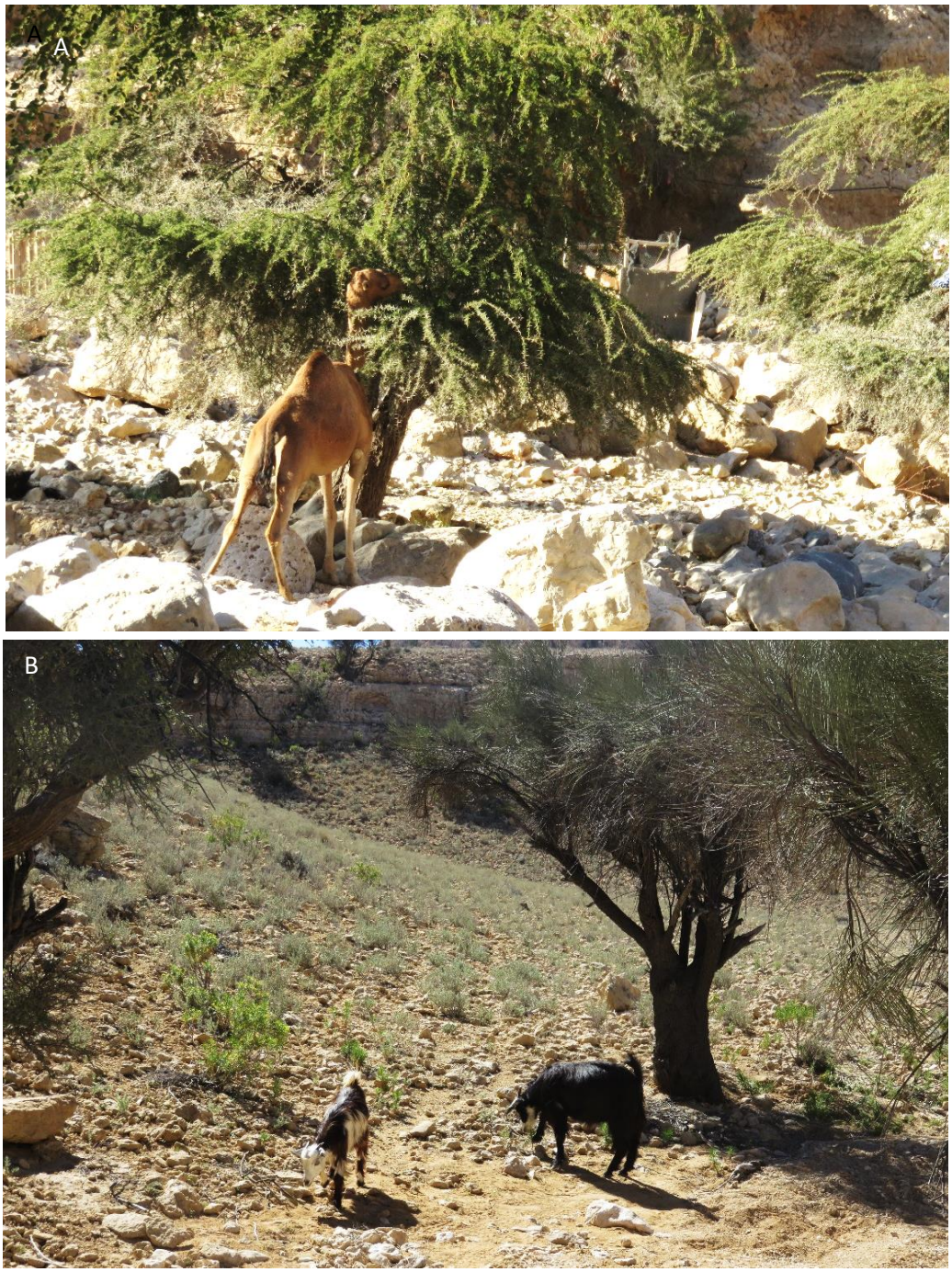


Figure 1.8. Over-grazing (A: camel introduced to the mountains only in the past five years; B: goats grazing) as the major threat to vegetation in the Eastern Hajar Mountains, Oman.



Figure 1.9. Tree-cutting for fuel and feeding animals is one of the noticeable vegetation threats in the Eastern Hajar Mountains.

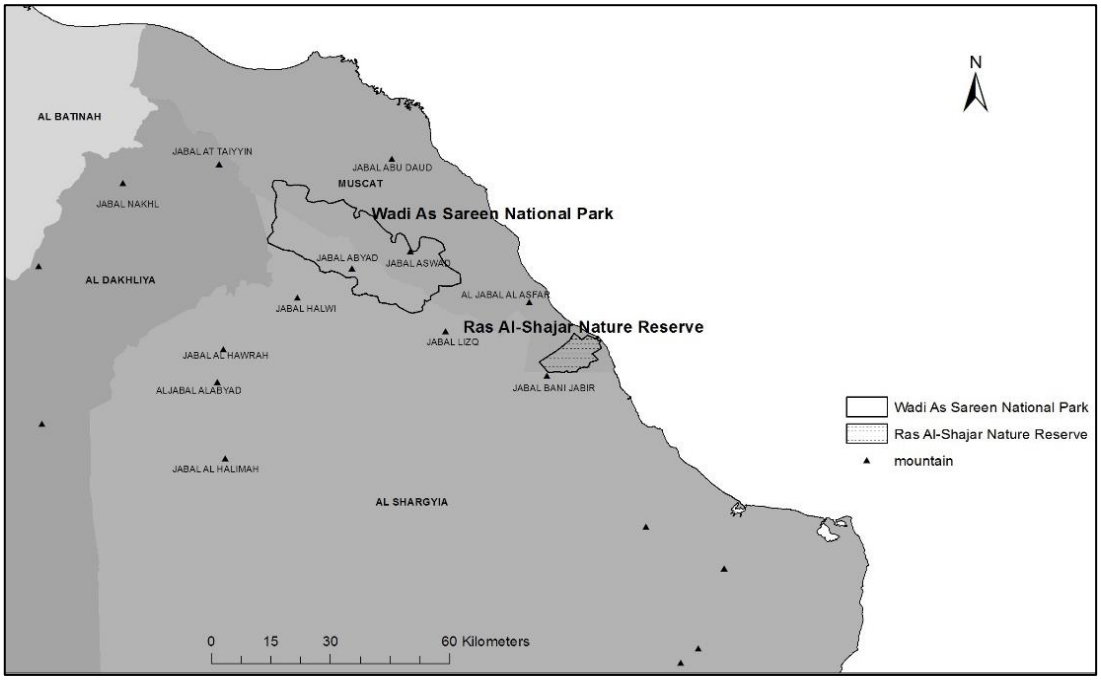


Figure 1.10. The two protected areas (Wadi As Sareen National Park and Ras Al-Shajar nature reserve) in the Eastern Hajar Mountains. Source: Office for Conservation and Environment (OCE), 2017.

CHAPTER 2

LITERATURE REVIEW

2 CHAPTER 2: LITERATURE REVIEW

2.1 VEGETATION DESCRIPTION AND CLASSIFICATION (PHYTOSOCIOLOGY)

There are two approaches used for vegetation classification (phytosociology): the physiognomic (structural) approach and the floristic approach. The physiognomic approach describes the life form and sizes of the plant species present in an area and is used for describing the vegetation of large areas (i.e. the world). Raunkaier's technique (Raunkiær, 1937, Beard, 1978) is the most popular method used to describe vegetation in the physiognomic approach. There are five main life-form categories used in this classification: *Phanerophyte* (plants with buds emerging from aerial parts of the plant); *Chamephyte* (plants with buds borne on aerial parts close to ground); *Hemicryptophyte* (buds borne at ground level); *Therophyte* (annuals) and *Cryptophyte* (buds or shoot underground or underwater). There are alternative techniques, such as the Dansereau, Küchler and Fosberg methods (Kent, 2011). These three methods have similar concepts with different approaches. In Dansereau's method, the dominant species are required for describing the community based on the life form, cover and leaf characteristics. The Küchler method divides the vegetation into woody and herbaceous, which is further split into ten vegetation types depending on the life form, cover and height. Fosberg's method describes the vegetation on a world scale. He used the International Biological Programme for his description based on the structural data of the vegetation.

The floristic approach focuses on the presence and abundance of the plant species and is used for smaller areas (plant communities). It was initiated by Braun-Blanquet (1928). He defined the association as 'a vegetation grouping more or less stable and in equilibrium with the environment, characterised by a particular floristic composition, in which some exclusive or almost exclusive elements (characteristic

species) reveal with their presence a particular and autonomous ecology'. The process of defining and classifying the plant communities for an area is known as phytosociology. Methods for classifying the communities are varied, with the Braun-Blanquet methodology being one of the earliest methods used, followed by more numerical methods based on mathematics and statistics (Shimwell, 1971).

The classification of the plant communities is followed by a process called syntaxonomy. Syntaxonomy (phytosociological classification) is the global hierarchical system of classification of the plant community, and its rules are presented in the 'International Code of Phytosociology Nomenclature' (Weber et al., 2000). Despite all the controversy surrounding the phytosociology methodology, from the ecological conceptual theory (community/continuum) that forms the basis of the vegetation classification, the sampling design and vegetation plot selection (representative and homogeneity/vegetation zones in between), which may affect the statistical analysis of the data (Botta-Dukát et al., 2007, Lájer, 2007, Økland, 2007), phytosociology remains a widely used tool. The approach offers hierarchical links between the land cover and plant diversity of the landscape (Biondi et al., 2004).

2.2 PLANT COMMUNITY COMPOSITION - DISTRIBUTION AND ENVIRONMENTAL FACTORS

Environmental gradients, such as topography, water availability and soil, have essential roles in determining the structure of plant communities in any given habitat. To understand the composition and structure of a plant community in a particular area, a study of the environmental variables and their correlations with the vegetation is significant. There are hundreds of publications that studied the effects of the environmental variables separately or combined, such as climatic factors,

elevation, slope, aspect and soil moisture. Austin and Van Der Maarel (2005) classify environmental variables into three non-biotic categories: 1) direct (e.g. temperature and rainfall); 2) indirect (i.e. slope, elevation) and 3) resource variables (i.e. soil nutrients). Other biotic variables may also affect the structure and composition of the plant community, such as the grazing, trampling and cutting of the vegetation (Kent, 2011).

Plant community datasets are typically analysed using programmes such as TWINSPAN and CANOCO. These are two of the most widely used computer programs for vegetation classification, ordination and correlation studies (Cooper et al., 1997, Monier, 2000, Jafari et al., 2004, Malik and Husain, 2006, Zhang et al., 2006). TWINSPAN is one of the most common hierarchical divisive classification techniques in community ecology and was developed by M. O. Hill in 1970. The relationship between the vegetation stands and species is displayed through a simultaneous classification of both of them. This produces a hierarchical classification of vegetation groups or plant communities. The algorithm of TWINSPAN starts with primary ordination of sites along the first axis of correspondence analysis (CA) and then the sites are divided into two clusters by splitting the first CA axis near its middle. Then, site classification is refined using a discriminant function that emphasises species preferential to one or the other half of the dichotomy (Hill and Šmilauer, 2005). Each of the two clusters, then, can be repeatedly divided in the same way.

For example, the plant communities of the Naukluft Mountains of Namibia were classified and described using TWINSPAN, and, by using the CANOCO programme, the correlation between these plant communities and environmental gradients was investigated. The results of this study reveal that plant community composition was determined by the slope, the elevation, and the clay and potassium

content of the soil. Other factors, such as the microclimate, disturbance and water availability, were found to have more significant effects on the composition of plant communities. Soil characteristics (i.e. electrical conductivity, pH, calcium carbonate, gypsum, organic matter, gravel, fine soil fractions) were found to significantly affect the vegetation structure in South Sinai, Egypt (El-Ghani and Amer, 2003). Soil clay content alone, in a dry river valley in SW China, explained 70% of the vegetation structure (Xu et al., 2008). Therefore, soil type and topography (e.g. elevation, aspect) are described as the main factors affecting the structure of the vegetation in multiple studies in arid and semi-arid environments (Batanouny and Baeshin, 1983, El-Demerdash et al., 1994, Sebastiá, 2004, Hejcmanovā-Nežerková and Hejcman, 2006, Cañadas et al., 2010). Furthermore, the amount, frequency and timing of the rainfall may strongly affect the structure of the vegetation in semi-arid and arid lands (Miranda et al., 2011).

2.3 SPECIES DISTRIBUTION MODELLING (SDM)

Species distribution modelling (also termed ecological niche modelling, or ENM), habitat modelling and bioclimatic modelling are tools to assess the association and occurrence of species with the environmental variables (Elith and Leathwick, 2009). Such modelling is becoming an essential tool for predicting the distribution of species using environment variables (Guisan and Thuiller, 2005, Elith and Leathwick, 2009). The sparse data relating to species distribution in many regions have led to the use of SDM to predict species distribution (Elith et al., 2006). The approach is based on the assumption that the species is in equilibrium with the environmental variables (Guisan and Zimmermann, 2000, Zimmermann et al., 2010) and that; therefore, the distribution of the species can be extrapolated in space to all tolerable climatic regions. Species distribution modelling is being used to guide many conservation actions, such as managing invasive species, identifying and

protecting critical habitats for plants and animals, and the selection of protected areas and translocation (Guisan et al., 2013). Species distribution modelling can be used to predict the current distribution of a species, or of multiple species and, thus, communities, and to predict change over time and space (e.g. predicting the change of vegetation structure under different climate scenarios) (Elith and Leathwick, 2009).

The selection of the prediction model appropriate to a given study begins with determining a wide range of ecological concepts (Austin, 2002), depending on the goals of the study. Details of these conceptual considerations are found, for example, in Austin (2002) and Brown et al. (1996). Some of the most important concepts are equilibrium versus non-equilibrium, fundamental versus realised niche, and direct versus indirect environmental predictors. The direct environmental variables are those that have a direct physiological impact on plant growth, such as temperature and pH. Indirect predictors, such as elevation and slope, do not have a direct physiological influence on the plant (Franklin, 1995). The fundamental niche of the plant species is where they can survive and reproduce, and the realised niche is where they show responses to any change over space and time. Predictive modelling is mostly based on the equilibrium concept, which states that the vegetation is in equilibrium with the climate or is based on the concept that different climate change scenarios will impact species distribution.

The methodology for predictive modelling has developed rapidly in the past two decades. There are multiple techniques available now, depending on the type of data available for modelling (Elith et al., 2006, Elith et al., 2011). These data may be presence-only data (i.e. false negatives may exist in the data) or presence/absence data collected in a designed sampling procedure. Elith et al. (2006) compared 16 different models for species distribution prediction. Three of these methods use the

presence-only data (BIOCLIM, DOMAIN and LIVES), and the rest use the background environment data of presence/absence. MAXENT, in addition to a few other methods, displayed high performance in predicting the distribution of the species (Elith et al., 2006). A detailed review of the methodology and models used in prediction with the presence-only data is found in Elith et al. (2006) and Franklin et al. (2010).

Static or correlative SDMs, the most commonly used SDMs, is based on an equilibrium assumption of species with its environment (Elith and Leathwick, 2009); however, ecologists started to question the reliability of the correlative SDMs (GUISAN et al., 2006, Dormann et al., 2012). Thus, and as an alternative of the correlative SDMs, there is a substantial body of literature increasingly describing and assessing the use of the process-based species modelling (Kearney and Porter, 2009). These models are expected to produce a better prediction of the species range and offer a better understanding of the forces behind a specific species distribution, considering they predict species distribution based on their underlying processes or mechanisms like the biotic interactions and disturbances (Evans et al., 2016). The most recent examples of process-based models include models based on metapopulation and metacommunity (Mokany et al., 2012, García-Valdés et al., 2013). Other process-models might include physiological (Kearney and Porter, 2009), phenological (Chapman et al., 2014), or demographic processes (Merow et al., 2014).

In practice, results from process-based models can be less accurate and robust in predicting the potential habitat of species when compared with SDMs based on equilibrium assumptions (Franklin, 2010b, Václavík and Meentemeyer, 2012). These models rely on the assumption that the underlying process formulations are correct and the reasons for the observed correlations are certain, which may lead to

incorrect predictions if the assumption is unfounded (Dormann et al., 2012). Process-based models are also difficult to implement due to the vast amount of data required to run the model, parameters to be estimated (such as details about species growth rate, dispersal and survival rate), and computational intensity. These detailed data are available for a small number of species, leaving many species with minimal data.

2.4 CONSERVATION OF THE EASTERN HAJAR MOUNTAINS

Many of the national reports and observations raise concerns over the negative impacts on vegetation due to the increase in development (road building, hotels and other construction), the increase in the number of animals, which led to overgrazing in many critical vegetation areas, and the potential effect of climate change. A recent survey of the Eastern Hajar vegetation describes the mountains as 'heavily degraded with little or no regeneration of the principal trees like *Ceratonia oreothauma, Prunus arabica, Olea europaea* and *Sideroxylon mascatense'* (Miller and Knees 2014).

2.4.1 Effects of grazing on vegetation

Land degradation (deterioration of soil and vegetation quality), decrease in plant cover, shift in the species composition, altering soil characteristics, soil erosion, and decrease of species richness are some of the effects of the overgrazing in arid and semi-arid lands (Tarhouni et al., 2007, Bo et al., 2013, Rutherford and Powrie, 2013, Tabeni et al., 2014, Gamoun et al., 2015). Reverting ecosystems to their initial state can be difficult, after the changes that can happen due to overgrazing (Clark and Covey, 2012).

The effects of grazing on species richness and diversity are not clear and cannot be generalised. While some studies recorded a decrease in species richness with

increasing grazing, others have reported an increase species richness due to heavy grazing, with some studies with inconsistent or no relationship between grazing and species richness. (Pacala and Crawley, 1992, Fu et al., 2004, Liu et al., 2016). Species richness was found to be consistently declining with high grazing in nutrient-poor ecosystems, while it exhibited significant increases or no response in nutrient-rich ecosystems under high grazing in different types of ecosystem (i.e. lake, stream, marine, grassland, and forest ecosystem) (Milchunas et al., 1988, Proulx and Mazumder, 1998). The decrease in richness with high grazing in the nutrient-poor ecosystem could be, probably, explained by the limited ability of the palatable species to regrowth after grazing, which is not the case with the nutrient-rich ecosystems with more available resources for plants to grow. (Haarmeyer et al., 2010, Rutherford and Powrie, 2010, Yayneshet and Treydte, 2015).

In arid and semi-arid areas, the availability of water and soil nutrients, usually, limit the plant growth. In these systems, small or moderate changes in plant communities are expected in response to grazing (Osem et al., 2004). The effects of grazing on the community composition and soil will depend on the grazing intensity, the topography of the area and the rainfall. For example, the development and growth of woody vegetation in Mediterranean ecosystems is generally inhibited by increased grazing, which changed the plant composition to more herbaceous cover (Carmel and Kadmon, 1999). Grazing may also create a better environment for the establishment of the woody seedling through trampling and reduce herbaceous competition (Carmel and Kadmon, 1999, Sutter and Ritchison, 2005).

The structure and composition of semi-arid western, interior forests of the United States have also changed dramatically because of grazing (Belsky and Blumenthal, 1997). The change in species composition due to grazing is reported in many other

arid and semi-arid areas (Batanouny, 1979, Brinkmann et al., 2009, Dreber et al., 2011, Herrero-Jáuregui and Oesterheld, 2018).

Grazing is considered a significant threat to land degradation in the Northern mountains of Oman (Ghazanfar, 1998). Brinkmann, 2009 found that the species richness varied with elevation and also, he recorded a weak correlation between the species richness and grazing in Jabal Akhdar (Western Hajar Mountains, Oman). The grazing effect on species richness in the Western Hajar Mountains was overlaid by the elevational gradient (Brinkmann et al., 2009). The relationship between grazing and the species richness varies along an elevational gradient and often depends on the palatability of the species and the relationship between the palatability and competitive ability of these particular species (Pacala and Crawley, 1992, Olff and Ritchie, 1998).

2.4.2 Important Plant Areas (IPA)

The Important Plant Areas (IPA) project is a programme developed by Plantlife International as a response to the biodiversity crises and the loss of wild plant species and their habitats (Plantlife International, 2004). This project was initiated to support the implementation of global strategies, specifically the Convention on Biodiversity Diversity (CBD), and to help in implementing, mainly, Target 5 with other targets of the CBD Global Strategy of Plant Conservation (GSPC). Target 5 states that ‘At least 75 per cent of the most important areas for plant diversity of each ecological region protected with effective management in place for conserving plants and their genetic diversity’ (CBD, 2012).

Anderson (2002) defines an IPA as ‘a natural or semi-natural site exhibiting exceptional botanical richness and/or supporting an outstanding assemblage of rare, threatened and/or endemic plant species and/or vegetation of high botanic value’. The criteria for the selection of the IPAs were initially developed by Plantlife

International for European countries. The criteria are as follows: Criterion A – The site holds significant populations of one or more species that are of global or regional conservation concern; Criterion B – The site has an exceptionally rich flora in a regional context in relation to its biogeographic zone; and Criterion C – The site is an outstanding example of a habitat or vegetation type of global or regional plant conservation and botanical importance. Taking habitat into consideration as an irreplaceable site for conservation is one of the major strengths of the IPAs (Al-Abbasi et al., 2010). The IUCN Arabian Plant Specialist Group (ASPG) adapted the IPAs programme for the Arabian Peninsula and several Middle Eastern countries (Al-Abbasi et al., 2010). The main adaptation is the inclusion of the refuge for the connectivity and climate change migration and the abandonment of the fixed thresholds used in the IPAs criteria. The adaptation also includes the *hima* or *himay* system (traditional protected areas used in some of the Arabian Peninsula countries, such as Oman and Saudi Arabia, where grazing is prohibited in some areas during droughts for the protection and better management of the land). The detailed methodology, guiding principles, and data-collection process for applying and selecting sites are described in the manual published by Plantlife International in 2002 (Anderson, 2002a).

Due to the limitations of the current IPAs criteria (see Darbyshire et al., 2017 for details), a revised global set of criteria was presented in 2017 (Darbyshire et al., 2017a). The main changes in the new revised IPAs criteria are the possible alignment of IPAs with Key Biodiversity Areas (KBA) due to the modification in the thresholds used in the assessment of the areas. Also, the new IPAs criteria consider socio-economically and culturally important plants as part of the assessment (Criteria Biii). The addition of these criteria will aid long-term conservation through sustainable use with the involvement of the local communities living in these areas.

2.4.3 Spatial conservation prioritisation

Human activities and climate change have led to a global loss of biodiversity. As a result, many ecological, social and economic implications are likely to occur (Hooper et al., 2012, Halpern et al., 2015). This biodiversity is not equally important, and the resources to protect all biodiversity are limited (Brooks, 2014), which led to the adoption of the systematic conservation planning (SCP) approaches (Pressey et al., 1993, Margules and Pressey, 2000). These SCP approaches are meant to guide conservation planning to best allocate conservation resources with minimum cost (Margules and Sarkar, 2007, Kukkala and Moilanen, 2013). Compared with the ad hoc approaches to conservation planning, systematic planning has the flexibility of providing different options and scenarios for protection according to conservation goals.

The methods of conservation planning evolved from simple complementarity-based minimum set reserve selection algorithms to more developed methods that incorporate costs (Bode et al., 2008), threats (Wilson et al., 2009), socio-political factors (Whitehead et al., 2014), and, most recently, a broader range of conservation actions, such as restoration or mitigating threats (Watts et al., 2009). More software has been developed recently to deal with large landscapes and a wide range of data types (Kukkala and Moilanen, 2013).

The ecological identification of important conservation areas (commonly known as spatial prioritisation) is a fundamental step used in conservation planning to achieve specified conservation goals (Pressey et al., 2007, Wilson et al., 2007, Ferrier and Wintle, 2009, Kukkala and Moilanen, 2013). Spatial conservation prioritisation is considered more systematic and accountable planning than the ad hoc allocation of conservation areas (Margules and Pressey, 2000, Wilson et al., 2009). Such prioritisation is a technical phase used inside a broader model of SCP (Margules

and Pressey, 2000, Margules and Sarkar, 2007, Kukkala and Moilanen, 2013, Lehtomäki and Moilanen, 2013). Spatial conservation planning is usually performed with a wider involvement from the land users and stakeholders (Ferrier and Wintle, 2009).

Spatial conservation prioritisation is the process of using available quantitative data for spatial analysis to select areas for conservation. It is based on many fundamental principles that have been discussed and reviewed in more detail in many publications since its appearance in the early 1980s (Margules and Pressey, 2000, Margules and Sarkar, 2007, Lehtomäki et al., 2009, Kukkala and Moilanen, 2013). Complementarity, irreplaceability, flexibility, persistence and vulnerability are the key principles used when applying spatial prioritisation (Margules and Pressey, 2000, Margules et al., 2002, Possingham et al., 2006, Margules and Sarkar, 2007).

The availability of data on all biodiversity features in an area is rare. Moreover, even with the availability of the data, the importance of biodiversity is not equal and varies according to the conservation goals of the analysis (Kujala et al., 2018). The importance of each of the features included can be determined by attributing greater weight to the more important features, which can be determined by characteristics such as rarity, threats and endemism. Therefore, considerations such as what biodiversity features to include, and what weight to give to the different features used in the analysis, are significant, as these may affect the areas designated as important.

Part of this present study describes a spatial conservation prioritisation approach for the Eastern Hajar Mountains using the Zonation programme (Di Minin and Moilanen, 2012, Moilanen et al., 2014). Zonation software is one of the decision support tools and is comparable to the other SCP and spatial prioritisation tools, such as MARXAN, ConsNet6 and C-Plan 7. One of the major differences between Zonation

and Marxan, for example, is that Zonation produces a complementarity-based and balanced ranking of conservation priority over the entire landscape for a fixed cost (Moilanen et al., 2005); whereas, MARXAN is designed to achieve feature-specific targets with minimum cost (Delavenne et al., 2012). Deciding which software to use for spatial prioritisation should be based on the main goals of the analysis. Therefore, further investigation into the differences between such tools is required (Moilanen et al., 2005, Moilanen et al., 2009b, Delavenne et al., 2012).

CHAPTER 3

FIELDWORK

3 CHAPTER 3: FIELDWORK

3.1 INTRODUCTION

In order to accomplish the objectives of this thesis, a qualitative study was carried out in the Eastern Hajar Mountains. Fieldwork was conducted not only in the wild, but also in semi-controlled environments such as the soil lab (i.e. soil and water research lab in the Ministry of Agriculture and Fisheries (MAF), and Oman Botanic Garden Herbarium (OBGH) and Nursery. In particular, the current study targeted the areas from 1000m elevation up to the highest point in the mountains (about 2200m). In total, 110 vegetation plots were sampled in order to cover as much variation in vegetation as possible (Chapter 4). The modified Braun- Blanquet scale was used to record the species abundance at any given plot; as a result, presence, percentage cover, and abundance for each species were recorded (Figure 3.1). Visual description and estimation of the total percentage of the plant cover, rock and bare ground cover percentage were recorded. Ten soil samples were collected per plot from the depth of 5cm and 10cm (Figure 3.2), among which five (5cm depth) were used for the soil seed bank germination experiment (Chapter 5), whereas the other five (10cm depth) were utilised for the soil analysis to be used for vegetation classification analysis (Chapter 4).

Notably, grazing threats to vegetation was measured using the grazing intensity scale (see Chapter 4 for details) in each plot, in addition to the recording of any signs of animal impact, such as soil compaction and animal droppings. Meanwhile, other threats such as the construction of new roads or new housing were also noted during the term of the study period. Species distribution modelling using the distribution of the perennial species in the study areas was used to predict the current distribution in unsurveyed sites of the mountains. The conservation status of

the mountains was examined using the Important Plant Areas (IPAs) criteria and spatial conservation prioritisation (i.e. Zonation) (Chapters 6 & 7).

The methods for vegetation classification and data collection have been applied extensively in the field worldwide. However, for Oman, the majority of applied vegetation data collection is considered new, as very few studies have been conducted based on systematic vegetation collection. As such, the research conducted here is novel but uses existing approaches. The methodology for the entire analysis required for this research was elucidated in detail in each chapter. Therefore, this chapter provides a general overview of the fieldwork, pre-planning and logistics required to run this project. In addition, it outlines the challenges observed during data collection in the extremely arid environment of the Eastern Hajar Mountains.

The landscape of the Eastern Hajar Mountains is harsh, and it was difficult to access several study locations. Therefore, fieldwork in these mountains required thorough and detailed planning, which proved to be a difficult task in many ways. Some of the major challenges before and during the fieldwork will be discussed in the following sections.

3.2 OVERVIEW OF THE PLANNING PROCESS AND FIELD METHODS

The planning and field methods for the Eastern Hajar Mountains vegetation classification, along with the conservation analysis, required the evaluation of existing data, the collection of new field data as well as the analysis and interpretation of the data. Detailed field methods, specifically for the vegetation classification data collection, are discussed in chapter 4. An overview of the planning and field process is illustrated in Figure 3.3**,** in addition to the products that will be subsequently developed at different stages of this process.

Planning for fieldwork in these mountains involved a skilled field team who could overcome any challenges encountered during the course of fieldwork. Being an employee at the newly under construction Oman Botanic Garden (OBG), I gained an incisive perspective into what was required and what types of vegetation data were found lacking in the garden's databases and generally in the entire country. Against this backdrop, my project contributed to the knowledge of vegetation in Oman and specifically to the garden flora, the vegetation database and work of the garden.

In pursuit of these objectives, a team from the OBG was formed to accompany me in my fieldwork. The OBG team supported my project through physical data collection, such as collecting the soil samples and also through helping me in identifying and verifying the plant species. Alternately, the OBG team benefited from the project through the acquisition of new skills in the methodology used for vegetation classification and description, in addition to exploring new sites that facilitated and expanded the OBG database and vegetation knowledge. Additionally, the team made use of these trips to collect plant materials (e.g. seeds and herbarium vouchers) for the garden.

3.3 PRE-FIELD TRIP

It is crucial to document the purposes of the vegetation data collection, considering the fact that the kind and details of data collected tend to vary for different purposes. For the existing project, the data collected were utilised for vegetation classification in the Eastern Hajar Mountains, which can then be used as an input to design reserves or to reintroduce and restore the native flora and habitats. Notably, considerations such as the timing for field sampling (e.g. to ensure most of the species are likely to occur), the time required to collect the specified quantitative data at each plot, the sampling detail (e.g. scope of the study and resources

available) were also necessitated. In addition, the dataset required to attain the objectives of the projects was planned and documented for the research.

Several steps were followed to ensure that the fieldworks will be as successful as possible and that the fieldwork team is ready to undertake the field trip.

- Clear definition of the aims of the project.
- Consultation with those with interests in the research and those that might be affected by the work along with its outcomes. This consultation intended to gain support through undertaking discussion with experts in the field as well as to gather existing information that could affect the overall new data collection, such as site selection and explanation.
- Obtaining the required permission for the field work such as the access permit for some sites, soil and plant vouchers collection permits.
- Collection of the existing information about the study area, evaluation of data, and how it can be used, if possible, in conjunction with the new data to be collected.
- After selecting the sampling methods, maps or data that are relevant to the research such as climate, elevation and other remotely sensed maps were obtained from different local authorities.
- Determination of the size of the area studied and logistics that are required to cover this area with regard to the time and period for data collection.
- Location of the vegetation plots using the remotely sensed maps and to determine, when possible, how far these locations are from any road and how to reach any inaccessible locations.
- Planning for the field trips' transport and equipment.

- Selection of the appropriate team for the field trip to ensure their capability and other relevant skills, such as plant identification, their knowledge of the field sampling methods, and their ability to drive in the harsh terrain of the mountains.

3.4 RESEARCH PLANNING HIGHLIGHTS

The current research enabled us to highlight some of the essential considerations in data collection for any further vegetation classification projects in the country. The following section encompasses what was done in this project and what can be used as a basis for the planning of future vegetation classification projects in general.

3.4.1 Gathering and revision of the existing data

Collection of the available data for the Eastern Hajar Mountains was one of the most challenging tasks for the research. Available data for these mountains can be used to build better planning and designing of the fieldwork along with an overall analysis of the study. These data included imagery of the mountains, biodiversity information and any other existing vegetation data and environmental information.

There was no published data that focused on the vegetation description of these mountains, and most of the existing data were scattered in different unpublished governmental reports or were known to experts in the area despite being documented. Collection of these data required contacting many authorities, personally and then officially, to pursue any researches or projects that were carried out in the Eastern Hajar Mountains and which involved the collection of any vegetation data. Revision and evaluation of the collected data were undertaken to determine its validity and potential future use within the current research.

3.4.2 Accesses and permits

One of the significant considerations for any vegetation survey that requires fieldwork is access to the study locations along with the right permits for these sites.

To illustrate, the Eastern Hajar Mountains include within its three-nature reserve, some rules and collection restrictions. Therefore, the right permits for the access and collection should be acquired before the commencement of the project.

3.4.2.1 Access methods

Eastern Hajar Mountains is one of the most challenging sites to access due to the high-elevation areas and steep, rugged mountain terrains. Access to the majority of these locations was challenging and risky in many ways. The main access to the mountains was via the four-wheel-drive cars, and about 80% of the vegetation plots were reached by this means. The roads are mostly graded, steep and risky, which requires skilled drivers who are adept for any road emergency (Figure 3.4). In order to cover a broader range of the mountain sites and to have comprehensive data for the current study, the isolated and inaccessible sites in the mountains were accessed via hiking, climbing (Figure 3.5) and helicopters (Figure 3.6). These inaccessible locations primarily included those above 2000m elevation on the mountains.

3.4.2.2 Site permits

Undertaking a project in the Eastern Hajar Mountains required different permits to access some of the study areas. These permits included permissions to access and collect materials from some locations in the Eastern Hajar Mountains, given that they are protected under the nature reserve laws and permissions. The access permissions are acquired from the Ministry of the Environment and Climate Affairs (MECA) and the Office for Conservation and the Environment (OCE).

In addition, permits were required to join the Royal Air Forces of Oman in their helicopter trips to the inaccessible and isolated villages in the mountains, or in this case, some of my study site locations. In addition to the site and data collection permissions, other permissions were also required from the Ministry of Agriculture

and water resources to use their facility in the research soil lab with a view to analysing the soil samples collected for the current study. Generally, the application for the permissions required specifications such as the aims of the research, study site, time and duration of the study. The process of granting the permissions was fast.

3.5 DURING FIELDWORK

Eastern Hajar Mountains is about 300km away from the location that I was based at. Different ways were used to reach the study locations in the mountains. These access ways included cars, hiking and helicopters. A total of 40 field trips were carried in the mountains, including the pilot trips to prepare for the field methods. The main and most frequently used method to access the plot locations was by cars. The other two methods (i.e. hiking and helicopters) inexorably required more preparation, and they were unusual trips to these mountains. Therefore, the section below discusses them briefly.

3.5.1 Hiking trip

There was only one hiking trip to the mountains, which was organised to reach the highest points in the Eastern Hajar Mountains at about 2200m. The trip was carried out during the winter (i.e. November 2019) in Oman. Before the decision of proceeding with the trip, a few meetings were organised between me, OBG team and the local guide from the area to discuss the trip route and the detailed plan, including all the logistics of carrying out this kind of trip.

The trip required thorough planning and organising due to difficulties and challenges that were expected to be faced during the field trip. The difficulty of this trip lies in 1) rough mountain terrains, 2) finding a local guide who could lead us through the mountain routes, so that we were able to reach the highest point in the area, 3)

logistics in organising a big team and 4) carrying our massive field and camp equipment, food and water for three days and for a team of 14 people (Figure 3.7). The team consisted of myself, eight researchers from OBG, the local guide, as well as four other locals to guide the donkeys. Ten donkeys were used in the trip to help carry our equipment, plant and soil samples through the harsh terrain of the mountains. They were also prepared to carry any person in the team if he was unable to walk or climb during the field trip.

The trip commenced from 0m elevation and reached the highest point in the Eastern Hajar Mountains at about 2200m. Thirteen vegetation plots were covered during this field trip. The trip proved to be the most challenging field trip among all the trips that were carried out in these mountains during the current study. For example, one of the major challenges of the trip was the paucity of drinking water. We had to carry our water for the entire duration of the trip and for 14 people as the mountains did not have any water points along the way. Unfortunately, we needed to change our route in the middle of the field trip and cut out one day of the planned time due to paucity of water. Other challenges of the trip will be mentioned in a following section.

3.5.2 Helicopter trips

The Royal Air Forces of Oman trips were principally organised to deliver food and medical aid to the locals in the isolated villages on top of the Eastern Hajar Mountains. After holding a few meetings with the authorities from the Air Forces, they did not agree to organise trips specifically for our research, but they accepted us to join them in their pre-planned trips to the villages. They also suggested that only a small team comprising of 3-4 people should be part of these trips. So, they contacted us whenever they planned a trip to the mountains, and we were always ready to join them.

These trips to isolated and inaccessible locations created an excellent opportunity for my research and to contribute to our overall vegetation knowledge of the Eastern Hajar Mountains. Despite this, sometimes we could only have a maximum of 15 minutes during each helicopter stop to work out our plot data collection and soil samples collection. A total of three helicopter trips were carried out in order to cover 14 vegetation plots. Some of the fieldwork challenges in the study area of the Eastern Hajar Mountains are summarised in Appendix 3.1.

The average number of plots that were carried out per day ranged from 3 to 5 plots. The duration of a field trip lasted from 1 to 4 days. The extended field trips (i.e. more than a day) required setting up camps across different locations of the mountains, primarily during the winter season. Usually, it gets very cold at the top of the mountains during the winter season; therefore, adequate precautions need to be undertaken. Overall, the fieldwork in the Eastern Hajar Mountains represents the most extensive fieldwork to have ever been carried out in these mountains. The amount of vegetation data collected, and the fieldwork experience gained by me and the whole of the OBG team is enormous.



Figure 3.1. The vegetation plots used to classify the vegetation in the Eastern Hajar Mountains.



Figure 3.2. Soil sampling in the field (a, b) and the work followed on them at the soil lab (c, d) for soil chemical and physical analysis and at the OBG nursery (e, f) for the germination experiment



Figure 3.3. The process used in vegetation sampling as well as data collection for vegetation classification in the Eastern Hajar Mountains.



Figure 3.4. The steep and challenging roads in the Eastern Hajar Mountains.



Figure 3.5. Hiking trip is one of the three access ways of reaching the highest elevation in the Eastern Hajar Mountains.



Figure 3.6. Helicopter trips to the remote villages and some of the highest study locations within the Eastern Hajar Mountains in collaboration with the Royal Army Forces in Oman.



Figure 3.7. Some of the physical challenges encountered during the field work in the Eastern Hajar Mountains.

CHAPTER 4

CLASSIFICATION AND ORDINATION OF THE MAIN PLANT COMMUNITIES OF THE EASTERN HAJAR MOUNTAINS, OMAN

4 CHAPTER 4: CLASSIFICATION AND ORDINATION OF THE MAIN PLANT COMMUNITIES OF THE EASTERN HAJAR MOUNTAINS, OMAN

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I certify that the work submitted as Chapter 4 and published as DOI https://doi.org/10.1016/j.jaridenv.2019.05.017 is indeed largely the work of the candidate. My contribution was to help design the preliminary analyses to demonstrate suitable sample size, to advise on the treatment of collinear variables and to provide general advice on how to structure the writing up of a paper for publication.

Richard Grenyer



4.1 ABSTRACT

This chapter presents a quantitative description of the plant communities of the Eastern Hajar Mountains of Oman and the primary environmental variables affecting their composition and distribution. Species inventories and environmental data were collected from 110 vegetation plots covering an elevation zone from 1000m to the highest point in the mountains at approximately 2200m. Measurements of 12 environmental variables were used in the analysis: aspect, slope, annual rainfall, soil pH, salinity, soil nutrients (N, P, K, Ca) and soil texture (clay and silt). TWINSPAN classification, Detrended Correspondence Analysis (DCA) and Canonical Correspondence Analysis (CCA) ordinations revealed four well-defined plant communities. Although some species overlap occurred in the transition zones between the communities, these plant communities were characteristic for their zones. Annual rainfall, total nitrogen and total calcium were the most important environmental factors affecting the distribution of plant communities. Using all the different data treatments, the high-elevation community was always distinctly identified, while the lower-elevation communities tended to overlap. Any grazing effect on plant community distribution appears to be overridden by the other environmental variables.

4.2 INTRODUCTION

Mountains generally contain about half of all identified global biodiversity hotspots, and in the extreme environment of arid regions, they become refugia for many plants and animals (Kohler et al., 2010, Garcia-Porta et al., 2017, Thomas et al., 2017). Mountains possibly also provide refugia for many species due to the various conditions created by their complex topography. While many early and simple models of climate change predicted simply an increase in the extinction rate of species, it is now thought some species will be able to escape, persist and expand

into refugial areas, including mountainous terrain (Walther et al., 2002, Thomas et al., 2004, Keppel and Wardell-Johnson, 2012).

Understanding current vegetation structure through the identification and description of the plant communities and their relationship to the environment is a crucial step in the understanding of arid ecosystems. Primarily, different plant communities are regarded as surrogates for the delimitation of ecosystems and community definitions; therefore, their analysis helps us understand the macroecological differences between components of the biosphere (Brown et al., 2013). Identifying and describing plant communities is another key component of any effective conservation planning (Kent, 2012, Brown et al., 2013). Environmental factors have a significant influence on vegetation structure and distribution in many habitats. Since the early 20th century, variation in environmental variables along elevation gradients has been used to study the changes in plant structure and distribution (Ghazanfar, 1991, Oksanen and Tonteri, 1995, Willis and Whittaker, 2002, Brinkmann et al., 2009). Climatic factors have proven to be key overriding variables determining the structure and distribution in arid and semi-arid habitats (Burke, 2001, Castillon et al., 2015). Elevation, topography, soil texture and chemical content have also been found to significantly structure the vegetation in arid regions worldwide (Higgins et al., 1999, White et al., 2004, El-Ghanim et al., 2010, Sanctis et al., 2013, El-Keblawy et al., 2016).

The Northern mountains of Oman (Al Hajar Mountains) are desert mountains, with barren, mostly treeless habitats characterised by low rainfall and high evapotranspiration (Mandeville, 1977, Edgell, 2006). The mountains bisect the eastern corner of Arabia for about 700km, and they are the only area with elevation above 2000m in eastern Arabia.

The complex structure, ancient geological origin, topography and isolation of the Hajar Mountains from other mountain ranges in Arabia make them one of the most diverse regions in eastern Arabia, with many endemic animals and plants (Ghazanfar, 1991, Patzelt, 2015c, Simó-Riudalbas et al., 2018). This endemicity makes for a distinct plant area in the region (Al Harthy et al., in review), and the range contains about half of the country's flora (about 700 species) (Patzelt, 2015c). The Hajar Mountains consist of three ranges: the Western Hajar, Eastern Hajar and the Musandam. Each of these ranges has its unique flora and vegetation, and the Hajar Mountains are identified as a national and regional centre of plant richness, diversity and endemism (Ghazanfar, 1991, Patzelt et al., 2014, Patzelt, 2015c). The mountains have more biotic and geomorphic features in common with the Zagros mountain range of south-western Iran than with the rest of Arabia. This is evident in the similarities in flora and plant communities between the mountains ranges (Zohary, 1973, Mandeville, 1977, Mandeville, 1984). These similarities are suggested, by many authors, to occur because the floras of the north-eastern Arabian Peninsula (including the Hajar Mountains), Iran, and south-western Pakistan were previously connected via a land-bridge during the Quaternary, and all belong to the Arabian tectonic plate (Mandeville, 1985, Kürschner, 1998, Ghazanfar, 1999).

Despite the rich flora of the Eastern Hajar Mountains and its heterogeneous physical environments, and apart from a single descriptive study by Mandeville (1977) in Jabal Aswad (i.e. within the Eastern Hajar range), the vegetation has never been classified. There have been only two multivariate analyses along the altitudinal gradients in the Hajar Mountains (or, indeed, the entire country), both of which were carried out in the Western Hajar Mountains (Ghazanfar, 1991, Brinkmann et al., 2009). In these studies, elevation, landform and grazing intensity were found to be the most significant factors affecting plant composition and distribution.

The objective of the present study was to classify the vegetation along an altitudinal gradient above 1000m and to explore and identify the environmental factors that may affect plant composition and distribution on a regional and local scale. Elevation, temperature, precipitation and soil characteristics are important environmental components of vegetation structure and distribution in arid habitats worldwide (Higgins et al., 1999, Bornman et al., 2008, Castillon et al., 2015, Rahman et al., 2017). Therefore, the study was based on our experimental design around these variables.

4.3 MATERIALS AND METHODS

4.3.1 Study area

The Hajar Mountains (Western, Eastern and Musandam) stretch along the northern coast of Oman from southwest of Muscat in the east to the UAE in the west. The Jabal Shams in the Western Hajar has the highest elevation of the Hajar Mountains (i.e. 3009m), followed by the peaks of the Eastern Hajar Mountains, with elevations of about 2230m.

There is no climate station in the Eastern Hajar Mountains. Therefore, the climate data were extracted and modelled from a recent national project that aimed to model and analyse climate change across the entirety of Oman (Ministry of Environment and Climate Affairs (MECA), 2015). All climate variables were extracted at a resolution of 1km. The annual mean temperature for the mountains is about 12.7°C (with a predicted increase over the next 20 years of about 1.5°C). The mean annual rainfall is about 120mm, with a general slight anticipated increase in dryness for the entire Hajar Mountains. The main rainfall season in northern Oman, including the Hajar Mountains, occurs between December and April and accounts for about 60-80% of the annual rainfall (Kwarteng et al., 2009). The current dry period, which

began in1999, is considered to be the most prolonged period of drought since climate records began (i.e. 1980) (Ministry of Environment and Climate Affairs (MECA), 2015).

The Eastern Hajar Mountains are comprised predominantly of Cretaceous limestone with metamorphic and igneous rocks, including ophiolites with unique soil chemistry (Hoffmann et al., 2016). They are mostly steep mountains with bare rock outcrops and very shallow soils on the slopes, runnels and wadis (Guba and Glennie, 1998). Gravel soils predominate in the valleys and alluvial fans. The terrain is crossed by dry wadis formed by flowing water during the rainy season. Although the vegetation was perceived to be in poor condition due to prolonged drought in the preceding few years, 431 species (31% of the total flora in the country) have been recorded from the Eastern Hajar Mountains by multiple authors (Ghazanfar, 1992a, Miller et al., 1996, Al Harthy et al., in review). The Eastern Hajar Mountains contain some range-restricted plant species, which are, therefore, of conservation importance based on national or regional endemism. For example, *Ceratonia oreothauma,* a relict species, is found only in Oman and Yemen, and *Prunus arabica*, an Irano-Turanian species recorded from Turkey to northern Iran and the Arabian Peninsula. Also, 15 endemic and near-endemic plant species to Oman, and 16 regional endemic species are recorded from the Eastern Hajar Mountains (Patzelt, 2015a, Al Harthy et al., in review).

4.3.2 Vegetation sampling procedures

A preliminary survey was conducted before the collection of the data. This survey guided the sampling design of the study, and, thus, the selection of the location and the size of the vegetation plots. Plots were sampled during all seasons of the year (i.e. October-April) from 2014 to 2016, except for summer. The vegetation survey

covered the elevation from 1000m to the highest point of the mountains at about 2200m.

A total of 110 600m^2 plots were randomly allocated using a Geographical Information System (GIS) (ArcMap 10.5.1), with the number of plots within each zone being proportional to the land area within each elevation interval (Figure 4.1). The size and number of the plots were determined using a rarefied species-area curve, derived from 60 plots between 1000 and 2000m in elevation over a single season, using EstimateS software (Colwell, 2013). Based on sampling data, EstimateS help in assessing and comparing the diversity and composition of species assemblages. Therefore, a pilot study was carried out prior the commencing of the actual data collection for the project to determine the size and number of plots required to cover the entire study area in the Eastern Hajar Mountains. The plots were combined for rarefaction, and the area associated with asymptotic species richness determined to be 600m^2 with an approximate number of plots of about 110.

Within each plot, the presence of all species (perennials and annuals) with their percentage cover was recorded using the modified Braun-Blanquet cover/abundance scale. Total vegetation cover, bare ground and rock cover were also visually estimated for each plot. Finally, elevation, slope and aspect (sine-transformed) were extracted from the 1km Digital Elevation Model (DEM) for each plot using ArcMap 10.5.1.

4.3.3 Grazing intensity

To estimate grazing pressure in the study area, the following scale was used to identify the damage for each plant species within a plot: 1 (lightly grazed)= 0-30% of a plant grazed; 2 (moderately grazed)= 30-60%; and 3= >60% is considered heavily grazed. The effect of grazing intensity on species richness and diversity was tested for significance (Table 4.2). The average grazing intensity was then calculated for

each plot and each plant community. A Chi-square test was carried out to examine whether the intensity of grazing was different between the significant indicator species of plant communities and the non-indicator species. Other disturbance indications, such as evidence of tree cuts or soil trampling, were also recorded for each plot.

4.3.4 Soil sampling and analysis

Five soil samples were taken from three random locations at about 10cm depth in each plot. The soil then was air-dried and sieved at 2mm. Each of the samples was analysed, and the following chemical assays carried out: pH, electrical conductivity (EC), calcium (Ca), magnesium (Mg), phosphorus (P), potassium (K), total nitrogen (N), organic matter (OM) and soil texture (sand, silt, and clay percentage). Soil-distilled water extract (1:5) was used for estimation of the soil pH (using pH metre) and soil EC (using a conductivity metre, WTW COND 7310 inoLab 7310). An atomic absorption spectrophotometer (Biochrom Libra S22 UV/Vis) was used to determine the soil phosphorus (P), and a flame photometer (Sherwood Model 410) to measure the potassium (K). Calcium (Ca) and magnesium (Mg) were measured using a titration procedure (with ethylenediaminetetraacetic acid EDTA), and a Bouyoucos hydrometer was used to measure the soil texture (Bouyoucos, 1962). Total OM was measured using Walkely and Black's titration method (Walkley and Black, 1934), and the Kjeldahl method (Bremner, 1960) was used to measure the total nitrogen (N) of the soil. All soil tests were carried out by the lead author at the soil research laboratory, Ministry of Agriculture and Fisheries in Oman, except for the OM and total nitrogen, which were run by Biyaq Laboratories (laboratories specialised in a wide range of chemical analysis of water, oil and soil). The soil laboratory followed the methods of soil analysis from Chapman and Pratt (1961).

4.3.5 Vegetation classification

All data analyses were carried out using PC-ORD 7.03 (MjM Software, OR, USA). This study is the first multivariate analysis of the Eastern Hajar Mountains vegetation. Therefore, two main datasets were assembled, one comprising all species, and the other only perennials and two ordination methods were applied to assess the consistency of results. TWINSPAN was performed to classify the vegetation in the study area (Hill et al., 1975, Hill, 1979). TWINSPAN classifies the samples and the species according to their ecological preferences. Four datasets were subjected to TWINSPAN classification: two datasets comprised all recorded species, and the other two comprised the perennial species only. Each pair of datasets also comprised one version with species occurrences treated as binary presence/absence, and the other containing abundance data. Due to the subjectivity and errors that may occur from the visual estimation of the species cover between different researchers, and for the Braun-Blanquet scale to be reliably used in multivariate classification, the species cover/abundance ordinal data were transformed. The modified Braun-Blanquet scale (i.e. cover estimation scale from r to 5) was first transformed to the extended 1-9 ordinal scale, which was then followed by the use of the optimum transformation value (OTV) to consider the species performance within plot (van der Maarel, 1979, Lepš and Hadincová, 1992, van der Maarel, 2007). The OTV scale is a near-metric scale that meets the assumptions of most multivariate analyses. The classification was based on 110 plots and the two datasets of all recorded species (i.e. 208), and only perennial species (i.e. 150). Annual and biennial species pose a problem for community ordination in extremely arid environments because they are relatively ephemeral species that are highly dependent on the rainfall received in the period before sampling. Ephemerality is not only a problem regarding detection but also for understanding their ecological role and meaning in a community. In this study, we

present our results including those annuals that were sampled. We present in the appendix 4.1 versions of the results in which annual species are excluded – these results differ in some aspects regarding community description and ordination. In particular, they include annual species which results in the description of two mid-elevation communities rather than one. From a conservation perspective, we feel our choice to be more precautionary, but, also, that establishing the nature and functional importance of these mid-elevation communities is, we believe, a future priority.

An indicator species analysis (ISA) was performed on the output groups of the TWINSPAN classification of all datasets to determine the final number of the plant communities and to identify diagnostic species for each community. This analysis provides an indicator value (IV) for each species based on the relationship between the species occurring in a set of sites surveyed and the classification of these sites into groups (Dufrêne and Legendre, 1997, Cáceres et al., 2009, De Cáceres et al., 2012). The diagnostic species were identified by the calculation of fidelity values from presence/absence data so that the fidelity values are not affected by the cover/abundance values of the species (Tichý et al., 2006). Dufrêne and Legendre's method was used for the diagnostic species analysis with cover/abundance data (Dufrêne and Legendre, 1997). A Monte Carlo randomisation test was used to test for the statistical significance of the indicator values for each species in each group (McCune et al., 2002).

4.3.6 Species diversity pattern

The data collected in this study were used to investigate and document the pattern of species diversity and its relationship to the variation in environmental variables along the altitudinal gradient (1000-2200m). This analysis aims to draw conclusions regarding the factors that might affect species diversity in these mountains, which

can be then investigated in detail. Species richness (S), the Shannon–Wiener diversity index (H'), and Simpson's index of diversity (D) were calculated to describe the species diversity pattern for each plot (i.e. Alpha diversity, α), and also for each plant community (i.e. Beta diversity, β) identified by TWINSPAN. Species richness (S) was indicated by the number of species in each plot, while the Shannon diversity index (H') counts all species based on their frequencies and regardless of their rarity and commonness proportions (Clarke and Warwick, 2001), and Simpson's index considers the number of species present relative to the abundance of each species. The correlation between species richness and the 13 environmental variables used in this study was examined using simple Pearson's coefficients.

4.3.7 Community ordination

Before running the communities and species ordination analysis, the entire set of 17 environmental variables, including grazing intensity, selected at the beginning of this study were tested for multicollinearity by calculating a variance inflation factor (VIF) and using a cut value of 10 (Dormann et al., 2013). The results reveal three clusters of collinear variables: one comprises elevation, annual maximum temperature and annual rainfall; a second comprises soil OM and total nitrogen content, and a third comprises soil types (Table 4.2). We retained the annual rainfall, total nitrogen, and clay and silt soil variables to represent these clusters, respectively.

Detrended correspondence (DCA) and Canonical correspondence analysis (CCA) were used to investigate the vegetation structure and distribution of species about the environmental variables. The DCA and CCA approaches were used as complementary analyses for a better and more robust understanding of plant community distribution. The correlation between the community and the effect of the environmental variables on their distribution was tested using the joint graph (biplot) method within ordination space (McCune and Mefford, 1999). This method plots the

environmental variables as vectors radiating from the centroid of the ordination scores with their length proportional to the strength of the correlation. In DCA, the gradient length, which represents the total beta diversity, was used to investigate the turnover in community composition along the axes. The gradient length is measured in standard deviation units, which range from 1SD (SD refers to standard deviation) to 4SD (Oksanen and Tonteri, 1995, ter Braak and Šmilauer, 2015). In general, higher SD values are related to higher beta diversity. For CCA, eigenvalues and the significance of the species-environment correlations were tested using a Monte Carlo test (1000 permutations), and the significance of each environmental variables was assessed using Pearson's inter-set correlations.

Significant differences within and between groups of sampling sites were tested using a multi-response permutation procedure (MRPP) with the squared Euclidean distance (McCune et al., 2002) on a matrix of 12 environmental variables (slope, aspect, annual rainfall, soil pH, EC, calcium (Ca), magnesium (Mg), phosphorus (P), potassium (K), total nitrogen (N) and soil textures (clay and silt) and grazing). Grazing was included to examine whether it had any effect on structuring the vegetation in the study area. The contribution of each of the variables in determining the structure and distribution of plant communities was examined using the similarity percentage analysis procedure SIMPLER (Clarke and Warwick, 2001).

4.4 RESULTS

4.4.1 Flora of the Eastern Hajar Mountains

Two hundred and eight species from 56 families were recorded from the Eastern Hajar Mountains at elevations above 1000m. The majority of the recorded species were perennials (74%), annual and biennial species accounted for the remaining 26%. Asteraceae and Poaceae (36% each) were the most species-rich families

recorded, followed by Fabaceae, Brassicaceae, Boraginaceae and Caryophyllaceae (29%, 16%, 14%, 14% respectively). Asteraceae, Poaceae and Fabaceae are the top three largest families recorded in several countries of the Middle East (Ghazanfar and McDaniel, 2015). Family delineation follows APG III (Angiosperm Phylogeny Group, 2009) (Bremer et al., 2009). Fifteen endemic and near-endemic species were identified in the study area, as well as 16 regional endemic species (Patzelt, 2015a, Al Harthy et al., in review). The most common species were *Helianthemum lippii*, *Teucrium stocksianum* ssp. *stenophyllum*, *Cymbopogon schoenanthus*, *Ochradenus arabicus* and *Dodonaea viscosa*; each occurred in approximately half of the study sites. *Aloe vera* and *Ficus carica*, recorded in very low numbers, are the only two cultivated species recorded within the study area. Both species were removed from the analyses.

4.4.2 Species diversity

The average number of species recorded per plot was 24 (range: 1-54). The correlation between environmental variables and diversity (Table 4.2) reveals that high annual rainfall has a significant adverse effect on species number (S) (r = -0.399) and diversity (H': r= -0.338). The results also reveal a significant positive correlation with soil magnesium (Mg) and a significant negative correlation with soil pH for both richness and diversity.

The high-elevation community had lower species diversity and richness in comparison with low and mid-elevation communities. There was a unimodal relationship between the species richness and diversity with elevation (Figure 4.2). The highest number of species and diversity was recorded from the mid-elevation plant community, the *Searsia aucheri-Acacia tortilis* community, followed by the low-elevation community, *Echiochilon persicum-Helianthemum kahiricum* (check sections from 4.4.4.1-4.4.4.2).

4.4.3 Grazing intensity

We found that 82% of the studied sites were moderately to heavily grazed. Grazing intensity was highest in communities below 1800m. There was no relationship between grazing intensity and species richness and diversity (Table 4.2), with no significant difference between the plant communities, except for the high-elevation community with lower grazing intensity. Aspect and clay content had significant positive correlations with grazing intensity, while it was negatively correlated with soil pH, total nitrogen and annual rainfall (Table 4.2). There was no significant difference in grazing intensity between community indicator and non-indicator species ($\chi^2 = 0.809$, df = 2, $p = 0.667$).

4.4.4 Vegetation classification and main plant communities

Although we performed classification and ordination on the abundance data, the results are not presented in the main paper (see Appendix 4.1), but we discuss the presence/absence results here. This decision was based on our preference to avoid the errors that may occur from the visual estimation of the cover/abundance using the Braun-Blanquet data between different researchers, which may lead to incomparable results from different studies in the region. However, the cover data display almost the same results as using the presence/absence data, with only slight differences in the number of communities produced by TWINSPAN classification.

Based on the number of indicator species (ISA, Table 4.3), we found the third level of the TWINSPAN division to be the most informative level (78 indicator species) in defining the number of plant communities when considering all species, and the fourth level division (59 indicator species) when using perennials. TWINSPAN classification identified four well-differentiated (but without discrete limits) plant communities at the third level. Level 4 of the perennial species classification resulted in the identification of six plant communities: four of these communities resembled

the Level 3 community, and one was indicated by only two species; one of which is *Solanum incanum,* which is considered a weed and commonly found in disturbed habitats. For the reasons above, we chose the third level of the species classification to represent the plant communities of the Eastern Hajar.

The MRPP results indicate that the groups identified by TWINSPAN had significantly lower mean within-group distances than expected by chance alone (A= 0.16, T= -26.3, Observed delta= 0.4, Expected delta = 0.50, p = 0.000), which indicates that there are significant differences between these groups in the environmental matrix (Appendix 4.2). The four plant communities are the *Echiochilon persicum-Helianthemum kahiricum* community, the *Searsia aucheri-Acacia tortilis* community, the *Prunus arabica-Ceratonia oreothauma* community and the *Ebenus stellata-Convolvulus ulicinus* community. Each plant community is identified, when possible, by the tree and shrub species with the highest indicator value (IVs; Table 4.4). Indicator species that are known to be a sign of habitat and vegetation disturbance were not used in the naming of the community. The plant communities were referred to without using phytosociological nomenclature.

4.4.4.1 The Echiochilon persicum-Helianthemum kahiricum community (Group 4: 1000-1600m)

A plant community of open shrubland on the summits and plateaus with some isolated trees on wadi beds and slopes. This plant community characterises most of the lowest-elevation (average elevation of 1218m) and continues into a mid-elevation of the study area. The most common shrub with the highest indicator value (60%) was *Echiochilon persicum*. This plant community has one of the highest total vegetation covers (avg. 44%) and one of the two highest species richness (avg. 27 species/plot) compared with other plant communities described in this study (Table 4.5). *Helianthemum lippii*, *Echiochilon persicum*, *Zygophyllum indicum*, *Ochradenus*

arabicus and *Teucrium stocksianum* ssp. *stenophyllum* are the most common species in this plant community.

4.4.4.2 The Searsia aucheri -Acacia tortilis community (Group 3: 1000-1700m)

An open drought-deciduous woodland plant community on gentle to moderate rocky slopes that characterises the low-to mid-elevation montane zone. This community is indicated by the Oman endemic shrubs *Searsia aucheri*, *Acridocarpus orientalis*, *Moringa peregrina*, *Dyerophytum indicum* and *Pulicaria glutinosa*. This plant community is described, as with the previous community, from the lowest to the mid-studied elevation (i.e. average elevation 1424m). It has an intermediate total vegetation cover (avg. 33%) and the highest species richness and diversity (avg. 29 species/plot) (Table 4.5). It also represents a well-defined and densely vegetated wadi mountain vegetation with drought-deciduous woodland dominated by species such as *Ziziphus spina-christi*, *Acriodocarpus orientalis* and *Euryops arabicus*. The drier and steeper rocky slopes support shrubland, with *Commiphora wightii*, *Pulicaria glutinosa* and occasional trees of *Moringa peregrina*. The dominant species for this community are *Pulicaria glutinosa*, *Acridocarpus orientalis*, *Searsia aucheri*, *Cymbopogon schoenanthus* and *Helianthemum lippii*. *Euphorbia larica* is one of the dominant species on the lower slopes of this community and most of northern Oman. In Arabia, the species' distribution is limited to Oman, and it is common in both Oman and southern Iran (Zohary, 1973). Other common species within this community, such as *Aerva javanica* and *Blepharis ciliaris,* also indicate the link with southern and south-western Iranian mountain flora, although these two species are sometimes considered an indicator species for habitat disturbance. *Lavandula subnuda* and *Ochradenus arabicus* are two regional endemic species recorded as indicators and common species in this community.

4.4.4.3 The Prunus arabica -Ceratonia oreothauma community (Group 2: 1200-2000m)

Mixed xeromorphic deciduous woodland and shrubland on gentle and steep mountain slopes, and plateau areas (at an average elevation 1576m). This zone is indicated and dominated by most of the principal tree species in the Eastern Hajar. These are the regional endemic Irano-Turanian *Prunus arabica*, *Ficus johannis*, *Acacia gerrardii* ssp. *negevensis*. *Ceratonia oreothauma* is a regional endemic and an indicator species for this community, recorded only in the Eastern Hajar in Oman and Yemen. The genus *Ceratonia* is believed to be of an ancient Eastern Mediterranean origin (Winer, 1980). This community represents the southernmost presence of the Iranian open dry deciduous woodland vegetation, with a unique plant assemblage including *Ceratonia* and *Prunus* trees that links the southern Arabian flora and phytogeography with that of central Asia (Zohary, 1963, Ghazanfar, 1999). This community has intermediate vegetation cover (avg. 40%) and species richness (avg. 24 species/plot) (Table 4.5). *Teucrium stocksianum* ssp. *stenophyllum*, *Helianthemum lippii, Ochradenus arabicus*, *Solanum incanum*, *Andrachne telephioides* are the most common species in this group. The presence of ruderal and unpalatable species, such as *Solanum incanum, Euryops arabicus* and *Chenopodium murale* among the indicator and the common species indicates the disturbance of this unique community.

4.4.4.4 The Ebenus stellata-Convolvulus ulicinus community ('HEEC', Group 1: 1500-2197m)

A treeless steppe and dwarf shrubland, on summits and plateaus with a rich plant community that has developed along the runnels and the wadis (average elevation 2023m). This community has the lowest species richness (avg.14 species/ plot), lowest diversity and the lowest vegetation cover (28%) in the study area (Table 4.5). The most common species are *Helianthemum lippii*, *Teucrium stocksianum* ssp.

stenophyllum, *Dodonaea viscosa* and *Ebenus stellata*. This community is distinguished from other groups by having, by far, the highest OM content and the highest total nitrogen values (Table 4.5).

4.4.5 Plant communities in relation to environmental variables

Variation in the floristic composition of the study sites was explored using DCA and CCA. Generally, TWINSPAN classification revealed a clear separation of the high-elevation plant community (the *Ebenus stellata – Convolvulus ulicinus community,* see 4.4.4.4, hereafter 'HEEC') using all the different datasets (perennial vs all species, abundance vs presence/absence). The CCA ordination generally revealed less distinct separation of all other communities, indicating sensitivity to data treatment that may result from either very high ranges for some physical environmental variables in an extreme environment, or perhaps a continuous response of many species to environmental variation.

For the third level TWINSPAN classification, both DCA and CCA ordination, suggested strong environmental correspondence, although DCA again more strongly separated the plant communities (Figures 4.3 & 4.4). For DCA, the first axis (eigenvalue= 0.4), with a gradient length of 3.9, represents a high beta diversity, with almost no species in common between the opposite ends of the axis, indicating high species turnover. The second axis (eigenvalue= 0.2) has a gradient length of 3.1 SD, an intermediate value representing lower diversity along the gradient, and lower community composition turnover. The eigenvalues of the first two axes of the CCA (eigenvalue= 0.3 and 0.2 respectively) almost resemble the eigenvalues of the DCA.

The CCA correlation with species-environmental variables for the first and second axes were 0.93 and 0.84, respectively, and the Monte Carlo test was significant (0.03). The correlation of environmental variables with the CCA axes indicates that

the first axis was negatively and strongly correlated with annual rainfall (r= -0.837) and total nitrogen (r= -422), and positively correlated with the slope and soil potassium (Table 4.6). Also, this axis correlates negatively with grazing intensity. The biplot in the CCA graph suggests a stronger correlation with soil properties, such as soil pH, clay, calcium, potassium and total nitrogen. Axis 1 reveals a strong, positive correlation with species richness and diversity, and Axis 2 displays a negative correlation (Table 4.6). The DCA first axis accounts for 5.9% of the total variance, and the second axis for about 3.6%. The total variance explained by the CCA axes is comparable to the DCA, with 4.8% explained by the first axis and 3.6% by the second axis. A significance test of the environmental variables revealed that there are no significant differences in the mean environmental variables between Plant Communities 2 and 3 or between 3 and 4 (p=0.08 & 0.4, respectively). Table 4.7 illustrates the significance and percentage contribution for the environmental variables in defining the plant communities. The significant variables in determining the high-elevation plant community are the annual rainfall, Ca, pH, and total nitrogen. The environmental similarity within a community was high for all four communities, with an average of 88.5%. Dividing the variables into three categories – soil (including all measured soil properties), topography (aspect and slope) and climate (annual rainfall) – indicated that soil contributed 66-76%, topography 9%, and annual rainfall contribution ranged from 0 to 12%.

4.5 DISCUSSION AND CONCLUSION

4.5.1 Classification and ordination

The vegetation of the Hajar Mountains (including that in this study) belongs, phytogeographically, to the Nubo-Sindian local centre of endemism, which is closely linked with the mountain floras of southwest Iran, Afghanistan and southwest Pakistan (Ghazanfar, 1991, Ghazanfar, 1992b). The flora and vegetation of the high

elevation of the Eastern Hajar found here bear a striking resemblance to the flora of central Iran. This link is evident through the distribution of many Irano-Turanian plant species and assemblages; for example, *Prunus arabica*, *Ceratonia oreothauma*, *Ebenus stellata*, *Dianthus critinus*, *Plocama aucheri*, *Euphorbia larica* and many others. *Prunus* and *Ceratonia* woodlands are unique plant assemblages in Oman and Arabia and are most closely linked to Musandam and Iran. The trees and shrubs in the first two plant communities are characteristic species found throughout the Arabian Peninsula. These are species such as *Acacia tortilis*, *Ziziphus spina-christi* and *Euphorbia larica*. Understanding their relationship to geological and climatological history will help to reveal the history of the plant composition and distribution within the Eastern Hajar Mountains.

To understand the composition and distribution of the plant communities in the Eastern Hajar Mountains, DCA and CCA were performed on the four plant communities described by TWINSPAN. The first axis (-1) of the CCA ordination describes, we believe, a grouping of environmental factors that are reflective of high-elevation, mountain-top conditions and which strongly delineate a high-elevation plant community (Figure 4.3 & 4.4). Annual rainfall loaded very strongly (r=-0.83, Table 4.6) on Axis -1, but since elevation and maximum temperature were only excluded via VIF for statistical reasons, it is important to interpret their collective influence as a combination of explanatory factors: elevation, temperature and precipitation being mutual components of an orogenic climatic syndrome (Dillon et al., 2006). The altitudinal structure is a widely-observed distribution pattern in many arid and semi-arid mountainous areas (Hegazy et al., 1998, Enright et al., 2005, Brinkmann et al., 2009, Rahman et al., 2017).

Considering only the environmental variables of the plant communities identified by TWINSPAN, there were no significant differences between Communities 2 and 3,

and between Communities 3 and 4; nevertheless, they remain significantly different in species composition. Although the measured environmental variables support the classification of the plant communities in these mountains, it does not, in general, explain the division particularly well, as only 7-10% of the variation is explained by the first two axes of ordination. These low values explain the lack of clear clusters corresponding to the TWINSPAN classification. Ecological plant communities are thought to be shaped by a large number of biotic and abiotic processes and mechanisms. The evolutionary history, environmental variations, biotic interactions between species and land-use modification of the environment through time influence the composition and distribution of plant assemblages (D'Amen et al., 2015). More detailed and targeted biotic and evolutionary studies of the Eastern Hajar are required to understand better the different plant communities. Furthermore, as already documented, these mountains contain some unique plant assemblages and species, such as the *Ceratonia- Prunus* community.

The HEEC plant community at high elevation in the Eastern Hajar Mountains was constantly and distinctly identified by classification and ordination using any of the various datasets in this study. The lower-elevation communities tend to overlap in a continuous series of communities, rather than as unique communities, depending on what or how we treated the data, and could, therefore, constitute transition zones at this altitudinal range. Although the classification and the ISA were able to differentiate the lower communities based on their species composition, the ordination on environmental bases did not reveal clear extrinsic limits between them, which may imply that there are other environmental or ecological factors affecting their structure, or that species at this elevation are more idiosyncratic, or Gleasonian, in their environmental responses.

Aspect, in many arid and semi-arid areas, has been recorded as having an essential role in explaining the vegetation structure and composition (Vetaas, 1993, Ai et al., 2017). In mid and high latitudes in the northern hemisphere, southwest-facing slopes have higher exposure to solar radiation than southeast facing slopes. We did not find this to be the case in the Eastern Hajar Mountains; aspect has a minimal role in defining the vegetation types in the study area. This result is, perhaps, explained by the extreme aridity of the area, with low annual rainfall (>300mm) and high evapotranspiration. In other words, differences in solar exposure due to aspect are relatively less important in structuring the environment. Land uses, although not considered explicitly in this study, except for grazing, have been defined by studies of other arid areas to lead to fewer differences between aspects that are commonly found in less-arid habitats (Kutiel and Lavee, 1999, Måren et al., 2015).

The variation in types of bedrock (limestone and ophiolite) of the Hajar Mountains is also believed to have a strong influence on plant distribution (Harrison and Kruckeberg, 2008, Feulner, 2011). There were significant differences in the soil properties between the plant communities of the Eastern Hajar Mountains, except between the lowest two communities, 3 and 4 ($p= 0.6$). Comparing the soil properties for the four communities revealed that the lowest- and middle-elevation communities have the highest levels of Ca, Mg, K and P; whereas, the total soil nitrogen was highest for the high-elevation community. Generally, and except for OM and nitrogen, the low- and mid-elevation had more soil fertility than the high-h communities, which may help explain the high species diversity and richness of mid-elevations. Soil characteristics contributed up to 76% in defining the plant community structure.

4.5.2 Species richness and diversity

There is a long history of species diversity theories that may explain the pattern in species richness and diversity in an altitudinal gradient (Colwell and Hurtt, 1994, Rahbek, 1995, Lomolino, 2001, Hawkins et al., 2003). We do not discuss the pattern of diversity in the Eastern Hajar Mountains in relation to the vast range of diversity hypotheses and theories, as this is beyond the scope of this thesis, but we try to draw preliminary conclusions regarding the most likely environmental variables influencing the diversity pattern of the mountain's flora. In our view, the species data collected in this study are insufficient to describe a general pattern of species diversity that covers the entire mountain gradient; such a study would need to incorporate the wetter and less-extreme lowland regions below 1000m. Nevertheless, within the mountains, we found that the highest species diversity and richness were recorded at the mid-elevation plots, with a decrease in diversity towards the higher elevation plots. The patterns of the mid-elevation peak of diversity and the decrease in diversity with elevation are probably the most commonly observed patterns in an elevational gradient (Nor, 2001, Hrivnák et al., 2014). Elsewhere in the Arabian Peninsula, elevation has a significant influence on vegetation structure, and it has been reported that the species richness is highest at an elevation of 1000-1480m (Deil and al Gifri, 1998). This is also the case in Jabal Shams and Jabal Akhdar in the Western Hajar Mountains of Oman (Ghazanfar, 1991, Brinkmann et al., 2009). Moreover, it is a characteristic diversity pattern recognised in many arid mountainous regions (Ghazanfar, 1991, Zimmerman et al., 1999, El-Keblawy et al., 2016, Haq et al., 2017). Mid-elevation in these areas provides a better environment for plant growth and plant diversity, since shallower slopes are found at mid-elevation, and consequently, lower rates of soil erosion allow for better holding of soil moisture and nutrients (Fu et al., 2004, Haq et al., 2017). Also, mid-elevation acts as a transition zone that has elements of both the

low and high elevations, which allow for more heterogeneity of community composition. The low plant diversity of the high-elevation plant community in the Eastern Hajar, despite the high levels of nitrogen and OM (Table 4.2), can be explained by many reasons that are not explicitly investigated here: the low temperature at high elevation may impose physiological limits on species and negatively affect their adaptation and survival (Namgail et al., 2012); there is less land area, higher solar radiation, wind speed and intensity, and seasonality (Körner, 2007). Also, the amount of any seed bank in the arid and semi-arid areas has an important role in species regeneration and ecosystem recovery following a disturbance. Grazing reduces the amount of the seed bank in the soil, which affects the overall composition of the community (Kinloch and Friedel, 2005, Kassahun et al., 2009, Dreber, 2011).

4.5.3 Grazing and land-use

While animal grazing may increase the soil OM and nitrogen content, a study on the Qinghai-Tibetan plateau in China recorded a negative correlation between these soil variables and plant diversity and richness (Wang et al., 2007). For the highest elevation community in the Eastern Hajar Mountains, the species diversity, richness and grazing were the lowest in the study area, and it had the highest level of soil nitrogen and OM. Overgrazing is well known for altering vegetation composition and structure through many factors, such as increasing soil erosion and changing soil properties, which influence plant composition (Brinkmann et al., 2009, Niu et al., 2018). Al Jabal Al Akhdar in the Western Hajar Mountains displayed a distinctive separation of the vegetation types on a grazing gradient (Brinkmann et al., 2009). Being part of the Hajar Mountains, the Eastern Hajar is expected to be affected by grazing in the same way as the Western Hajar.

Also, archaeologically, many Hafit (3100-2700 BC) and Umm an-Nar (2700-2000 BC) tombs have been found in the Eastern Hajar Mountains, which may indicate an old pastoral land (e.g. Maqta) (Siebert et al., 2005). The widespread increase of semi-nomadic pastoralists or agro-pastoral settlements has placed extra pressure on the vegetation of the mountains. Traditionally, the land was managed for grazing through a system called 'Hima' (i.e. temporary stone-fenced protected areas). This practice allows for the rotation of the animals during certain seasons to allow the rangelands to recover. This system is not used anymore, and the animals now graze in an unmanaged way (as per informal discussion with residents and pastoralists while sampling for this study).

There was no previous quantitative grazing study in the Eastern Hajar Mountains, so it was difficult to measure the changes in vegetation composition and diversity. Nevertheless, from the results of this study, it is evident that all elevation ranges of the mountains were heavily disturbed due to grazing. Grazing is one of the predominant threats; more than 80% of the studied sites were moderately to heavily grazed, with the remaining 20% showing signs of disturbance. The grazing effect was evident also from the presence of unpalatable and spiny species such as *Solanum incanum*, *Aerva javanica*, *Echinops erinaceus*, *Zygophyllum indicum* and *Blepharis ciliaris*. During the period of the study, and from the continuous observation of the vegetation over the past decade, there has been no regeneration of the main tree species (e.g. *Ceratonia oreothauma*, *Prunus arabica* and *Olea europaea*) in the Eastern Hajar Mountains, which is indisputably due to grazing. The grazing effect was the same on indicator species and non-indicator species (X^2=0.809, p=0.667), which indicates the strong intensity of grazing for all species and communities. However, the high-elevation community had significantly less grazing (r=0.2-0.3, p<0.001, for significant test comparison between the high-elevation community and the other 3 communities), and this may indicate that

decreasing pressure from grazing may lead to a better understanding of community composition and better discrimination between communities. Overall, we did not find grazing in the Eastern Hajar Mountains to be an important driving factor in the delimitation of the present plant communities, and other environmental variables overruled the effect of grazing on community distribution.

4.6 SUMMARY AND IMPLICATIONS

We find strong support for the existence of the HEEC community, a discrete plant community structured by the orogenic environmental syndrome of higher rainfall, lower temperatures and associated higher nitrogen content. Further down the Eastern Hajar, the picture becomes more complicated, with the number, identity and environmental structuring of further communities becoming less clear and more dependent upon choices of data treatment and statistical technique. In this thesis, we present what we believe is the most explanatory of these outcomes – three other communities mostly well differentiated in composition but only weakly defined by soil conditions. We believe this finding suggests a species-level approach to the biogeography and conservation of the Eastern Hajar, which is a more sensible option, and the use of species-specific distribution models for conservation planning (Al Harthy et al., in prep).

The current plant richness, plant diversity and plant community composition are likely to be a result of many combined factors, such as pre-grazing intensity, environmental variation through time and the evolutionary history of the mountains' flora. Different environmental conditions and different levels of disturbance have different impacts on species diversity and composition. Understanding the pattern of diversity and richness along the altitudinal gradient of the Eastern Hajar Mountains and, more generally, the entire Hajar Mountain range requires a detailed study incorporating the unique historical role of these gradients in developing the current

biogeography, evolutionary biology and ecology of the area. Tree-cutting is one of the other noticeable threats to vegetation in the Eastern Hajar Mountains. Five percent of the studied sites were recorded as having signs of the cutting of major trees, including *Olea europaea*, *Ziziphus hajarensis* and the relict species *Ceratonia oreothauma*.

During the period of this research, the road network in the mountains increased, and many new roads were built, which increased the use of off-road vehicles around settlements. This has resulted in significant vegetation and soil disturbance. Further investigation and studies are required to measure and compare the effects of the roads on vegetation structure and diversity. Roads allow for increased access to the mountains, which will place more pressure on the vegetation. The improved access to the mountains and the better wellbeing of the people have put extreme pressure on the vegetation due to increased number of farm animals (i.e. goats, sheep and camels in the past four years being introduced into the mountains) and feral donkeys (Ministry of Agriculture and Fisheries (MAF), 2013). Socioeconomic studies of the mountains are urgently required to understand the past, and present land uses in the Eastern Hajar Mountains. Such studies are a priority for the conservation of the flora of the Hajar Mountains.

The current and expected climate change through the increase in temperature and dryness of the Hajar Mountains is another major threat to the vegetation (AlSarmi and Washington, 2011). As described previously, the annual rainfall and the maximum temperature (i.e. the maximum temperature is excluded due to its collinearity with the annual rainfall, Table 4.1) are the two main environmental variables affecting the composition and distribution of the plant communities in the Eastern Hajar Mountains. Additionally, in a previous publication of this research, the Eastern Hajar Mountains were nominated as an IPA/KBA in the Arabian Peninsula

(Al Harthy et al., in review), and one of the main criteria of considering the area as an IPA is its role as biogeographic and bioclimatic refuge, in the modified Arabian Peninsula IPAs criteria, for some plant species and assemblages, such as the relict species *Ceratonia oreothauma*, *Prunus arabica*. This study reveals that the composition and distribution of plant communities in the Eastern Hajar Mountains are related to climatic factors and soil chemistry reflected in the altitudinal gradients. Consequently, any conservation planning for these mountains should consider the environmental and climatic conditions required by the species to protect them.

This study is the first to use multivariate and ordination methodology to describe the plant communities of the Eastern Hajar Mountains. We believe it is the first attempt at a phytosociological analysis of the vegetation of these mountains. However, the data collected during this study do not support placing the plant communities into the formal and established syntaxonomical classification (Mueller-Dombois and Ellenberg, 1974, Weber et al., 2000). If undertaken, such analysis will require a larger scale study covering the entire altitudinal gradient of the Eastern Hajar Mountains.

This study identifies a set of plant communities organised by climatic factors with strong altitudinal gradients. These communities occur consistently across the mid- and high elevation of the Eastern Hajar Mountains, a potential global IPA. Our detailed vegetation structure and distribution in this paper will help model the current and future responses of plant species under climate change. It is essential to understand and describe the relationship between vegetation distribution, the physical environment, climate and land-use history in these mountains for their effective conservation.

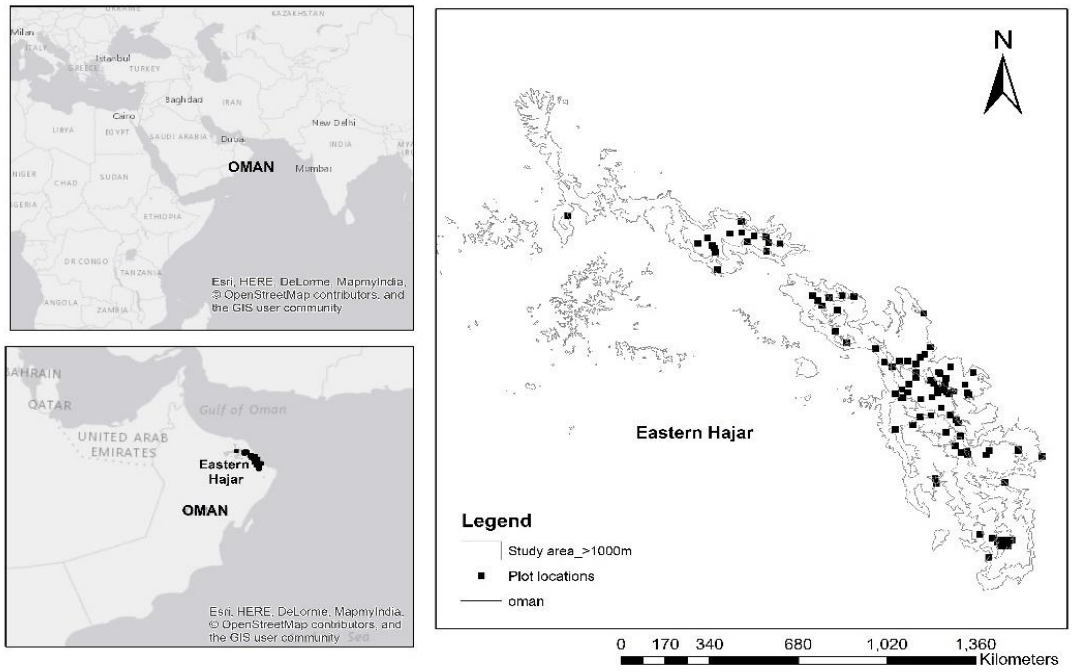


Figure 4.1. Plot locations in the Eastern Hajar Mountains at an elevation above 1000m.

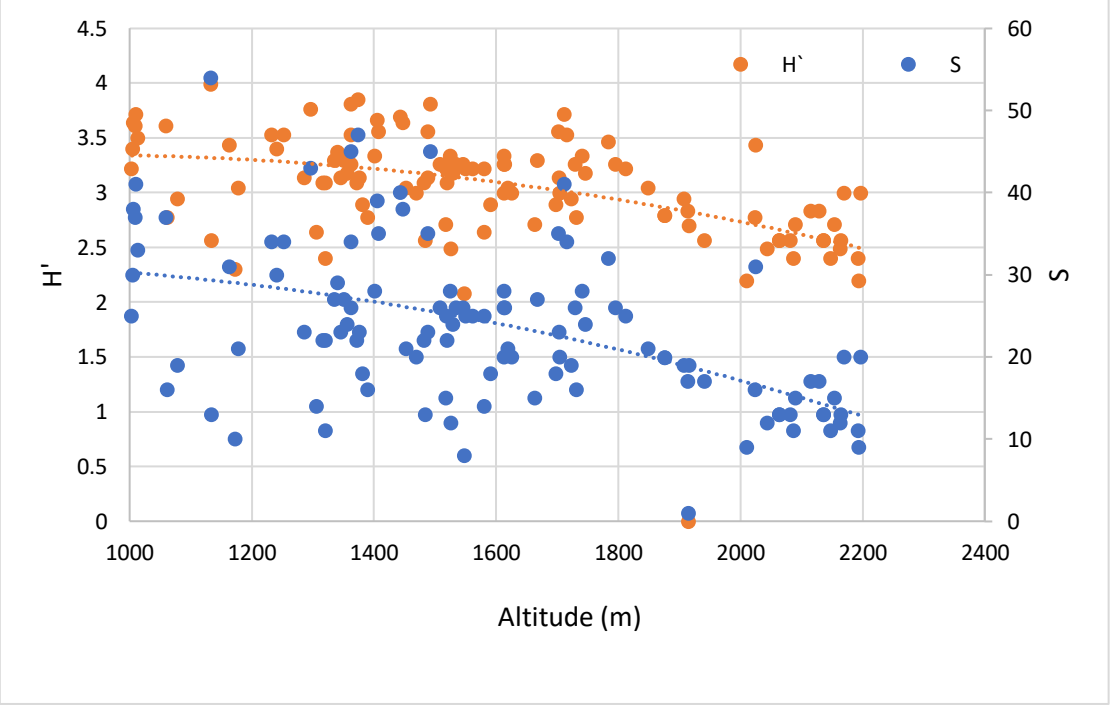


Figure 4.2. Species diversity (H') and species richness (S), arranged by elevation for all studied plots in the Eastern Hajar Mountains. Lines indicate a quadratic regression fit (equation not reported).

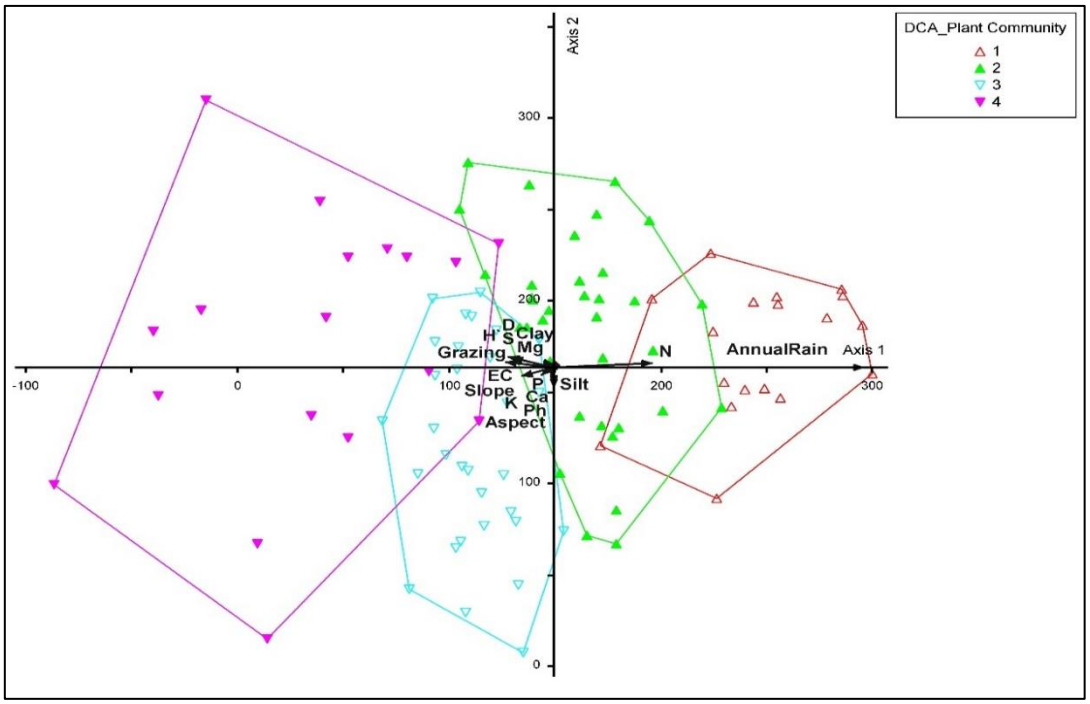


Figure 4.3. DCA ordination of Level 3 presence/absence data for all species (plots belonging to the same plant community are enclosed by a polygon); the lines radiate from the centroid of the ordination scores and the angle and length of the line represent the direction and strength of the relationship.

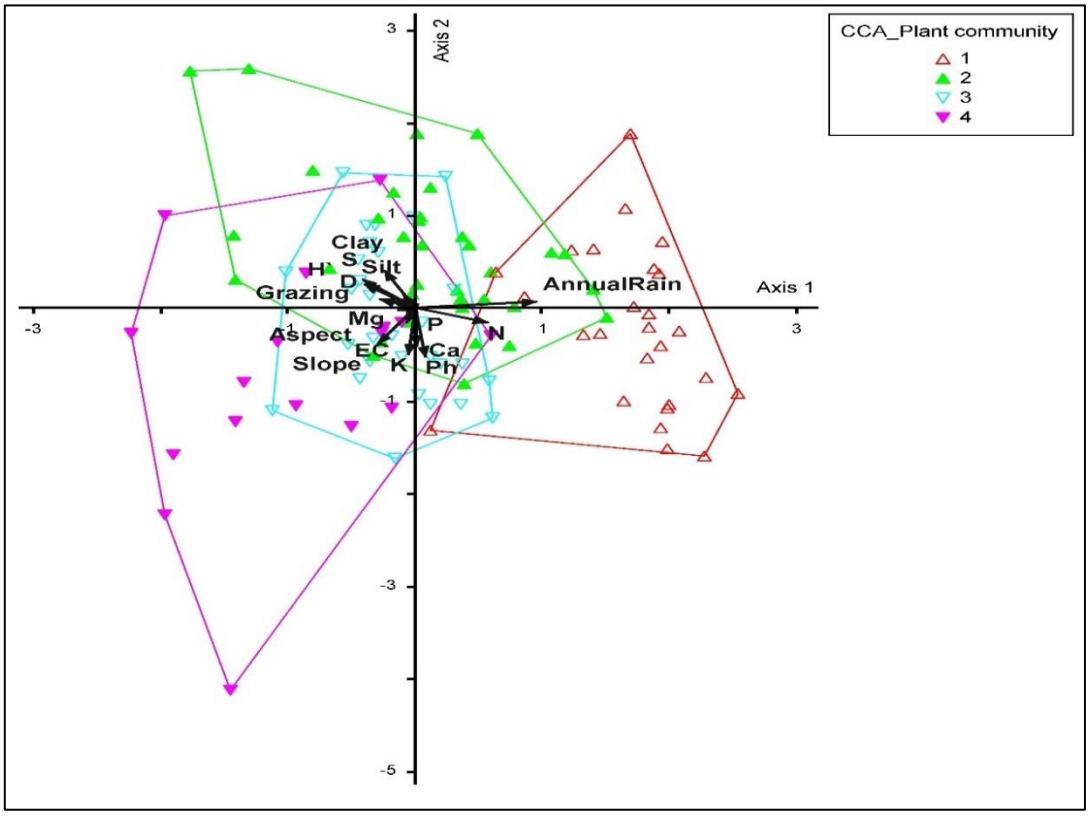


Figure 4.4. CCA ordination of Level 3 presence/absence data for all species (plots belonging to the same plant community are enclosed by a polygon); the lines radiate from the centroid of the ordination scores and the angle and length of the line represent the direction and strength of the relationship

Table 4.1. The 12 environmental variables plus grazing left after the multicollinearity test (variables with VIF>10 is excluded, marked in bold).

Environmental variable	VIF value
Elevation	**14.228**
Slope	1.118
Aspect	1.199
EC	2.962
Ph	1.523
Ca	2.739
Mg	2.021
P	1.883
K	1.556
N	1.745
OM	**21.100**
Annual maximum temperature	**166.594**
Annual rain	1.797
Clay	1.834
Silt	1.449
Sand	**78940.328**
Grazing	1.251

Table 4.2. Pearson's correlation between species richness (S), Shannon (H') and Simpson (D) diversities, and grazing intensity, with other environmental variables.

Variables	S	H`	D	Grazing
Slope	-0.109	-0.072	-0.018	-0.090
Aspect	-0.011	-0.048	-0.111	0.214*
EC	0.186	0.167	0.079	0.019
pH	-0.252**	-0.248**	-0.144	-0.197*
Ca	0.060	0.051	0.039	-0.062
Mg	0.200*	0.195*	0.101	0.128
P	0.047	0.047	-0.003	0.094
K	-0.035	-0.066	-0.107	-0.014
N	-0.157	-0.147	-0.046	-0.192*
Annual Rain	-0.339**	-0.338**	-0.171	-0.313**
Clay	0.136	0.086	-0.039	0.266**
Silt	-0.066	-0.153	-0.274**	-0.026
Grazing	0.172	0.168	0.121	-
* p= 0.05 level. **p= 0.01 level.				

Table 4.3. Indicator species analysis results with the number of the significant plant species and p-values for all the vegetation groups (communities) in each level of TWINSPAN classification in the study site using presence and cover data (i.e. the number in the first column represent the division level from TWINSPAN).

TWINSPAN classification levels	**Species used**	**Data type**	**Number of Significant indicator species**	**Avg. P-value**
LEVEL 3	All species	Presence	77	0.01
LEVEL 3	All species	Cover	69	0.014
LEVEL 3	Perennials	Presence	50	0.01
LEVEL 3	Perennials	Cover	46	0.012
LEVEL 4	All species	Presence	74	0.013
LEVEL 4	All species	Cover	68	0.014
LEVEL 4	Perennials	Presence	59	0.012
LEVEL 4	Perennials	Cover	52	0.009

Table 4.4. Indicator values (IV) and p-values of the 10 most important indicator species per vegetation group in the Eastern Hajar Mountains, Oman: only 10 significant indicator species with the highest IV are displayed in the table.

Species	**IV**	***p**
Group 4. *Echiochilon persicum-Helianthemum kahiricum* community (11 significant indicators)		
Helianthemum kahiricum Delile	0.398	0.001
Argyrolobium crotalarioides Jaub. & Spach	0.379	0.0012
Launaea bornmuelleri (Hausskn. ex Bornm.) Bornm.	0.346	0.0014
Viola cinerea Boiss.	0.337	0.0014
Echiochilon persicum (Burm.f.) I.M.Johnst.	0.32	0.0028
Andrachne telephioides L.	0.304	0.0096
Telephium sphaerospermum Boiss.	0.284	0.012
Helichrysum glumaceum DC.	0.269	0.0144
Ephedra pachyclada Boiss.	0.259	0.0256
Asphodelus fistulosus L.	0.243	0.0424
Group 2: *Searsia aucheri-Acacia tortilis* community (31 significant indicators)		
Acacia tortilis (Forssk.) Hayne ssp. *tortilis*	0.595	0.0002
Tribulus terrestris L.	0.533	0.0002
Pulicaria glutinosa Jaub. & Spach	0.519	0.0002
Aerva javanica (Burm.f.) Juss. ex Schult.	0.481	0.0002
Tephrosia purpurea subsp. *apollinea* (Delile) Hosni & El-Karemy	0.472	0.0004
Indigofera arabica Jaub. & Spach	0.45	0.0006
Plocama aucheri (Guill.) M.Backlund & Thulin	0.445	0.0002
Searsia aucheri (Boiss.) Moffett	0.445	0.0002
Morettia philaeana DC.	0.432	0.0012
Acridocarpus orientalis A.Juss.	0.426	0.0006
Group 3*: Prunus arabica-Ceratonia oreothauma* community (25 significant indicators)		
Astragalus fasciculifolius Boiss. ssp. arbusculinus (Bornm. & Gauba) Tietz	0.593	0.0002
Solanum incanum L.	0.479	0.0002
Ceratonia oreothauma D.Hillcoat, G.P.Lewis & Verdc.	0.46	0.0002
Prunus arabica (Olivier) Meikle	0.456	0.0002
Olea europaea ssp. *cuspidata* (Wall. & G.Don) Cif.	0.407	0.0006
Ziziphus hajarensis Duling, Ghaz. & Prend.	0.39	0.0008

Species	IV	*p
Hemionitis acrostica (Balb.) Mosyakin	0.368	0.0018
Dyerophytum indicum (Gibbs ex Wight) Kuntze	0.364	0.0022
Andrachne aspera Spreng.	0.35	0.0044
Erodium neuradifolium Delile ex Godr.	0.342	0.0024
Group 1*: Ebenus stellata-Convolvulus ulicinus* community (10 significant indicators)		
Ebenus stellata Boiss.	0.572	0.0002
Convolvulus ulicinus Boiss.	0.513	0.0002
Dodonaea viscosa (L.) Jacq.	0.479	0.0002
Diplotaxis harra (Forssk.) Boiss.	0.379	0.0016
Teucrium stocksianum Boiss. ssp. *stenophyllum* R.A.King	0.347	0.0012
Dianthus crinitus Sm.	0.328	0.0098
Farsetia linearis Decne. ex Boiss.	0.315	0.0102
Cymbopogon schoenanthus (L.) Spreng.	0.292	0.0028
Plocama calycoptera (Decne) M.Backlund & Thulin	0.281	0.0166
Helianthemum lippii (L.) Dum.Cours.	0.237	0.011

Table 4.5. Summary of environmental variables (i.e. mean) and the mean value of species diversity for the four plant communities identified by TWINSPAN.

Plant community	1	2	3	4
Slope (%)	18	20	29	30
Aspect (degrees)	164	137	147	183
Ec (µs/cm)	605	627	836	696
pH	7.8	7.7	7.7	7.7
Ca (meq/1)	4.8	3.6	4.7	5.1
Mg (meq/1)	1.1	1.9	2.2	3.2
P (ppm)	23.2	22.2	23.2	27.0
K (ppm)	206.2	201.9	215.7	265.7
N (mg/kg)	1273.1	928.7	726.4	716.8
Annual rainfall (mm)	267	220	210	185
OM (%)	2.5	1.6	1.2	1.1
Clay (%)	5.8	11.3	8.9	7.8
Silt (%)	16.7	18.9	17.3	15.8
S	14	24	29	27
H`	2.5	3.1	3.3	3.2
D	0.9	1.0	1.0	1.0
Grazing (%)	37	55	51	54

Table 4.6. Pearson's inter-set environmental correlations from CCA ordination.

Variable	Axis 1	Axis 2	Axis 3
Slope	0.388	0.199	0.557
Aspect	0.03	0.047	0.153
EC	0.111	0.099	-0.142
pH	0.121	0.439	-0.07
Ca	0.138	0.321	-0.278
Mg	0.121	-0.026	-0.405
P	0.009	0.045	-0.174
K	0.23	0.373	-0.46
N	-0.422	0.314	-0.243
Annual Rain	-0.837	0.265	-0.02
Clay	0.062	-0.391	-0.11
Silt	0.031	-0.146	-0.202
Grazing	0.199	-0.159	-0.415
S	0.235	-0.376	-0.196
H`	0.242	-0.323	-0.19
D	0.123	-0.114	-0.126

Table 4.7. The average percentage similarity within each of the four plant communities from the Eastern Hajar Mountains and the contribution of each of the variables in determining the structure of the community using the similarity percentage analysis procedure SIMPLER; the significance of the variable is marked by the star sign, $P<0.05$.

Plant community	**1**	**2**	**3**	**4**
% Similarity average	91.0	89.0	88.0	86.0
% Environmental contribution				
Annual rain	11.5*	8.2	8.0	0.0
Aspect	7.8	8.5	9.2	8.4
Slope	7.8	8.2	8.5	9.0
P	8.3	8.4	8.3	9.0
Mg	8.2	8.6	8.8	8.9
N	9.4*	8.3	0.0	7.4
EC	8.2	8.3	8.9	8.9
K	7.7	8.0	8.1	8.8
Ca	8.6*	7.8	8.2	9.0
pH	8.4*	0.0	8.1	8.9
Clay	0.0	9.4	8.1	8.0
Silt	7.5	8.7	8.0	7.5

CHAPTER 5

SOIL SEED BANK IN THE EASTERN HAJAR MOUNTAINS, OMAN

5 CHAPTER 5: SOIL SEED BANK IN THE EASTERN HAJAR MOUNTAINS, OMAN

5.1 ABSTRACT

This study is a synopsis of the seed bank composition of the Eastern Hajar Mountains (above 1,000m elevation), which is compared with the area's above-ground vegetation as sampled and described in Chapter 4, in which 208 species were recorded. Species richness and diversity were very low in the seed bank, with only 34 species recorded. 21 (i.e. taxa that were identified to a species level) of a total of 208 species were found in both the seed bank and the above-ground vegetation. Such relative incongruence could be explained by factors comprising disturbance (for instance grazing and development) and drought. Other biotic and abiotic factors may also have contributed to the dissimilarity and the low number of species germinated in the seed bank. The effect of a set of environmental variables on the seed bank's composition was measured using canonical correspondence analysis (CCA). None of the environmental variables measured appeared to have any effect on the soil seed bank composition. Although grazing pressure did not significantly differ between the sites and communities, it was not enough, from this analysis, to conclude the impact of grazing in the soil seed bank.

5.2 INTRODUCTION

Increased interest in improving tools and methods for conservation planning and vegetation management has necessitated an understanding of the ecological requirements of plant species. Seed banks play a significant role in maintaining ecological and genetic diversity in plant populations and communities (Thompson and Grime, 1979, Venable, 1989). Defining an area's flora and understanding its

plant population and community dynamics constitute the primary reasons for estimating seed banks (Espeland et al., 2010). Moreover, understanding the seed bank's spatiotemporal responses to local disturbances represents a significant rationale for seed bank studies (Dreber, 2011). The results of these studies have largely been influenced by the sampling strategies and seed quantification methods used, especially in arid and semi-arid environments that are characterised by heterogeneous and patchy vegetation (Major and Pyott, 1966, Kemp, 1989). Seeds in these environments have developed a wide range of strategies and mechanisms to cope with unpredictable environmental conditions such as irregular rainfall (Venable and Brown, 1988, Gutterman, 2000).

Transient and persistent seeds are the two main seed types identified in seed banks (Thompson et al., 1997). Transient seeds are capable of immediate germination and remain viable in the soil for less than a year, while persistent seeds stay viable for several years, being found in areas with unpredictable environmental conditions and disturbances. Furthermore, seed banks can contain persistent seeds that no longer constitute part of the current plant composition (Jacobs et al., 2018). Therefore, a persistent seed bank represents an effective strategy for plants in order to overcome severe environments, disturbance and destruction (Thompson, 2000, Fenner and Thompson, 2005, Gomaa and Picó, 2011), hence one might expect persistent seeds to be common amongst plant species in arid and semi-arid environments (Kemp, 1989, Wright and Clarke, 2009).

Ephemeral annuals tend to dominate vegetation in arid and semi-arid environments (Gomaa and Picó, 2011, Hegazy et al., 2016). A flush of ephemeral seedlings is usually produced from the seed bank following rainfall (Gutterman, 2000) and so it is more likely that the seeds of these species will occur in the seed bank (Turnbull et al., 2000). In contrast, woody herbaceous and perennial plants are seed-limited and

poorly represented in the seed banks of arid environments (Guo et al., 1999, Turnbull et al., 2000, Facelli et al., 2005).

Vegetation composition is closed related to the density and diversity of the soil seed bank (Thompson et al., 1997, Thompson et al., 2003, Pakeman and Small, 2005, Page et al., 2006). Disturbances such as heavy grazing have varied effects on seed bank composition and richness. Some studies have found that heavy grazing reduces the density of the seed banks (Ma et al., 2010), whereas others have indicated that grazing has no impact or even increases the density of seeds (Navie et al., 1996, Meissner and Facelli, 1999). Moreover, drought and other human-related activities may adversely affect seed bank recruitment (Skoglund, 1992, Kinloch and Friedel, 2005). For natural vegetation to regenerate, especially following disturbance, seed banks are considered the major source that can be used to establish above-ground vegetation (Kinucan and Smeins, 1992, Thompson et al., 2003, Jacobs et al., 2018). Therefore, knowledge concerning seed bank composition and its relationship to above-ground vegetation is essential in order to formulate conservation activities and plans (Snyman, 2004, Solomon et al., 2006, Kassahun et al., 2009).

To my knowledge, no seed bank studies are currently available in Oman at all, indicating a lack of basic knowledge of seed bank characteristics and germination requirements for seeds facing drought and disturbance. Knowledge is also inadequate regarding the mechanisms and effects of above-ground vegetation degradation on the soil seed bank. It also means that locally specific knowledge about the effectiveness of artificial germination techniques in the glasshouse is very poor. Therefore, seed bank studies here are essential to developing an understanding of how the area will respond to future changes and protection, as well as providing primary baseline data that can be used for further detailed seed bank

investigations. The Eastern Hajar Mountains, like the rest of the country, have experienced prolonged drought for the last 20 years (Ministry of Environment and Climate Affairs (MECA), 2015). In addition, overgrazing and the rapid development of the mountains have exerted considerable pressure on its vegetation, leading to overexploitation, the emergence of species unpalatable to grazing animals and the failure of many important mountain trees to regenerate (Miller and Knees, 2014, Patzelt, 2015c, Al Harthy and Grenyer, 2019).

The primary motive for collecting the soil seed bank in the Eastern Hajar Mountains was to quantify and identify ephemeral species, given their poor representation in above-ground vegetation. Thus, it was expected that ephemeral species would predominate in the seed bank. Furthermore, the collection of the soil seed bank was considered an opportunity to facilitate essential preliminary analysis, evaluating seed bank composition and density and relating it to the environmental variables that may affect the seed bank. The data analysis and results presented here provide a snapshot of the seed bank composition and its relationship to the above-ground vegetation, as well as some of the environmental variables used to describe the latter. Several unavoidable constraints on this seed bank study were imposed by the nature of the field sampling undertaken for Chapters 4 and 6. The consequences of these are discussed at the end of the chapter in the section on directions for future study.

5.3 STUDY SITE

This study was conducted as part of a larger investigation describing, classifying and predicting the vegetation of the Eastern Hajar Mountains above 1,000m elevation (Al Harthy and Grenyer, 2019). The study area is characterised by an arid climate, with cold, dry winters and hot summers. More details about the study area can be found in Chapters 1 and 3.

Four plant communities were identified from adult plant censuses in the Eastern Hajar Mountains (Chapter 4) (Al Harthy and Grenyer, 2019). These plant communities were partially organised along an elevational gradient, strongly influenced by climatic factors. Annual rainfall and soil properties including total nitrogen and calcium, were the most important environmental factors affecting the distribution of plant communities. This is an important area of vegetation, but one that has been disturbed or degraded by development and overgrazing.

5.4 METHODOLOGY

5.4.1 Sampling strategy

Within each plot of 600m^2 (as described for vegetation classification in chapter 4) (Al Harthy and Grenyer, 2019), five soil samples measuring 25 × 20 × 5cm were randomly collected (Figure 5.1). Due to the difficulties involved in accessing high-elevation locations (requiring hiking and climbing), the numbers of soil samples collected at such plots were reduced to three and sometimes two in order that they could be carried across the steep mountainous terrain for up to 2200m. Soil seed bank sampling was undertaken throughout the year for a period of two years (2015–2016), and samples often contained both transient and persistent seeds.

5.4.2 Greenhouse germination

Two main methods were used for the soil seed bank analysis: the seed extraction technique and the seedling emergence method (Malone, 1967, Thompson et al., 1997, Kinloch and Friedel, 2005, Dreber, 2011). The seed extraction technique, in which seeds are floated out of soil samples in a dense liquid medium, provides better estimates of seedling density, but is time-consuming and may overestimate the number of seeds in the soil because it includes non-viable seeds. It additionally requires excellent skills in seed identification and is not useful in finding small-

seeded species (Brown, 1992, Baskin and Baskin, 2014). The seed emergence method, in which soil samples are treated to promote the germination of seeds, which are then identified and counted as seedlings, provides a good indication of readily germinable seeds. Nevertheless, this method can underestimate the seed bank due to the specific treatment that may be required to break seed dormancy, as well as the specific environmental conditions essential for germination (Wright and Clarke, 2009). The seed emergence method is also perceived as offering an effective perspective for *in situ* conservation because it determines only the viable seeds in the soil seed bank, as opposed to the extraction method, which may overestimate the seed bank due to the inclusion of non-viable seeds (Espeland et al., 2010). It proved very challenging to extract any seeds from test samples using the extraction technique, hence the seed emergence method was used.

A total of 520 soil samples 5cm deep, from 110 plots were collected for seed bank analysis. These plots corresponded with previously collected vegetation plots, so the above-ground species composition was already available for comparison. The soil samples were air-dried and stored at room temperature until use for germination (Figure 5.2A). The samples were then prepared for germination by being sieved through a 2mm mesh in order to remove or reduce coarse plant material, gravel and stones (Figure 5.2B). Each soil sample was spread out in a 22 × 36cm plastic tray to a depth of about 5cm on a sand and peat mix. Different soil germination mixes were tested before running the actual experiment. For example, one of them was using only the soil collected from the sites in the germination trays which resulted in a very clayish mixture that held the water and didn't allow for good aeration of the soils. The second mix was using only sand as a base for the actual site soil, but the soils got dried fast. The soil mixture selected was discussed and agreed with the propagation and botany experts at the Oman Botanic Garden (OBG); which was using a ration of 30peat/70 sand for this experiment. Trays were then placed in a

random arrangement in a greenhouse under controlled conditions, with a diurnal cycle of 12–14 hours of light at 26^{o}C ± 5 ^{o}C and 10–12 hours of darkness at about 15–18^{o}C (Figure 5.3). The seed trays were kept moist by daily watering via an overhead irrigation system. As there were no prior references for preferred green-house germination variables for these mountains, it was hoped that these light and temperature conditions would be close to optimal natural mountain conditions. There is no previous study, and therefore there are no existing data on ideal germination practices in these types of habitats. Consequently, the germination trial presented here represents the first attempt to examine how the soil seed bank reacts to the germination conditions applied. The number of emerged seedlings was counted every two days for five months until the germination rate reached almost zero. Representative seedlings of each species were transplanted in separate trays and grown to a stage where they could be identified to species. If seedlings died before they were reproductive, their identification was recorded at the family, or genus level where possible.

5.4.3 Data analysis

Seed bank richness and diversity were calculated. The Shannon-Wiener diversity index (H') and Simpson's index of diversity (D) were used to describe the species diversity pattern of each plot. Correlations between seed bank and environmental parameters (the same environmental variables used in the vegetation classification study, Chapter 4, Table 4.1) were examined by canonical correspondence analysis (CCA) using PC-ORD 7.03 (MjM Software, OR, USA).

In Chapter 4, grazing was identified as one of the major threats to vegetation in the Eastern Hajar Mountains. In order to measure the effect of grazing on the soil seed bank, the soil samples/plots were assembled into three groups based on the grazing pressure of the above-ground vegetation. The grazing pressure was divided into

three pressure levels: level 1 to represent lightly grazed plots, 2 for moderately grazed plots and 3 for heavily grazed plots (Al Harthy and Grenyer, 2019). Any significant differences between groups were tested using a multi-response permutation procedure (MRPP) with the squared Euclidean distance (McCune et al., 2002) using PC-ORD 7.03 (MjM Software, OR, USA). The correlation between grazing pressure and the number of seedlings germinated per plot was also measured.

The correlation between the above-ground vegetation composition and seed bank composition was calculated. The Sorenson index of similarity, based on the presence/absence of species, was calculated to determine the similarity in species between above-ground vegetation and the seed bank (Hopfensperger, 2007). The test was performed using the Community analysis package (CAP5) program (Henderson and Seaby, 2014). Furthermore, the same similarity test (i.e. Sorenson index) was carried out between the seed bank and the above-ground vegetation only for the heavily grazed sites.

5.5 RESULTS

5.5.1 Seed bank composition

The first seedling emerged four days after the start of the germination study (i.e. in May 2015) in the greenhouse, and it took an average of two to four weeks for seeds to germinate. Observations were continued for a further 16 weeks to ensure the germination of all possible seeds in the soil, as well as to identify the seedlings. The number of seeds germinated ranged from no germination to 40 seeds and 0-4 species per plot, with a total of 558 seedlings. Seventy-five per cent of the plots had an average germination of about five seedlings per plot, with only 4% (5 plots) exhibiting an average of more than 20 seedlings (Figure 5.4).

26 species were recorded in addition to four unidentified Poaceae and four unknown dicot species belonging to 18 plant families (Table 5.1). The average number of species recorded per plot was two species with an average diversity of 0.6 for H' (p= 0.4) and 0.4 for D (P= 0.4), with no significant difference between the plots (*p* =0.4). A small number of species dominated the germinated seeds across the plots. More than half of the emerged seedlings represented only three species (out of 34 species). *Telephium sphaerospermum* was the most frequently recorded species with 187 seedlings germinated, followed by an unidentified Poaceae with 80 plants and the perennial short-lived grass *Eragrostis papposa* with 78 plants. Poaceae dominated the seedlings germinated in the soil seed bank with a total of eight species (i.e. 24% of the total seed bank flora), followed by Fabaceae and Plantaginaceae, each with 9% of the total flora (i.e. three species), whereas the remainder of the families were represented by only one species each. Caryophyllaceae and Phyllanthaceae each contributed 6% of the species identified (two species), while the other families were represented by only one species (Table 5.1, Figure 5.5).

5.5.2 Seed bank relationships with environmental variables

There was no significant correlation between the number of seedlings germinated and any of the environmental variables. Also, according to the CCA graph, the species presented no particular association with any of the environmental variables (Figure 5.6).

There was no correlation between seed bank and the grazing pressure per plot (Pearson correlation= 0.024, *P*= 0.8). Nevertheless, the MRPP results (A= 0.075, T= -11.6, Observed delta= 0.46, Expected delta = 0.50, p = 0.000) indicate that the groups that were classified based on the grazing pressure on the area exhibited a significant difference between them. There was a significant difference between the

lightly grazed and moderately grazed sites (A= 0.045, T= -5.87, *p* <0.0001), as well as between the lightly grazed and heavily grazed sites (A= 0.077, T= -15.54, p <0.0001). There was no significant difference between the moderately grazed and heavily grazed sites (A= -0.007, T= 0.76, p= 0.776).

5.5.3 Comparison between above-ground composition and seed bank composition

Four plant communities (Chapter 4) were previously described in the Eastern Hajar Mountains. A total of 208 species belonging to 56 families were identified above 1,000m, with a total flora of 433 species and 82 families covering the entire elevational gradients of the Eastern Hajar mountains (Al Harthy et al., in review). Seventy-four per cent of the recorded species (208 species) were perennial, and 26% were annuals/biennials. Asteraceae and Poaceae were the most species-rich families recorded, followed by Fabaceae, Brassicaceae, Boraginaceae and Caryophyllaceae.

The Sorensen similarity index between seed bank and above-ground communities was 0.18. Since the index can run from 0 to one, this indicates a lack of similarity between the above-ground vegetation and the seed bank. Nevertheless, 21 species (i.e. only including taxa identified to species level) out of a total of 208 species recorded from above-ground vegetation were common to them (Table 5.2). All of the recorded and identified seed bank species were found in the above-ground vegetation, with no species recorded only in the seed bank. To examine the effect of grazing on the seed bank composition, the results from comparing seed bank with the above-ground vegetation of the heavily grazed sites exhibited slightly lower similarity (similarity index= 0.16), with 16 species in common between them. 74% of the above-ground vegetation recorded comprised perennials, while the numbers between annual/biennials and perennial were almost equal in the seed bank;

however, this does not take into account the unknown species, which may alter this proportion. Species richness and diversity were significantly higher in the above-ground vegetation relative to the soil seed bank.

5.6 DISCUSSION

The results from this study must be treated with some caution because of the low number of species found, and since there may be some experimental limitations. This investigation only examines current seed bank composition, and so it may have missed certain species. In addition, it is possible that some biotic and abiotic factors that affect germination may not have been either present in the greenhouse experiment or captured by the measurements in the field. Furthermore, some caution is necessary when comparing this study with other studies of soil seed banks owing to the wide variety of documented studies, such as with respect to sample size, sample pre-treatment and preparation, time, number of germination cycles and many other variables.

5.6.1 Seed bank composition and relationships with environmental variables

The germination trial showed little of the diversity of the flora of the study area, with approximately 90% of the species absent from the seed bank. Certainly, glasshouse germination determines only the 'readily germinable' component of the seed bank by providing conditions suitable for the germination of a wide range of species (Thompson and Grime 1979) and so it may not detect all species present in the seed bank (Kinloch and Friedel, 2005). Dormant seeds in the soil seed bank may not germinate using the emergence methods, which are unable to determine seed bank persistence (Scott and Morgan, 2012). Furthermore, it is difficult to detect species with low seed production or species with a short germination season using the emergence method, as they will generally be classified as persistent seeds

(Thompson and Grime, 1979). Given that the seed bank may contain persistent seeds, the latter may remain dormant for more than one year, with no upper limit in terms of longevity, thus ultimately reducing the number of species germinated (Thompson and Grime, 1979). Transient seeds, which have a life span of less than one year, will germinate only if the environmental conditions are suitable and the seeds are viable for this process. In addition, the soil seed bank sampling was spread over two years across diverse seasons, which may not capture the full range of species in the seed bank.

Seed banks in arid and semi-arid environments are characterised by high spatial and temporal variability (Guo et al., 1998, Facelli et al., 2005, Dreber, 2011). Therefore, germination trials of soil seed banks are highly sensitive to environmental conditions (Facelli et al., 2005). Light, temperature and soil moisture are the most pertinent factors that affect seed germination (Baskin and Baskin, 1988). These environmental conditions play a significant role in influencing the strategies used by seeds to ensure their germination and establishment at the right time. The Eastern Hajar Mountains have been under a prolonged drought for the last 20 years, with deficient localised rainfall, potentially contributing to the low rate of seedling germination and establishment.

5.6.2 Seed bank composition and relationships with grazing

Heavy grazing, as recorded by many studies, has variable impacts on seed bank size and species composition. The relationship between grazing and seed bank may be affected by diverse factors such as environmental conditions, site and species characteristics (Savadogo et al., 2016). However, grazing is consistently showing constant changes in vegetation composition (Kinucan and Smeins, 1992, Bertiller, 1996, Navie et al., 1996, Meissner and Facelli, 1999). Many studies reported decreases in the total number of seeds germinated after heavy grazing (Navie et al.,

1996, Tessema et al., 2012), others have recorded no impact of grazing on the soil seed bank (Kinucan and Smeins, 1992, Meissner and Facelli, 1999). Annual species are dominating the heavily grazed sites in many arid and semi-arid areas, which eventually affects the above- ground (Tessema et al., 2016, van Langevelde et al., 2016, Jacobs et al., 2018). Although the results of this study have indicated that the current grazing pressure did only significantly different in the HEEC, it is not yet possible to draw a conclusion regarding the impact of grazing in the soil seed bank due to the many limitations of this study, which are discussed in a following section. Nevertheless, the low regeneration of major tree species, the absence of most of the annual species and the lack of similarity between the seed bank and vegetation could constitute an effect of the grazing alongside other environmental factors.

The soil seed bank of the Eastern Hajar Mountains was equally represented by annual and perennial species, an uncommon result in arid and semi-arid environments (Assaeed and Al-Doss, 2002, Dreber, 2011, Dreber et al., 2011, Savadogo et al., 2016). It is not fully understood why annual plants did not dominate the seed bank. However, the full range of biotic and abiotic factors affecting annual seed germination can help explain their low representation. Indeed, factors such as day length, distribution and amount of rain, daily temperature and drought (Gutterman, 2000, Gutterman, 2002, Baskin and Baskin, 2014) force annual plants to develop a wide range of strategies and mechanisms in order to persist in the seed bank under unpredictable environmental conditions and disturbances. Such diversity renders it difficult to identify the optimal conditions for germination. Nevertheless, this study was able to detect some of the most common annuals in the area, such as *Viola* sp., *Asphodelus* and *Eragrostis*. This may indicate low seed abundance or sample size, rather than the absence of germination conditions in the glasshouse. These species generally have tiny seeds that can escape grazing and be quickly buried in the soil (Fenner and Thompson, 2005).

Most of the perennial plants identified were seen as indicators of disturbance, such as *Corchorus depressus***,** *Forsskaolea tenacissim*a and *Zygophyllum indicum.* The predominance of these species potentially implies their wide geographical distribution and efficient seed production (Caballero et al., 2003), as well as that they are unpalatable to grazing animals. Furthermore, the low occurrence of perennial woody plants in the seed bank may be explained by their larger seeds, which may fail to escape heavy animal grazing in the area (Thompson, 1987, Wright and Clarke, 2009). Some studies have suggested that perennial species (unlike annuals) do not require a persistent seed bank and instead rely on annual and continual seed production, facilitating their presence in the seed bank (Thalen, 1979, Auld, 1993). In this study, no pre-treatment was used to affect perennials' dormancy. The study concentrated on readily viable seeds for germination, which may explain the low occurrence of perennial species in the seed bank. There also exists some evidence from arid and semi-arid areas that grazing pressure inhibits the germination of perennial species (Assaeed and Al-Doss, 2002).

To understand the composition and distribution of the seed bank and how it is related to some of the environmental variables in the Eastern Hajar Mountains, CCA was performed. No evidence was found that the environmental variables that were considered, and which were demonstrated to have important effects in structuring the above-ground communities, significantly affected the seed bank. These variables may not have been most appropriate for investigating the environment's effects on seed bank composition and distribution. Seed bank studies with more targeted environmental variables are thus required to understand germination success inside greenhouses and *in situ*.

5.6.3 Comparison between above-ground composition and seed bank composition

It is difficult to determine the seed bank composition simply by comparing it with above-ground vegetation. There was almost no similarity between seed bank composition and above-ground vegetation. Almost 90% of the above-ground species did not occur in the seed bank. In contrast, none of the species germinated from the seed bank and identified to species was absent from the above-ground vegetation. This lack of similarity between the seed bank composition and the above-ground vegetation has already been documented in many studies (Caballero et al., 2003, Solomon et al., 2006, Dreber, 2011). Numerous factors can explain this lack of similarity, including the amount of disturbance (such as grazing and development) affecting seed production and therefore the number of seeds represented in the seed bank. One of the significant factors that may affect the results presented here, reducing the similarities between soil seed bank and above-ground vegetation is the fact that this study covers a very short time span, hence many species with transient seeds may have been missed in the samples collected.

5.6.4 Limitations of the study and considerations for future studies

Seed bank studies are lacking for the Eastern Hajar Mountains, so this analysis is the first study in these mountains and Oman, generally. Therefore, many of the experimental variables used in the analysis, such as soil mixture, the amount of water given to the seed trays and the environmental condition used for germination were tried for the first time inside the glasshouse. There were no bases of the best practices in these types of analysis in the country, so this experiment was based on similar studies in the region which might not completely be applied to our analysis due different study site location and, hence a priori analyses with adequate sampling

design (Page et al., 2006) and analytical methods that are capable of accurately detecting seed bank composition and density are required (Gross, 1990).

Future soil seed bank studies should also ensure that the time for both sampling and germination follow seasonal seed bank dynamics. Considering these temporal changes may affect the number of germinated species, as well as affect similarity with above-ground vegetation (Facelli et al., 2005, Dreber, 2011).

No significant effect of the environmental variables used, in this study, was observed on the seed bank composition. Numerous environmental variables are affecting seed bank density and composition. Acknowledging the exact environmental requirements for the seed bank studies, and specifically, greenhouse germination studies requires detailed investigations to identify these variables in order to run more robust germination analyses. In this study, I tried to use the optimal environmental conditions that resemble the actual study sites with some of the variables that were hard to accommodate inside the greenhouse. The knowledge gained from this study regarding the germination conditions required for the seed bank germination is a valuable baseline data that can be used to develop and improve future seed bank studies in the country. Indeed, varying the environmental conditions is important in order to ensure maximum germination of the soil seed bank.

An *in-situ* seed bank germination experiment was investigated in this study. This trial was carried out to check the ability of the seed bank to germinate under the actual environmental conditions of the study site. An enclosure of 1.5 × 1.5m was built and placed at approximately 1,500m elevation in the Eastern Hajar Mountains (Figure 5.7). The rationale behind experimenting with the *in-situ* enclosure was to retain environmental conditions such as light and temperature, as well as to eliminate grazing for the duration of the study. Given the low rainfall, the area inside the

enclosure was intended to be regularly irrigated for the period of the study. Unfortunately, however, substantial challenges exist in running such an experiment in an area like the Eastern Hajar Mountains. For example, the enclosure disappeared in the second month of the experiment, and watering on a regular basis was almost impossible without living in the area for the entire period or collaborating with locals to help.

In this study, the emergence method was deemed preferable for analysing the seed bank. Indeed, it is most appropriate for short-term evaluation. However, future seed bank studies should make use of a combination of the available seed bank germination methods. for example, the emergence method would be used in combination with the extraction method to maximise the accuracy of the seed bank estimation.

Table 5.1. Species identified in the soil seed bank, with their total number and the number per plot germinated.

Species	Family	Seedlings germinated	Count (Nr. of plots)
Andrachne aspera Spreng.	Phyllanthaceae	24	6
Andrachne telephioides L.	Phyllanthaceae	13	6
Argyrolobium crotalarioides Jaub. and Spach	Fabaceae	1	1
Asphodelus fistulosus L.	Xanthorrhoeaceae	9	7
Cenchrus ciliaris L.	Poaceae	6	1
Corchorus depressus (L.) Peterm.	Malvaceae	9	4
Eragrostis papposa (Roem. and Schult.) Steud.	Poaceae	78	36
Eragrostis sp.	Poaceae	4	2
Erodium sp.	Geraniaceae	1	1
Zygophyllum indicum (Burm.f.) Christenh. & Byng	Zygophyllaceae	4	3
Fern species	Pteridaceae	1	1
Ficus salicifolia (Vahl)	Moraceae	1	1
*Forsskaolea tenacissim*a L.	Urticaceae	20	1
Galium setaceum Lam.	Rubiaceae	2	2
Launaea sp.	Asteraceae	2	2
Nanorrhinum hastatum (R.Br. ex Benth.) Ghebr.	Plantaginaceae	1	1
Plantago ciliata Desf.	Plantaginaceae	3	3
Plantago sp.	Plantaginaceae	1	1
Polygala erioptera DC.	Polygalaceae	1	1
Salvia aegyptiaca L.	Lamiaceae	1	1
Silene chirensis A.Rich.	Caryophyllaceae	1	1
Telephium sphaerospermum Boiss.	Caryophyllaceae	187	33
Tephrosia purpurea subsp. *apollinea* (Delile) Hosni and El-Karemy	Fabaceae	17	5
Tetrapogon villosus Desf.	Poaceae	1	1
Verbascum akdarense (Murb.) Hub.-Mor.	Scrophulariaceae	2	2
Viola cinerea Boiss.	Violaceae	34	29
Indet 1	Indet	33	18
Indet 2	Poaceae	1	1
Indet 3	Poaceae	80	44
Indet 4	Poaceae	1	1
Indet 6	Poaceae	1	1
Indet 5	Indet	1	1
Indet 7	Indet	5	4
Indet 8	Indet	1	1

Table 5.2. The species identified in both the above-ground vegetation and soil seed bank in the Eastern Hajar Mountains.

SPECIES	SPECIES
1. *Andrachne aspera*	2. *Launaea sp.*
3. *Andrachne telephioides*	4. *Nanorrhinum hastatum*
5. *Argyrolobium crotalarioides*	6. *Plantago ciliata*
7. *Asphodelus fistulosus*	8. *Polygala erioptera*
9. *Cenchrus ciliaris*	10. *Salvia aegyptiaca*
11. *Corchorus depressus*	12. *Silene chirensis*
13. *Eragrostis papposa*	14. *Telephium sphaerospermum*
15. *Zygophylium indicum*	16. *Tephrosia purpurea* subsp. *apollinea*
17. *Ficus salicifolia*	18. *Tetrapogon villosus*
19. *Forsskaolea tenacissima*	20. *Verbascum akdarense*
21. *Galium setaceum*	22. *Viola cinerea*



Figure 5.1. Soil sample collection for the seed bank study in the Eastern Hajar Mountains.



Figure 5.2. Soil sample preparation for the seed bank analysis in the Eastern Hajar Mountains. A) Samples dried at room temperature; B) Sieving coarse materials from the samples.

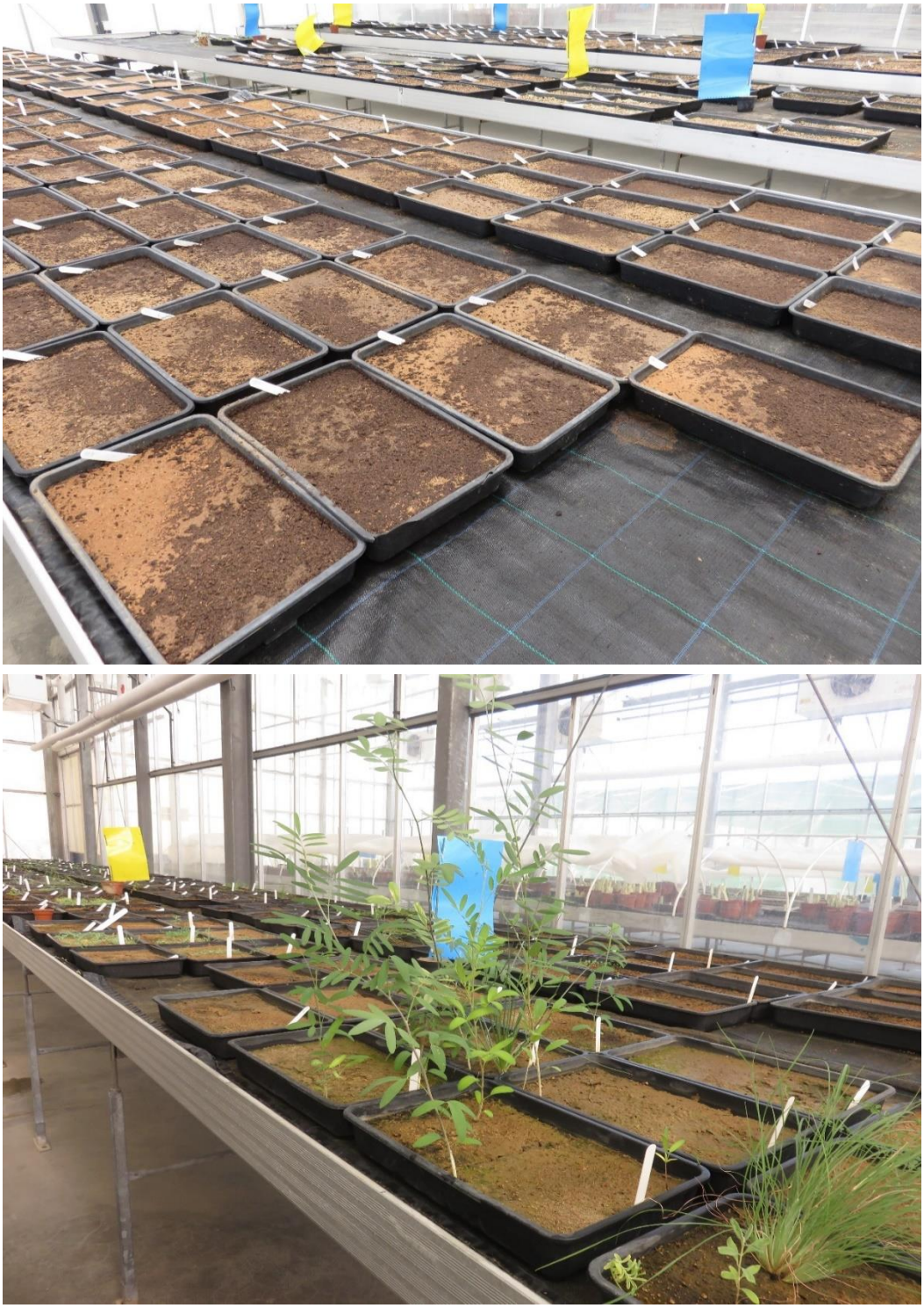


Figure 5.3. Seed bank germination experiment in the Eastern Hajar Mountains, under controlled temperature inside greenhouse.

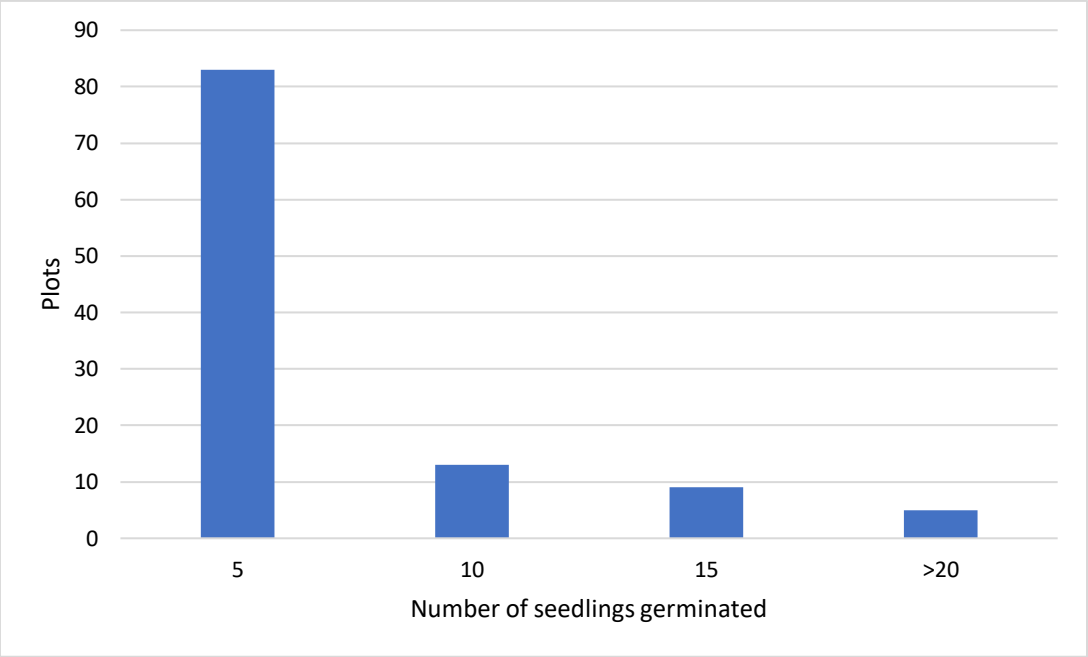


Figure 5.4. Seedlings germinated per plot, in the seed bank of the Eastern Hajar Mountains, above 1,000m elevation.

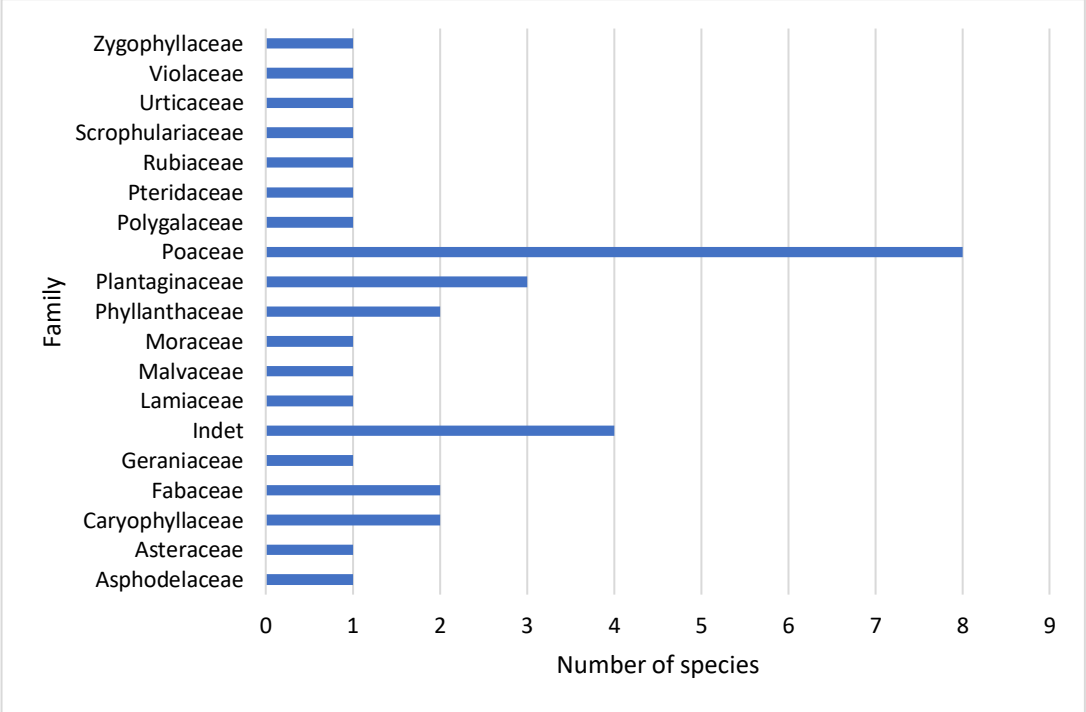


Figure 5.5. The number of plant species in each of the families recorded in the soil seed bank, above 1,000m elevation in the Eastern Hajar Mountains.

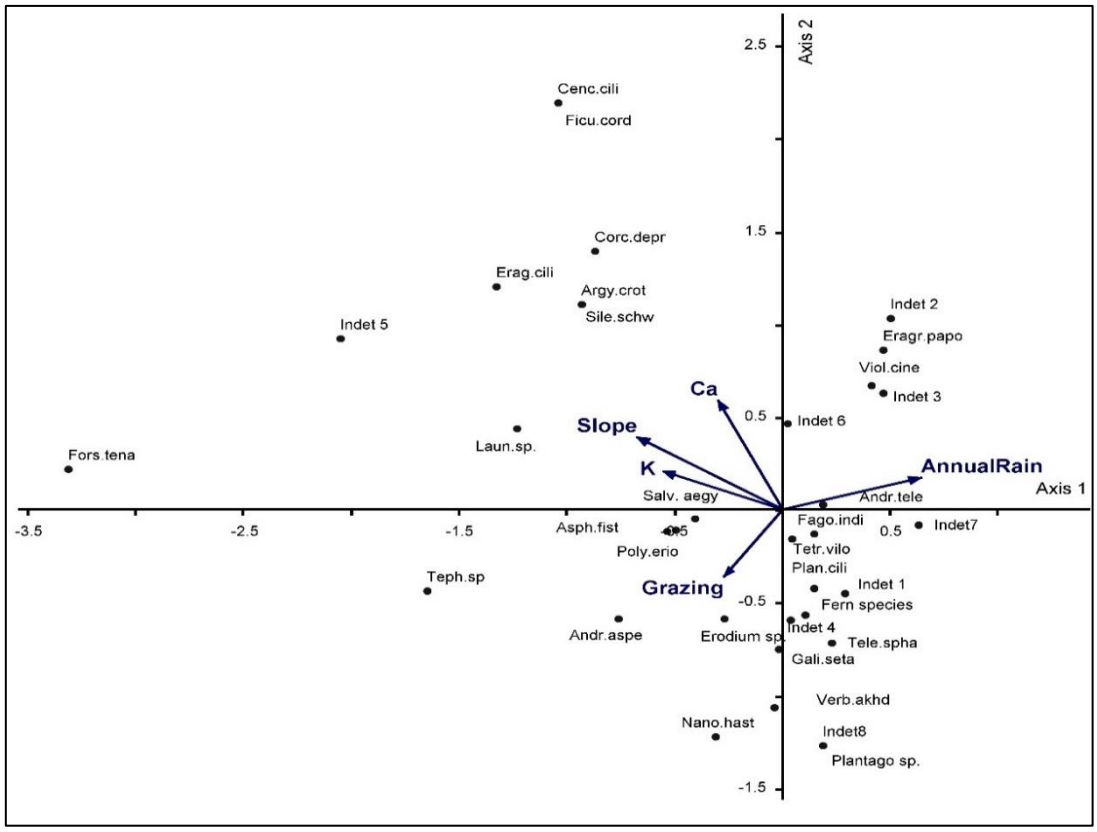


Figure 5.6. Biplot from a CCA of species to environmental variables in the seed bank of the Eastern Hajar Mountains. The species are listed by the first four letters of the genus and the specific epithet.



Figure 5.7. The enclosure that was built for the in-situ germination trial in the Eastern Hajar Mountains.

CHAPTER 6

SPECIES DISTRIBUTION MODELLING FOR FLORISTIC CONSERVATION PLANNING, EASTERN HAJAR MOUNTAINS, OMAN

6 CHAPTER 6: SPECIES DISTRIBUTION MODELLING FOR FLORISTIC CONSERVATION PLANNING, EASTERN HAJAR MOUNTAINS, OMAN

6.1 ABSTRACT

Conservation planning is crucial for countries like Oman that are undergoing fast development and changes that are negatively affecting their biodiversity. In this analysis, I identified priority areas of high conservation value in the Eastern Hajar Mountains. I used a combination of species distribution modelling and prioritisation analysis. First, species distribution modelling was carried out for 101 perennial species found at 500m elevation and above. I made species distribution models using classification tree analysis (CTA), generalised additive and linear modelling (GAM, GLM), MAXENT and Random Forest(Rf) modelling techniques. I also used ensemble modelling techniques to combine all these techniques and selected the best performing model. Based on these 101 species distribution models, a site prioritisation analysis was carried out using Zonation. Five different Zonation analysis scenarios were used to identify the priority areas within Eastern Hajar by giving different weight to the various species. The five scenarios varied in respect of giving equal weight to all species used in prioritisation analysis, changing the weight according to rarity and endemism of the species, and whether to consider existing PAs in the analysis.

I found that although the modelling performance was generally good for most of the modelling techniques, ensemble models outperformed all of the other methods, with an AUC ≥0.9 for 99% of the species. From all scenarios analysed, the top 10% priority conservation areas were identified to be at the mid-elevation and outside the existing protected areas, with only 25% overlap in the top 10% priority area between

including and excluding the nature reserves in the area. My results indicated that the average representation of plant diversity for the top priority areas was 50%. The current PAs represent only 17% of the plant diversity for the Eastern Hajar mountains. The analysis showed that the existing protected areas had limited overlap with the highest priority conservation areas and thus were suboptimal for the protection of the plant diversity of the area. Therefore, my approach will help to find more representative and efficient conservation areas and guide further conservation activities in the country.

6.2 INTRODUCTION

6.2.1 Species distribution modelling

The increasing threats to biodiversity and the continuous loss of natural habitats are causing conservation planners to be more concerned about designing more effective conservation programs. This now not only involves an understanding of the species ranges but, increasingly, predicting habitat suitability and identifying sites with high conservation values in order to protect them (Groves et al., 2002, Joppa et al., 2016). Oman has been involved in the protection of its biodiversity since the early 1970s when the first large-scale flora and fauna survey was carried out to select areas with rich biodiversity. For the last few decades, Oman has been under rapid development, which has lead, unfortunately, to the destruction of the natural habitat of many species. Unfortunately, the country lacks the basic knowledge of species distributions that can support different conservation activities.

Although the botanical surveys and knowledge of the flora and vegetation have increased dramatically in the last decades, the Eastern Hajar mountains, like many other areas in Oman, are still poorly surveyed and more detailed studies about the vegetation classification, plant communities, species ecology and many other

related studies are needed. The difficulty in studying these mountains comes from the tough terrain, steep slopes and problems of access to many of the locations. Information on the spatial distribution of plant communities and species diversity was scarce prior to this study. Moreover, although the important plant areas (IPA) areas have been identified (Chapter 7) and plant communities described (Chapter 4), neither of these analyses cover the entire range of the mountains, and more field-work in these mountains will be unlikely to happen any time soon. Therefore, the current gaps in the species distribution data and knowledge necessitate the use of all available information from the different sources available in the country. Species distribution modelling became an essential tool for selecting areas for biodiversity conservation planning and management. It is a valuable tool, more specifically, for poorly surveyed areas (Guisan and Thuiller, 2005). By determining the current distribution of species under the current climate, it is possible to locate areas where populations are predicted to be present but as yet not observed in the field. Here, I model and predict the current distribution of the perennial plant species I have recorded within the Eastern Hajar mountains as part of the community description and ordination analyses presented in Chapter 4.

A wide range of species distribution modelling techniques that can be used for current and predicted future distribution of species range had been developed over the last three decades. There is great variation in the accuracy of species distribution prediction from using different modelling methods, and there is no single best method which is suitable for all species in all contexts (Guisan and Zimmermann, 2000, Thuiller et al., 2003, Guisan and Thuiller, 2005, Elith et al., 2006, Wisz et al., 2008, Guisan et al., 2013). The use of ensemble (consensus) models from various modelling techniques is generally thought to increase model performance (Araújo and New, 2007).

My work is based on modelling the presence data for each species across the mountain range, which is a novel contribution on a regional and national scale. Using species distribution models will help in overcoming the limitations of the available occurrence data for many species in the study area. The model outputs will assist the identification of high-priority sites for conservation through their use in systematic conservation planning or other conservation activities for the Eastern Hajar mountains. Species distribution modelling will also provide baseline data for predicting species' response to landscape alterations and climate change.

6.2.2 Species data in Oman

Most of the historical and recent species records in Oman are collected from small-scale studies, through universities and other governmental and private related organisations. Only in the last decade have species data been transferred from voucher specimens stored at the country's herbaria to electronic databases, which so far are held separately within each institution. Many data, to my knowledge, are still to be found only in unpublished reports and studies. Oman Botanic Garden, established in 2006, is the first dedicated governmental organisation for both botanical and conservation research and started species collection in more systematic ways to cover the full range of the country's flora in all habitats.

Generally, species data, as expected, are prone to errors as diverse organisations and studies collect them. The species data can be misidentified, spatially mistaken records or they may have been collected from a biased subset of geographical locations (Hijmans et al., 2000, Graham et al., 2004). I also noticed from more recent data (e.g. OBG collections) that there are some species biases, which means that some species are collected more often than others (which could be for different reasons such as higher abundancy or because of their preference by specific researchers over other species). Resolving the errors found in the species data is a

crucial step before any further use of them. Also, these data were recorded as point data representing the presence of the species but missing the locations where the species does not occur. The current format of the species data; i.e. as only presence points, is of limited value for conservation planning. The point locality species data for the Eastern Hajar mountains, therefore, lacks the detail and quality that are required for any conservation planning. I, therefore, chose species distribution modelling as a tool that can be used to deal with the problems of the species data and reduce the bias and other errors associated with them.

6.2.3 Spatial conservation prioritisation

The lack of an efficient, protected areas network is of significant concern in the countries of the Arabian Peninsula (AP) (Omari, 2013). Protected areas in the AP cover 15% of the land area, which is represented in about 230 PAs. Oman is one of the countries with extensive land area protection, and about 14% of the land is covered under PAs. Most of the reserve and protected areas in Oman, and within the Arabian Peninsula, were designated for iconic species protection (e.g. Arabian oryx, Arabian leopard and Arabian tahr). Although there was a great success in many of these conservation efforts, they were based on an *ad hoc* approach to prioritise areas for conservation. in 2011, two conservation planning workshops were held in the region as part of the Conference on Biodiversity Conservation in the Arabian Peninsula. Part of the aims of these workshops was to test the potential use of the systematic conservation planning (SCP) approach for a more robust assessment for the Arabian Peninsula biodiversity. Although the underlying dataset was far from complete for this exercise, the preliminary results showed that the existing protected areas do not adequately represent the biodiversity of the area (Holness et al., 2011), and the Al Hajar mountains are a key unprotected area.

PA designation in Oman was based on the scientific results of the fauna and flora survey that was carried out in 1975 (Harrison, 1977). So far, only two designated plant-based protected areas are found in the country. One of them is the 'Al Khuwair' reserve, which was established mainly to conserve the *Acacia* trees and other flora within the area. Recently the government announced an initiative to develop this reserve to be more like a national park, with more emphasis and focus on developing nature reserve and promoting eco-tourism. The aims of the reserve have been altered to include preserving the rich heritage and culture of the area and also conserve the ecological treasures of the Sultanate. The reserve is located in the capital area of the country, and it is about 300km from the Eastern Hajar mountains. The other reserve is the 'Al Jabal Al Akhdar' nature reserve. This reserve is located within the Western side of the Hajar Mountains at an elevation of about 2900m, and it was established to recognise the uniqueness and threat to the biodiversity of the mountains (Ministry of Environment and Climate Affairs (MECA), 2019).

The Eastern Hajar mountains are one of the plant diversity hot spot areas in Oman, identified as being under increasing threat from development and grazing (Al Harthy and Grenyer, 2019). There is an immediate need for identification of priority conservation areas within the mountain ranges as Oman, recently, has begun developing a spatial conservation plan for the whole country, with contributions from all the governmental and private environmental institutes that are concerned with development and conservation. Jabal Bani Jabir, within the Eastern Hajar mountain range, has been identified, among another ten sites, as one of the top priority conservation sites in the country based on the number of endemic or regional endemic plant species, threatened species and species richness (Clarke et al., 1986, Ghazanfar, 1998) (Figure 6.1). Recently, the conservation priority for several

locations within the Eastern Hajar Mountains has been confirmed through the current research on the entire Eastern Hajar range.

The extensive data collection during the term of the current research led to the compilation of the first complete plant checklist for these mountains (See appendix 7.2). Also, the data collected from this research facilitated the application of the IUCN Important Plant Areas (IPA) criteria for the Eastern Hajar Mountains which led to it being described as one of the IPAs in the Arabian Peninsula (Al Harthy et al., in review). Based on general observation by many researchers, the Eastern Hajar mountains have been identified as one of the most biodiverse areas in Oman (Miller and Cope, 1996, Ghazanfar, 1998, Miller and Knees, 2014, Patzelt et al., 2014, Patzelt, 2015c, Al Harthy et al., in review).

When species distribution data are available, a set of priority areas for conservation can be determined using many of the available systematic conservation planning programs such as Marxan and Zonation (Moilanen et al., 2009a, Watts et al., 2009, Smith et al., 2010, Lehtomäki and Moilanen, 2013). Site selection based on any prioritisation analysis algorithm has not yet been used for identifying areas for conservation in Oman. Applying this methodology for identifying conservation sites in the Eastern Hajar mountains using plant species diversity will provide guidelines for using this approach at a national scale for other components of biodiversity. Using this approach should be the basis for conservation planning that aims for biodiversity representation on their conservation areas.

The present analysis aims to identify the areas of high conservation values within the Eastern Hajar mountains and to examine how much of this diversity is represented in the existing protected areas (PAs) within the study area. Also, it will provide a flexible prioritisation map based on the conservation goals and size for the

area. The results of this analysis could be used to identify new protected areas and/or extend the existing areas in these mountains.

6.3 METHODOLOGY

6.3.1 Study area

The study area for the conservation prioritisation is the entire Eastern Hajar range above 500m. The area is described in detail in Chapters 1 and 2. The spatial heterogeneity of the Eastern Hajar mountains landscape has resulted in a rich and diverse flora in them. Environmental variation in aspect, slope, and climate have both a direct and indirect effect on species occurrence and distribution. Open deciduous woodlands with scattered trees characterise the Eastern Hajar mountains. These mountains contain plant species of local and regional importance and are considered one of the most species-rich habitats within the country (Patzelt et al., 2014). Two hundred and ninety-three species were recorded previously from the Eastern Hajar range (Ghazanfar, 1992a, Miller et al., 1996, Ghazanfar, 2007). With further exploration in the last decade, the number of species has increased from 324 species in 2015 (Patzelt, 2015c) to 432 in the current research. The number of species is likely to increase with continued identification and verification of the current collections (Miller and Knees, 2014, Patzelt, 2015c, Al Harthy et al., in review). The Eastern Hajar mountains contain within its range: Wadi As Sareen National Park, Ras Al-Shajar nature reserve and Jabal Qahwan reserve.

6.3.2 Modelling potential species distribution

6.3.2.1 Species data

One hundred and one perennial species distributed across an elevational gradient from 500m to about 2200m of the Eastern Hajar mountains were modelled in this analysis. The presence and absence data for the species selected were recorded

during field sampling of 110 vegetation plots distributed randomly across the study area. Historical data collected of the same species were also extracted from the three main herbaria in the country: The National herbarium (NO), Sultan Qaboos University herbarium (SQUH) and the Oman Botanic Garden herbarium (OBGH). The data from the herbaria provide presence-only locations of the species. The herbaria data, as extracted, required some manipulation to be consistent with the quality of the field sampling data. The species occurrences of all recorded perennials in this study (i.e. 157 species) ranged from 1 to 94 with 79% of the species with fewer than 20 occurrences. Fifty-six species were excluded from the modelling process because they have only one recorded occurrence.

The species data used for this analysis are a combination of presence only and presence/absence data. First, a 1km x 1km dataset of presence per species was generated. To overcome the mixed-species occurrence types and as the species distribution models tend to perform better with presence/absence data (Elith et al., 2006), a dataset of pseudoabsences was generated for the modelling procedures. The number and method of selecting pseudoabsences depended on the modelling techniques and the number of occurrences data used in the modelling (Barbet-Massin et al., 2012). The same number of available presences with the surface range envelope (SRE) method for pseudoabsence selection or a 100 pseudoabsences when less than 100 presences, gave the best results according to Barbet-Massin et al. (2012). As the recorded presences in my study were less than 100 for all of the species modelled, 100 or 200 pseudoabsences were used when the true absences are more than presences and the same number as presences when the true absences are less than presences, again following Barbet-Massin et al (2012).

6.3.2.2 Environmental data

A combination of bioclimatic and topographic variables in raster format was assembled and used as predictors for the species distribution modelling. Because very little instrumental climate data is available for Oman generally, a climate model was used by the Ministry of Environment and Climate Affairs (MECA) to map seasonal and annual mean, minimum and maximum temperature and annual precipitation for the country (Ministry of Environment and Climate Affairs (MECA), 2015). I extracted the climatic variables at 1km resolution for the study area in the Eastern Hajar mountains at, and, above 500m elevation using ArcMap 10.5.1. Slope and aspect maps were generated from a digital elevation model (DEM) at 1km resolution, available online (https://earthexplorer.usgs.gov/). As I noticed during the field study and as observed previously by other researchers, there was a seasonal cloud cover over some parts of the mountains, so an annual mean cloud cover map was generated from a high resolution online dataset (Wilson and Jetz, 2016) to be used as one of the variables in the modelling process. The cloud cover may act as a proxy for fog distribution and therefore as a potential environmental predictor variable particularly relevant to the distribution of xerophytic plants and other ecological processes (Sklenář et al., 2008, Wilson and Jetz, 2016). A solar radiation map for the study area was also extracted from WorldClim version 2 at about 1km resolution (Fick and Hijmans, 2017). Rasters of environmental variables were reprojected, resampled and clipped to give a uniform extent at the 1km grid.

A set of twelve environmental variables were tested for collinearity using variance inflation factors (VIF) (Dormann et al., 2013). The VIF of a particular variable is 1/(1-R^2) of the regression of that variable on all the others. Variables were sequentially removed in order of decreasing VIF, recalculating each time until no variable had a VIF of more than 10. Eight environmental variables were retained using this test (Table 6.1).

6.4 SPECIES DISTRIBUTION PREDICTION AND EVALUATION

Species distribution modelling was performed in R program using the BIOMOD2 package. BIOMOD 2 allows for species modelling using more than one technique at the same time, which enables the selection of the most accurate model for each species (Thuiller, 2003). Five modelling techniques were used for the analysis. These are two regression methods: Generalized Linear Models (GLM) and Generalized Additive Models (GAM), one classification method: Classification Tree Analysis (CTA) and two machine learning methods: Random Forest (RF), and Maximum Entropy (MAXENT. Phillips). All of the modelling methods were run using eight environmental variables (Table 6.1).

As concluded by many studies, different modelling techniques will result in more-or-less different predicted spatial distributions for the same species and each model would have its strength and weakness depending on the data and objective of the study (Pearson et al., 2006, Sahragard and Chahouki, 2015). The ensemble (consensus) model has been widely suggested to have more advantages than the individual distribution models in reducing uncertainty, significantly increasing the accuracy of the model prediction and producing more stable and less sensitive models (Araújo and New, 2007, Breiner et al., 2018). The ensemble model was run based on the results of the five individual modelling techniques used for each species, so I produced about 500 (i.e. 10 runs for 10 PA, for each species) individual models per species, in addition to 7 ensemble models for the 101 perennial species (i.e. a total of 51,207 models). The relative importance of each environmental variable was calculated using random permutation test from 10 replicate models for each species (Thuiller et al., 2009). The importance is computed by simple correlation (Pearson coefficient) between the reference and shuffled variable data; which results in a value between 0 and 1; with 1 indicating a stronger influence of the variable on the model.

To evaluate the quality of the prediction, the data was randomly split using 70% of the data to train the models and 30% to test the agreement between known presence/absence and modelled distribution. This data split followed the guidelines provided by Huberty (1994) , and it was chosen because of the small dataset used in the analysis (Guisan and Zimmermann, 2000). The area under the curve (AUC) of the receiver-operating characteristic (ROC) was selected to evaluate the performance of the individual and ensemble models. Ten replicate models for each species were generated using cross-validation. The cross-validation is robust, spatially, as it randomly selects the occurrences that are used to build the ten models. The average of the 10 model replicates then used for all further analysis. The AUC ranges from 0 to 1; where 1 indicates perfect agreement between the presence/absence records and the predictions, while <0.5 value indicates poor model performance. AUC became the standard and preferred evaluation metric that enables comparisons across many modelling techniques (Elith et al., 2006, Pearson et al., 2006, Gastón and García-Viñas, 2013); because of its independent threshold and prevalence (Fielding and Bell, 1997, Pontius and Parmentier, 2014). An AUC threshold of 0.7 was used in this analysis to turn the continuous probability outputs of the model projection into a binary presence-absence output for each species.

Trying to compare the model performance on a species basis becomes difficult when comparing a large number of species. Therefore, the species were grouped based on their spatial distribution (Segurado and Araújo, 2004). The spatial distribution for each species was calculated using two measures: 1) the area of occupancy (AAO), which is the number of species occurrences by 1km grid cells; 2) the extent of occurrence (EOO) that is the straight line between the two most distant occupied cells. These measures were calculated using the Geospatial Conservation Assessment Tool (GeoCAT). GeoCAT is an online open-source tool designed and developed by Kew Gardens to help to assess the Red Listing process of species

specifically. It uses the occurrences data of a species to produce a geographically related measure (i.e. AOO and EOO) (Bachman et al., 2011).

Agglomerative clustering was then used to group species according to their spatial distribution. ANOSIM (analysis of similarity) was used to test for the significant difference between the groups (Clarke and Green, 1988). Both cluster analysis and ANOSIM were performed using the Community analysis package (CAP5) program (Henderson and Seaby, 2014). The Friedman test was used to test the differences between the overall performance of the modelling methods (Sprent and Smeeton, 2001). The Friedman test is a non-parametric version of one-way repeated measures ANOVA. This test works by assuming that there is no difference between the different modelling methods. A *post hoc* multiple comparison analysis using Dunn's test was then performed to find out which models are causing significant discrepancies if any (Klockars and Sax, 1986). Two-way repeated measure ANOVA-tests were also performed to test the differences between the groups of species in order to check if the model performance varied between species with different spatial distributions.

6.4.1 Species richness

Species richness (SR) is a widely used measure of the biodiversity of an area (Whittaker, 1972). An estimation of the species richness was carried out by stacking the 'mean of probability' outputs of the ensemble models' for the individual species models (S-SDM) (Lehmann et al., 2002, Gelfand et al., 2005, Guisan and Rahbek, 2011). Correlations between observed and predicted species richness were calculated. Differences in predicted species richness were tested for significance between plant communities identified in chapter 4 using a multi-response permutation procedure (MRPP) with the squared Euclidean distance. Also, the mountain was divided into 400m elevational interval (i.e. 1000-2200m) to test the

species richness on an elevation gradient. The species richness map will help in identifying most species-rich sites within the Eastern Hajar mountains, which can eventually support establishing conservation strategies for the area. Species richness alone is not regarded as a good measure for conservation priority (Wilson et al., 2006).

6.5 SPATIAL CONSERVATION PRIORITISATION

Representative areas for plant diversity conservation within the Eastern Hajar range were identified using *Zonation* software, GUI V.4 (Moilanen et al., 2009a). Zonation produces a conservation priority map based on the hierarchical ranking of the landscape, with increasing ranking values from 0 to 1 indicating increasing conservation priority of an area. The priority ranking map depends on the cell removal algorithm used in the analysis, which for example, gives higher priority or value to the cells or areas with high species richness. The total value of an area is the sum of species-specific values that are measured by the representation level of a species in a cell. Zonation works by assuming the whole landscape is protected and then removes cells one at a time based on maximising the overall conservation value of the remaining area (Moilanen et al., 2005, Moilanen et al., 2009b, Moilanen et al., 2011, Moilanen, 2013).

Additive Benefit Function (ABF) analysis was used as a cell removal rule for the spatial prioritisation in the Eastern Hajar Mountains (Moilanen, 2007, Lehtomäki and Moilanen, 2013, Kujala et al., 2018). ABF is a method that works by summing values across species in a cell (i.e. used in the analysis), and so gives higher priorities or values to the cells with higher species richness and favours complementarity. Since the ABF determines the value of an area over the sum of species, that means one or more species can compensate the absence of another species from an area (Moilanen, 2007) The primary aim of the site prioritisation approach I have adopted

is to highlight relatively areas with cumulatively and individually high species richness, for which the ABF method is an appropriate tool. Spatial prioritisation analysis in the Eastern Hajar mountains was more towards finding species-rich locations within the mountain range and not retaining the core areas for all species (Moilanen, 2007). Selecting the additive benefit function (ABF) cell removal methods within zonation was based on the reasons that species found in the Eastern Hajar range are mostly representatives of a larger local and regional species pool, and there are no species that are locally restricted to the Eastern Hajar mountains. The use of the ABF method emphasised the selection of the areas that optimise the representation of all the biodiversity features used in the prioritisation analysis (Moilanen, 2007). The predicted species distribution models of 101 species were used as input diversity features for the prioritisation in order to simulate priority conservation areas.

The distribution of the priority conservation areas for the 101 biodiversity species may be affected by different analytical criteria that could be used in the prioritisation analyses. I conducted five different scenarios based on the existing protected areas, endemism and rarity (IUCN red list categories) of the diversity features used. The first scenario gave equal weight for the 101 species to optimise the selection of the maximum priority areas within the study area, while the second scenario was derived from the first scenario and by adding the existing protected areas layer as a removal mask to estimate the proportion of diversity features represented within the current protected areas system in the study area.

Although the starting point in many Zonation analysis is to give equal weight to all features (species), higher weight is needed sometimes to prioritise some species. Weight can be assigned, for example, according to rarity or endemism of a species. This weight is used to define species importance with respect to other species

(Moilanen, 2007) which means that the distribution of species with the higher weight will be retained during all levels of cell removal in Zonation analysis (Moilanen et al., 2005). Assigning specific weight to a species is a subjective procedure that is not based on exact science. However, with the Zonation algorithm, the balance between species is attained even with the equal weight. The weight of the species, in addition to other analysis consideration, is usually developed by an expert or a team of experts with the relevant knowledge and data (Lehtomäki and Moilanen, 2013).

The other three scenarios were more concerned with the range-restricted species within the study area. The term range-restricted species are used in the Oman Red Data Book as summarising term including endemic, near-endemic and regionally endemic species. An endemic species are species that occur only in one country, Oman in this case; while, the near-endemic species occur in one geographical entity but in two countries; for example, in Oman and any adjacent country. Species that are restricted to the Arabian Peninsula, and occurs in at least two countries and more than one geographical entity are defined as the regional endemics (Patzelt, 2014). Therefore, in the third scenario, a higher weight (i.e. 2) was used for the Oman endemics while the rest of the species having an equal weight of 1, and the fourth scenario gave higher weight for vulnerable (VU) and near threatened (NT) species. The last analyses gave higher weight for both the Oman endemic and species with VU and NT IUCN category and equal weight for the rest of the species. using a different weighting of species allows for Weights can be assigned, for example, according to conservation status

The scenario that included the existing protected areas was conducted to measure the current contribution of these areas in protecting the plant diversity in the Eastern Hajar range. In the zonation processing, this analysis was carried out by specifying a mask that identifies the locations of the existing reserves through hierarchical

prioritisation (Kremen et al., 2008, Proctor et al., 2011). This was guaranteed by giving the existing reserves the highest-ranking weight. Sixteen range-restricted species were used in the analysis.

6.5.1 The overlap between the prioritisation scenarios

An overlap analysis was carried out to compare the different prioritisation scenarios. For the ease of comparison between the different scenarios, only one scenario used from the three range-restricted species prioritisation scenarios (i.e. the scenario that gave higher weight to the all of the Red List species). Therefore, the three scenarios used for the overlap were: the first scenario which gave equal weight for the species without including the nature reserves, a second scenario which also gave equal weight to the species but excluding the nature reserves from the analysis and the last scenario which gave higher weight to the Red List species. The overlap was calculated on the top 10% priority areas identified by each scenario. The range-restricted species were entirely removed from the prioritisation analysis to clearly understand the effect of the presence of the range-restricted species in identifying the priority areas within the study site. The amount of overlap on the distribution of the top 10% ranking cells between including/ excluding of the red list species was calculated.

6.6 RESULTS

6.6.1 Species Distribution Modelling

Individual models generally provided fair to good results for most species, with 48% of the species having an AUC of ≥0.7 (useful discrimination). For 97% of the species, the models performed better than random (AUC ≥0.5) and only 4 species performed poorly (AUC <0.5). Comparison of models across all species indicates that the highest performing models of AUC values of 0.7 or more were RF, MAXENT

and GLM, in 68 %, 61% and 51% of the species, respectively. The lowest performance model was GAM, with only 15% of the species having an AUC of ≥0.7 (Figure 6.2).

Overall there was slight modelling accuracy variation within individual species (AUC ranged mostly from 0.5 to 0.8), with some species that were modelled well or poor by most methods. *Convolvulus ulicinus* and *Sideroxylon mascatense* were the best-predicted species (AUC= 0.9) followed by *Helianthemum lippii*, *Trichodesma africanum* and *Heliotropium calcareum* with slightly lower but still high accuracy (AUC=0.82, AUC=0.81 and AUC=0.80, respectively). The lowest-performing models were predicted for the species *Cynodon dactylon* and *Chrozophora oblongifolia* with the AUC value less than 0.5. The variation among the species prediction accuracy was not consistent with the type of modelling method used (Figure 6.3), with EM, RF and MAXENT performing better for most of the species (Appendix 6.1). In contrast to this variation on the model performance for individual species, 99% of the ensemble model had an AUC of 0.9 or higher, which indicates nearly perfect discrimination for all species.

The results of the Friedman test showed that there is a significant difference between modelling methods in the model performance. The mean rank order did vary between the different methods and was significant according to multiple comparisons Dunn tests (Table 6.2). The ensemble model (P >0.001) outperformed all other methods, followed by RF and MAXENT, while GAM and CTA were the weakest performing models.

Four groups resulted from the cluster analysis based on the spatial distribution of the species used in the modelling procedure. This analysis was run to easily compare modelling performance between a large number of species in the form of groups (Figure 6.4). The groups were significantly different from each other

(ANOSIM, *P* <0.02). These groups are: 1) widespread species, i.e. species with high area of occupancy and intermediate extent of occurrence; 2) species with mixed distribution; i.e. species with both intermediate areas of occupancy and extent of occurrence, 3) narrowly distributed species, i.e. species with low area of occupancy and narrow extent of occurrence; 4) predominant species, i.e. species with high area of occupancy and large extent of occurrence. Model performance did not vary according to the number of presences nor to the extent of the species for nearly all the models (Table 6.3). GAM and CTA were significantly different using the extent of occurrence comparison, and only GLM was significantly different when the comparison was based on the area of occupancy grouping (Table 6.3).

The climatic factors were the variables with significant importance to all five species distribution models (Figure 6.5). These are the mean annual temperature, annual precipitation, solar radiation and maximum seasonal temperature (for March and April). Elevation was also of significant importance to the modelling procedures. Annual cloud cover, aspect and slope were slight with lower importance to the modelling techniques. Despite the agreement of the variable environmental importance to the modelling methods, it appears that MAXENT is more affected by the topographic variable aspect and slope than the climatic variables (Figure 6.5).

6.6.2 Species Richness (SR)

Species richness analysis integrated the spatial models of 101 perennial species. Even more than the individual models, species richness highlighted the importance of elevation in identifying the diverse areas within the Eastern Hajar mountains (Figure 6.6). There were significant differences between the three elevational gradient of the mountains (MRPP results: A= 0.09, T= -18.6, Observed delta= 0.45, Expected delta = 0.50, p = 0.000). Prediction of the species richness along the elevational gradient also indicated that the middle elevation (i.e. 1400-1800m) has

the highest richness and a lower species richness toward the high and low elevations (p <0.0001) (Figure 6.7). There were significant differences between the four plant communities identified in the Eastern Hajar Mountains (MRPP results: A= 0.16, T= -26.3, Observed delta= 0.42, Expected delta = 0.50, p = 0.000). The high richness at the mid-elevation is a pattern that is extensively documented and discussed by many studies (Ghazanfar, 1991, Brinkmann et al., 2009, Haq et al., 2017, Al Harthy and Grenyer, 2019).

6.6.3 Spatial Conservation prioritisation - Zonation

The Zonation method of prioritisation provides a wide range of options based on the conservation goals aimed to be accomplished by the decision-makers. The results from the different scenarios used in building Zonation prioritisation are presented below.

6.6.3.1 All biodiversity features (Species)

The first scenario analysis, using equal weight for all species in zonation analysis, indicated that, as expected, the average representation of plant species distribution increased in corresponding with increasing area of protection. Figure 6.8 shows the minimum and mean species' distributions retained during the cell removal process in Zonation analysis. Protecting the top 10% of the land in the study area, retained about 26% of the species' distributions; while 74% of the species' distributions were retained with 50% protection. Results of the priority conservation ranking map confirmed the importance of many of the same locations identified by the individual species models. It highlighted the importance of the mid and high-elevation mountain ranges for plant species diversity at the Northern-east sites of the mountains.

6.6.3.2 Existing protected areas

There are three protected areas within the Eastern Hajar mountains, ranging in size from 87km^2 to 746km^2. These protected areas (PAs) currently cover about 10% of the total area above 500m of the study site. The current protected areas map was used as a mask layer in the prioritisation analysis in order to force their inclusion in the areas first selected. Figure 6.9 shows the priority conservation ranked maps for the mountains from the two scenarios: A) including the existing PAs so they will be first selected to be in the top 10% high priority areas and B) excluding them from the prioritisation analysis. 17% of the total plant diversity recorded in the study area was found inside the PAs. Increasing the protection of the study area, including the PAs, increased the plant diversity to about 67% inside the PAs. Figure 6.10 shows the borders of the three protected areas found in the study area on top of the output of the Zonation map of the high priority conservation areas in the Eastern Hajar Mountains.

6.6.3.3 Range-restricted species

For the sixteen range-restricted species, the three different scenarios used in the analysis identified almost identical priority conservation areas, which also represent the same results from the equal weight analysis (Figure 6.11). Furthermore, excluding the range-restricted species from the analysis did not affect the priority areas identified by Zonation (Figure 6.12). Additionally, it highlighted the mid and high-elevation areas within the mountain range as areas with high conservation values.

6.6.3.4 The overlap between the prioritisation scenarios

Of the top 10% priority areas identified by the three scenarios (detail of the scenarios is in the methodology section), 25% overlap was found between the first and second scenario, 79% overlap between first and third scenario and about 30%

overlap between the second and third scenario (Figure 6.13). The percentage area overlaps between excluding and including the red list species in the prioritisation analysis was 93%, which indicate a minimum contribution of the Red List species in highlighting the high priority conservation areas in the Eastern Hajar Mountains.

6.7 DISCUSSION

6.7.1 Species Distribution Modelling (SDM)

The results of this analysis using the available species occurrence data showed that I could obtain reliable SDMs in arid mountains like the Eastern Hajar with relatively little input data. This suggests this technique may well apply to other arid and dryland regions with similar characteristics. In this study, five individual models (CTA, GAM, GLM, RF and MAXENT), and seven ensemble models were used to predict the current distribution of the perennial plant species in the mountains above 500m elevation. Although the average model performance for 97% of the species was good, AUC ≥0.5, the ensemble models for all species outperformed all other methods (AUC= 0.9). Results also indicated that the ensemble model (AUC = 0.9) outperformed the best predictive performance individual model, which is RF (AUC= 0.7). For the four groups resulted from the clustering analysis, the model performance did not vary according to the number of presences nor to the extent of the species (Table 6.3). This indicates that there was no clear association between the modelling quality and the species distribution range. Therefore, the species range of distribution cannot be used as a guide to the likely success of the models and careful assessment of the models before using them in conservation planning is required.

Selecting one model as the best model to be used in species distribution prediction is challenging as the spatial pattern for individual models might be different even

with the same evaluation accuracy performance (Figure 6.3). The model performance differences are more likely to be because of the different representation of some locations in the study area in the evaluated samples. In addition, the model performance may be affected by many other ecological characteristics of the species such as range size, niche width and position, commonness, and other traits like dispersal, light requirement, or drought (Kadmon et al., 2003, Thuiller et al., 2004, Schwartz et al., 2006, Guisan et al., 2007). Environmental variables and data quality used in the modelling techniques could also be reasons for variation in model performance (Segurado and Araújo, 2004). For these reasons, the use of the ensemble model is recommended. High-performance individual models from this analysis (i.e. AUC ≥ 0.7) were used as the bases of the ensemble model, which yield strong and accurate predictive results.

Although my models did return high AUC values for most of the species (even those with low numbers of occurrences for many species; 79% had less than 20 records), these high AUC values might not hold when the models are evaluated on independent data. This result has been documented by many studies (Pearson et al., 2007, Hernandez et al., 2008, Breiner et al., 2015, van Proosdij et al., 2016)., and for some of my species, there were no true absences available, which can also decrease prediction accuracy. In the above studies and many others, the model performance and prediction accuracy increase as the sample size increase (Guisan et al., 2007, van Proosdij et al., 2016). For example, Wisz et al (2008) found that from 12 modelling algorithms used; none performs consistently well for sample size less than 30 occurrences. However, sometimes a very few species occurrences - as small as 5, 10 and 25 – have been found sufficient to predict accurate species ranges (Hernandez et al., 2006, Williams et al., 2009), whereas in other cases, these low occurrences are inadequate to characterise the range of species (Hernandez et al., 2008).

In my analysis, I do not claim that my models provide a general valuation of the modelling platform for small sample sizes but the model performance presented here signify a great value and a case study that may be used, for example, in targeting the discovery of new populations and new species (Pearson et al., 2007, Williams et al., 2009) and also could be used in conservation management and planning. Therefore, careful evaluation and validation of the model outputs are required to accurately identify the species ranges in the Eastern Hajar Mountains, and this should ideally take the form of a more widespread collection of field observations across a spectrum of environmental conditions.

This is the first attempt in the country and the region at performing species distribution modelling for a large number of species and will provide baseline guidance for further and improved conservation planning. The scarcity of the species distribution data in high-elevation Oman will need to be overcome by methods that go along with the fast planning procedures. Species distribution modelling (SDMs) is a method that yields quick and variable results that will, definitely, improve our understanding of the potential habitats of many of the species and thus provide essential baseline data for the planning process.

The accurate model predictions (i.e. from ensemble models) from this study make the models appropriate and reliable support tools that can be used by decision-makers on their conservation planning. As mentioned earlier, the country is under rapidly changing economic, social, demographic and resource infrastructures. Therefore, and for more guided comprehensive spatial development, Oman is setting up a framework through the development of the Oman National Spatial Strategy (ONSS) to ensure a sustainable social, economic and physical environment development. The data collected during this field study and the species distribution maps will improve the botanical knowledge of the area and will act as

baseline data to assist the National Spatial Strategy and any further conservation planning.

6.7.2 Spatial conservation prioritisation

The primary purpose of using zonation is to identify and propose areas with high conservation values for more robust planning and not to suggest a comprehensive reserve network. As a first attempt, my results provide a primary support tool for conservation planning in the country. The Zonation method of prioritisation provides a wide range of options based on the conservation goals aimed to be accomplished by the decision-makers. The priority conservation ranking using zonation also allows for various solutions depending on the conservation goals.

The Eastern Hajar mountains have been identified as a national and regional important plant area. The plant species diversity in these mountains is affected negatively by well-known environmental and social threats (Al Harthy and Grenyer, 2019, Al Harthy et al., in review). Therefore, there is a need for protecting species diversity through different and appropriate conservation and management planning. Although the Eastern Hajar mountains contain three protected areas, these areas retained only about 17% of the plant diversity within them, and the rest of the areas are currently without any protection. The analysis showed that the existing protected areas had limited overlap with the highest priority conservation areas and thus did not optimise the protection of the plant diversity.

Consequently, current protected areas failed to identify most of the highest value conservation priority areas identified by Zonation software for plants. From the maps (Figure 6.8 & 6.9), it is clear that the south-eastern part of the Eastern Hajar mountains is not included in any of the protected areas within the mountain range. These areas were identified at the top 10% priority areas in Zonation analysis. The same areas were also identified to be the highest species richness locations within

the elevational gradient of the mountains. Thus, my conclusions emphasise the need for creating new reserves to complement the existing ones, which were primarily designated to protect large animals like the Arabian tahr and gazelles.

Spatial prioritisation analysis indicated that the highest top 10% priority conservation areas for plants are located at the mid-elevation of the Eastern Hajar mountains range. These priority areas reflect a well-known phenomenon of species-richness peaking at mid-elevation elevational gradients that is previously recorded in the Eastern Hajar mountains and many other arid and semi-arid mountains (Ghazanfar, 1991, Brinkmann et al., 2009, Haq et al., 2017, Al Harthy and Grenyer, 2019). This suggests that the priority areas resulted from this analysis are soundly grounded and I, therefore, urge the need for protecting them. These spatial priority conservation areas could be used to guide the decision-making and conservation planning for these mountains. No other studies used any of the systematic conservation planning previously in the country, and I think that this methodology should guide future conservation actions in Oman.

While the range-restricted species are one of the conservation priorities, their contribution to the regional species richness in my study area was minimal. The prioritisation results were almost similar with or without including the range-restricted species in the analysis (i.e. about 93% overlap), which indicated their low contribution in prioritising areas for conservation. The highest overlap in the priority areas suggested by the Zonation analysis was between the first scenario, which gave equal weight to the species, and between the third scenario that gave higher weight to the National and regional endemics in the Red List species (i.e. 79 % overlap). In this analysis, the use of the range-restricted species for prioritising areas for conservation proved not to be of particular importance for the representation of the flora of the Eastern Hajar mountains. These results could be explained by the

wide distribution of most of these range-restricted species within the country and the low occurrence points of them, which were used in building up the species models that were used in the prioritisation analysis.

6.8 CONCLUSIONS AND FUTURE CONSIDERATIONS

The different modelling techniques used for the species modelling in the Eastern Hajar mountains offered varying and inconsistent prediction performance between different species, while the ensemble models were, always, significantly more accurate and robust. The results of this study will act as a guide for any other research to be carried out in this type of habitat with the same data quality and availability. Generally, I identified priority areas with high conservation values that will lead the decision process for the country's spatial conservation planning. These areas may be used as bases for different conservation activities such as designing new protected areas or expanding the existing ones to increase the representation of the plant diversity within them and to support the decision-makers in where to focus their efforts of protection.

Although this study used intensively surveyed plant species data in the Eastern Hajar mountains, many species have been excluded from the analysis. These species were the annual/ biennial species and perennial species with very low occurrences that make them difficult to be modelled. One of the limitations of the modelling process was not considering the individual species characteristics, such as dispersal patterns and biological interactions between species (Kearney and Porter, 2009) due to the absence of this knowledge in the country.

For a better description of areas of importance for conservation, socioeconomic considerations need to be accounted for in future analyses, as they may have a strong influence in identifying areas with high conservation values. In the spatial

prioritisation, I did not consider the factors such as incorporating the land use, habitat condition, land ownership, tourism and cost to protect these lands. Not considering climate change scenarios is another significant limitation to my study. Species ranges may shift as a response to future climate change. Therefore the climate change scenarios should be included in the species distribution modelling and prioritisation analysis to predict this future shift, especially in countries like Oman, which are more likely to be impacted by climate change.

Table 6.1. Environmental variables used in the species distribution modelling in the Eastern Hajar Mountains, Oman, with their VIF values; all data were at 1km resolution.

Environmental Data	VIF	Source
Annual mean temperature (mm)	10	Oman Climate Data Model
Annual precipitation (mm)	5	Oman Climate Data Model
Seasonal Maximum Temperature_ March/April (^{0}C)_ end of the summer	8	Oman Climate Data Model
Elevation (m)	7	Global 30 Arc-Second Elevation (GTOPO30); https://earthexplorer.usgs.gov/
Mean Annual cloud cover	1	http://www.earthenv.org/
Solar Radiation	1	WorldClim
Aspect	1	DEM_ Oman National Survey
Slope (degrees)	1	DEM_ Oman National Survey

Table 6.2. Model multiple comparison significance test results for the 101 species; Dunn's test P<0.05; Eastern Hajar Mountains Oman

	EM	RF	GLM	MAXENT	CTA
GAM	0	0	0	0	0.352
CTA	0	0	0	0.003	
MAXENT	0	0.05	1		
GLM	0	0.198			
RF	0				

Table 6.3. One-way ANOVA test for the species groups based on their spatial distribution; EOO: Extent of occurrence and AOO: Area of occupancy.

	ANOVA /by EOO		ANOVA /by AOO	
	F	Sig.	F	Sig.
EM	1.298	0.535	0.883	0.666
GAM	27.183	0.036	1.326	0.145
GLM	0.390	0.919	2.427	0.000
CTA	132.882	0.007	1.013	0.473
RF	1.811	0.423	0.652	0.933
MAXENT	0.945	0.650	0.924	0.604

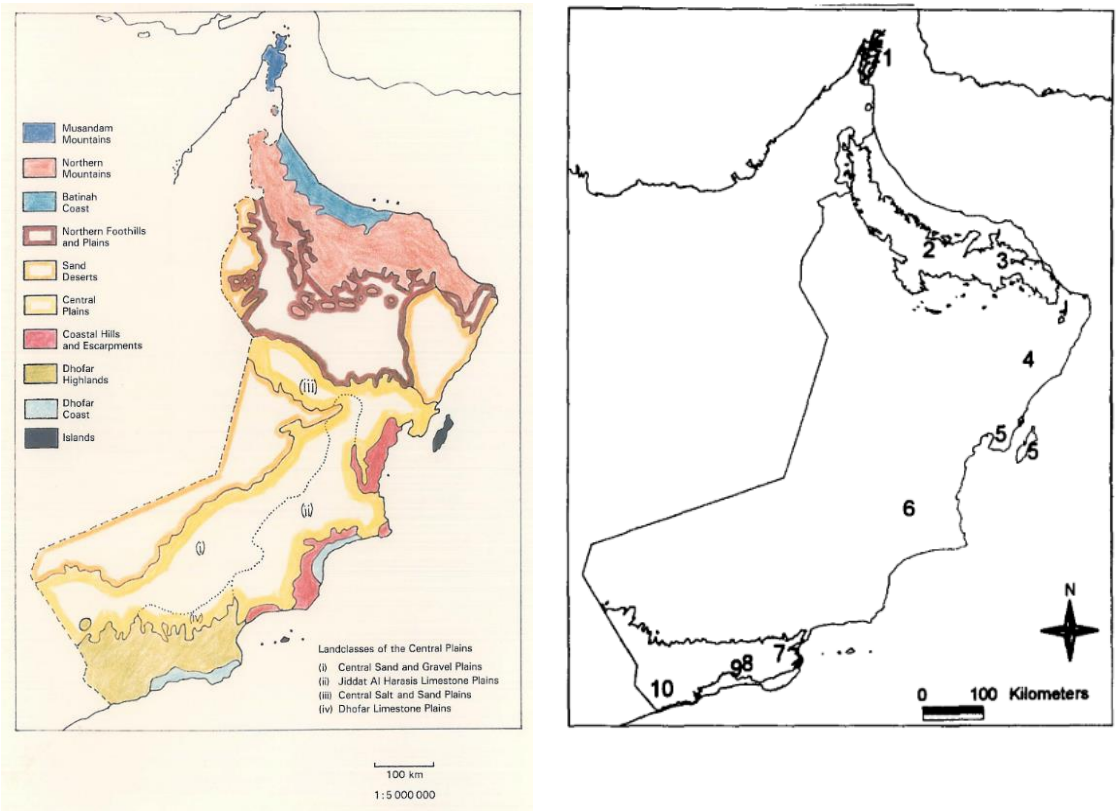


Figure 6.1. Left: Proposed protected areas in Oman (Clarke et al., 1986). The whole of the Northern Mountains was proposed for protection; Right: Oman, showing location of sites for high priority conservation based on the number of endemic or regional endemic plant species, threatened species and species richness; 3: Jabal Bani Jabir, within the Eastern Hajar Mountains range is among the top 10 sites identified, Source: Ghazanfar, 1998.

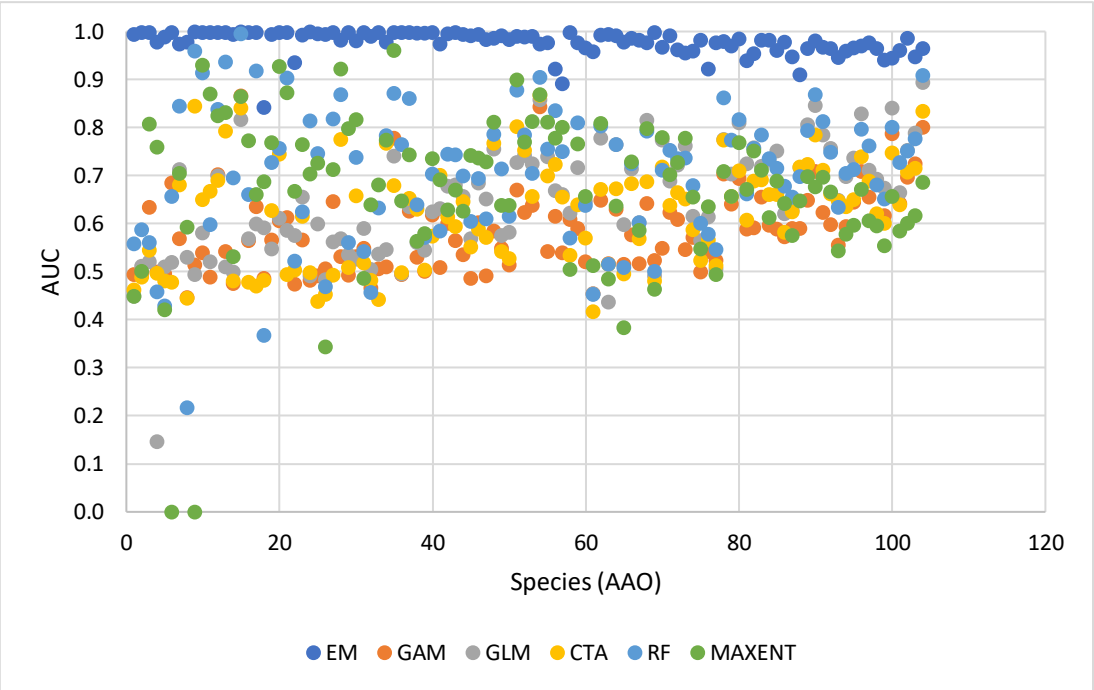


Figure 6.2. AUC for the modelled species in the Eastern Hajar using five modelling methods (i.e. GAM, GLM, CTA, RF and the Ensemble model (EM); species are ordered by their Area of Occupancy (AAO), higher occupancy to the left.

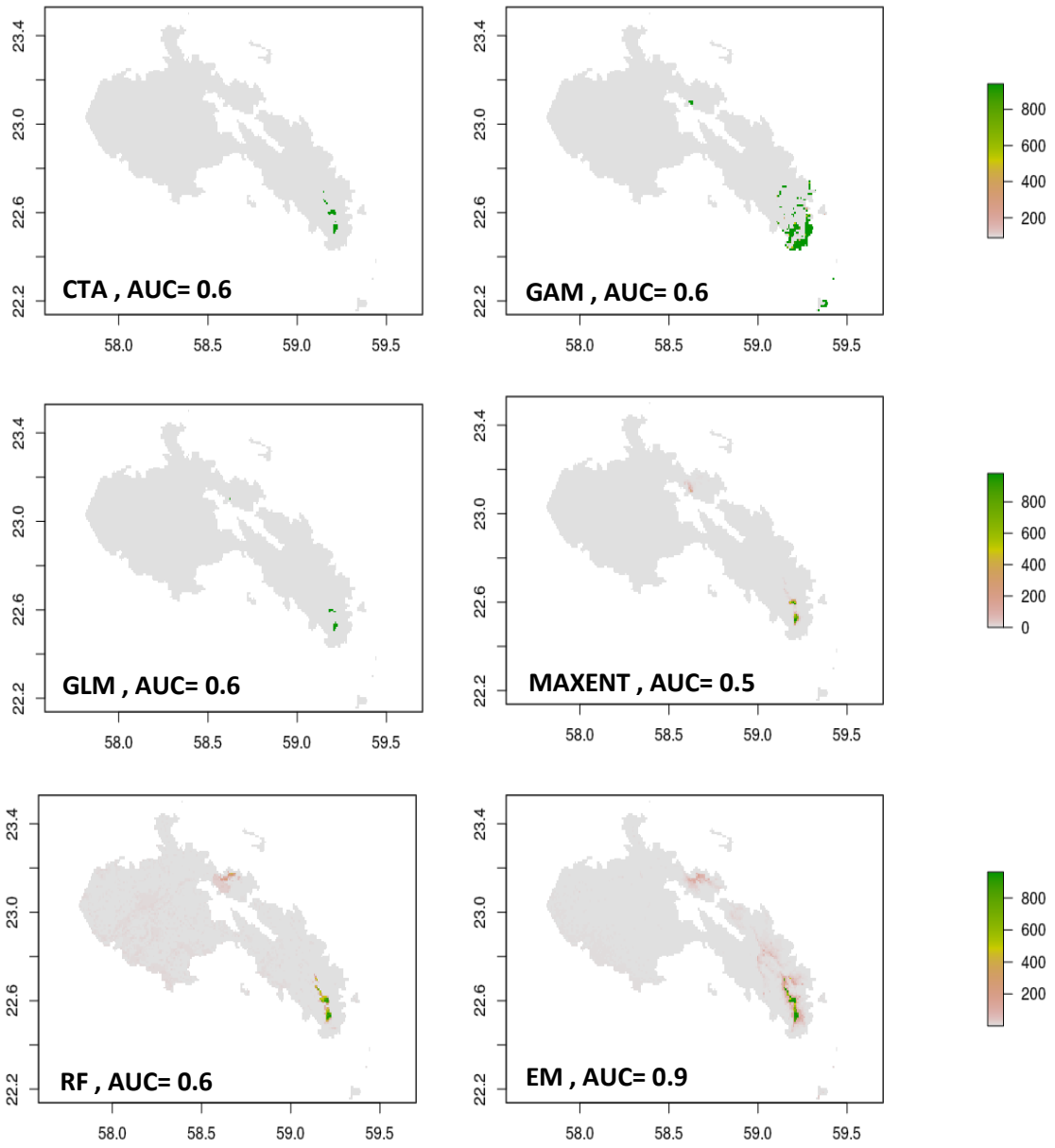


Figure 6.3. Five predicted models for the species *Convolvulus ulicinus* with their AUC value for each of them; EM: Ensemble model, Eastern Hajar Mountains, Oman

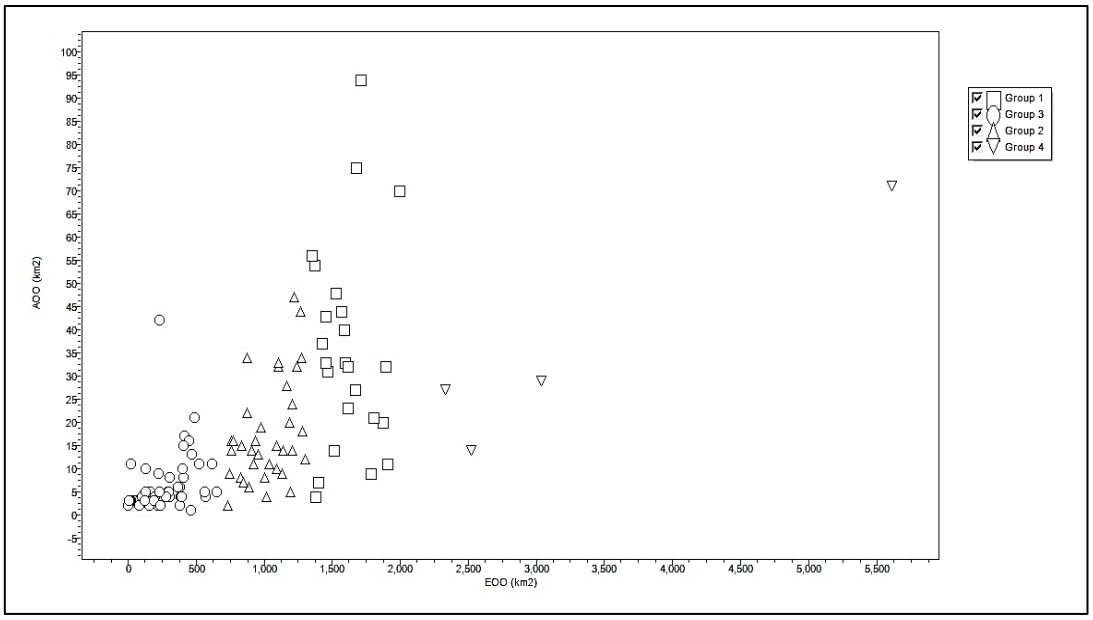


Figure 6.4. The four species groups resulted from the clustering analysis based on their spatial distribution (i.e. using their area of occupancy (AOO) and their extent of occurrence (EOO) in km^2.

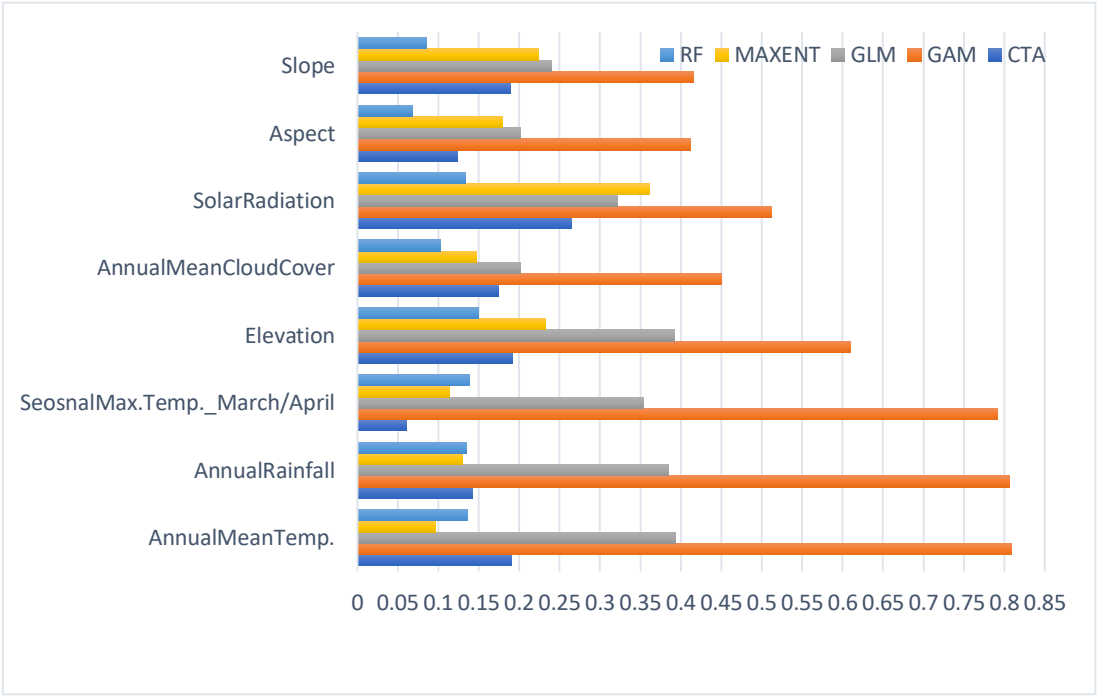


Figure 6.5. The relative importance of each of the eight environmental variables used in the SDMs for 101 perennial species in the Eastern Hajar Mountains; with value of 1 indicating a stronger influence of the variable in the model.

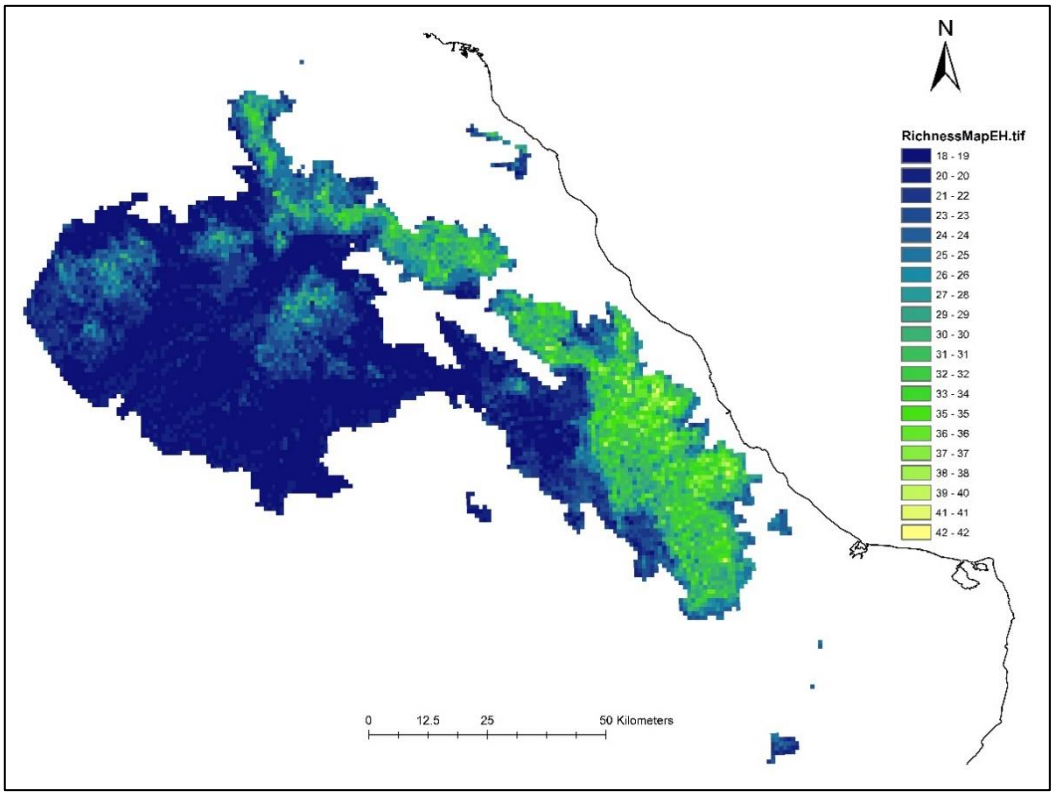


Figure 6.6. Predicted species richness map for the perennial species above 500m in the Eastern Hajar Mountains, Oman.

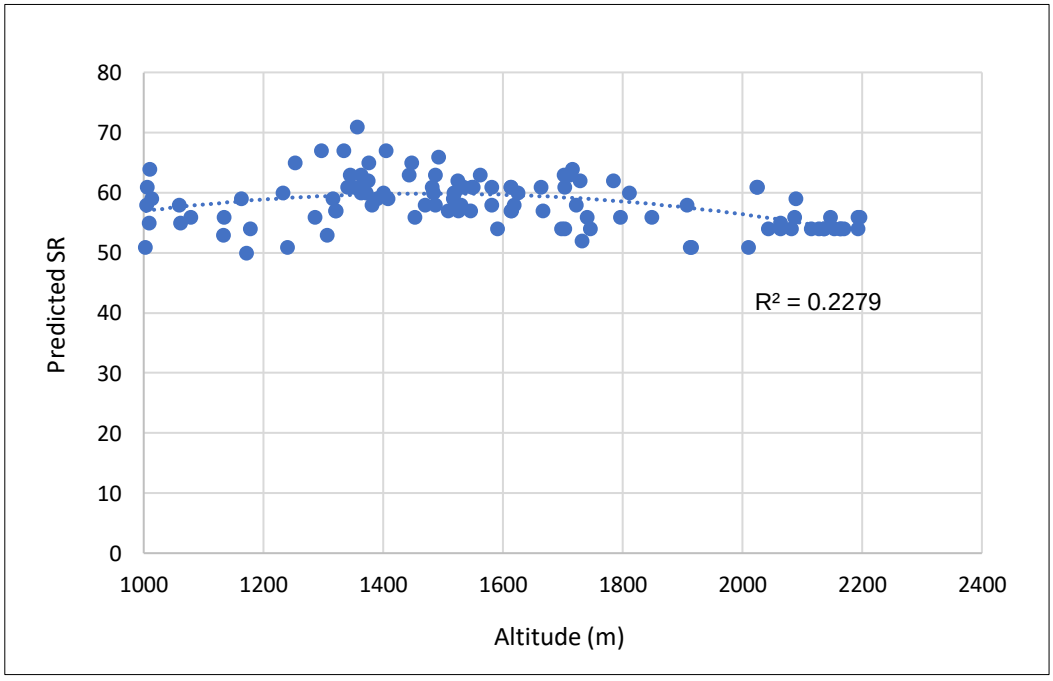


Figure 6.7. Predicted species richness (SR) of the 110 plots (i.e. extracted from the richness map) in relation to elevation in the Eastern Hajar Mountains, Oman; the line is from a quadratic regression through the data.

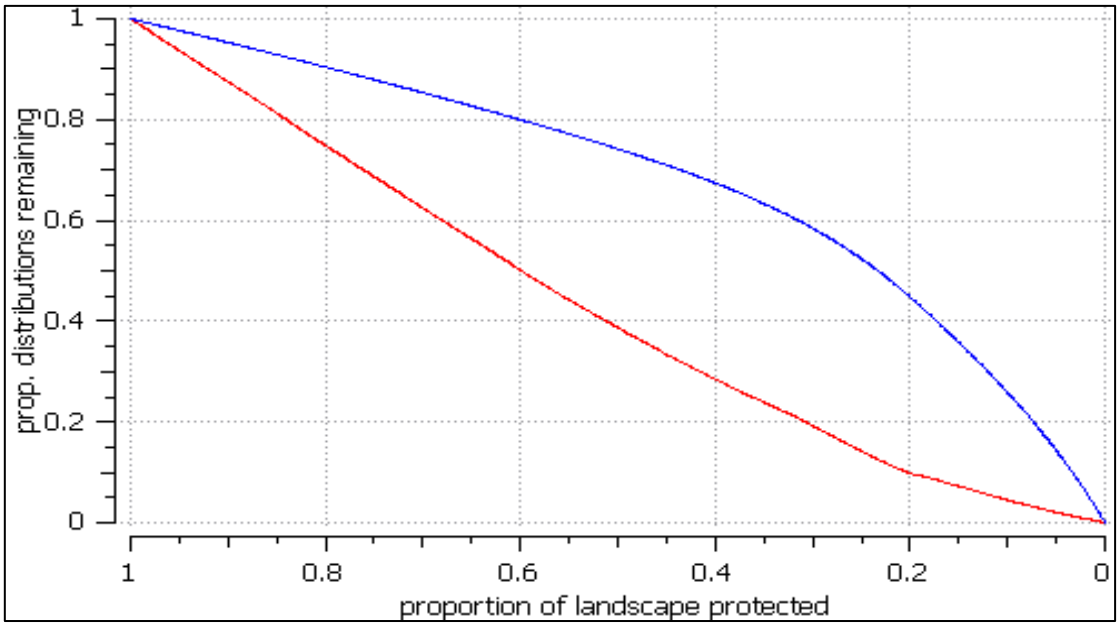


Figure 6.8. The Zonation curves show that the average (blue line) and minimum (red line) proportions of species distributions are declining as landscape is removed in the Eastern Hajar Mountains, Oman.

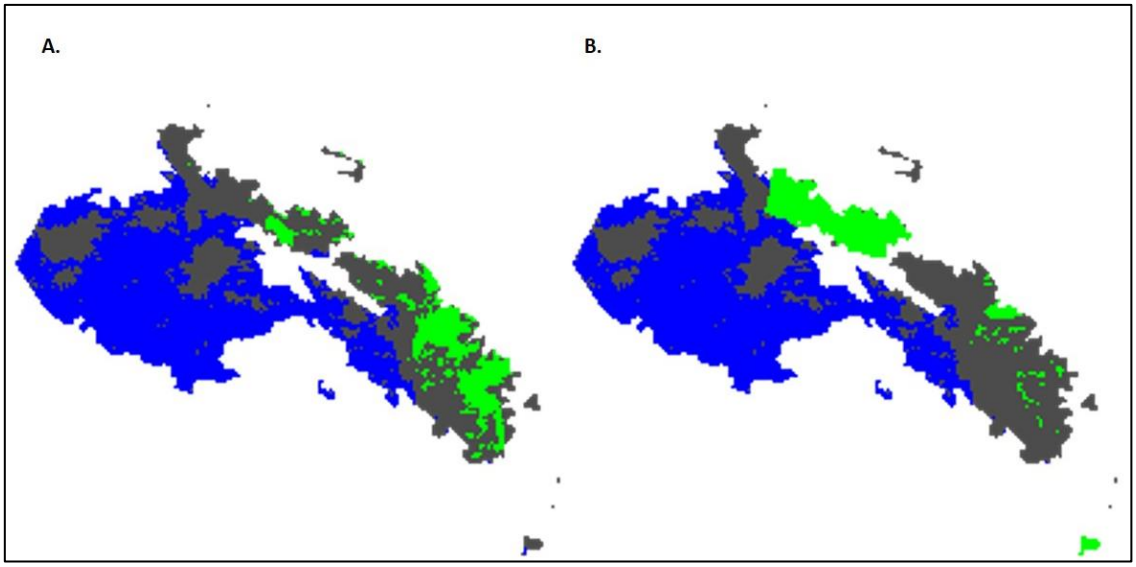


Figure 6.9. Priority conservation ranking maps using equal weight for all species, A. excluding the existing protected areas, B. including the three existing protected area within Eastern Hajar Mountains; i.e. green: top 10% priority areas, grey: top 50%.

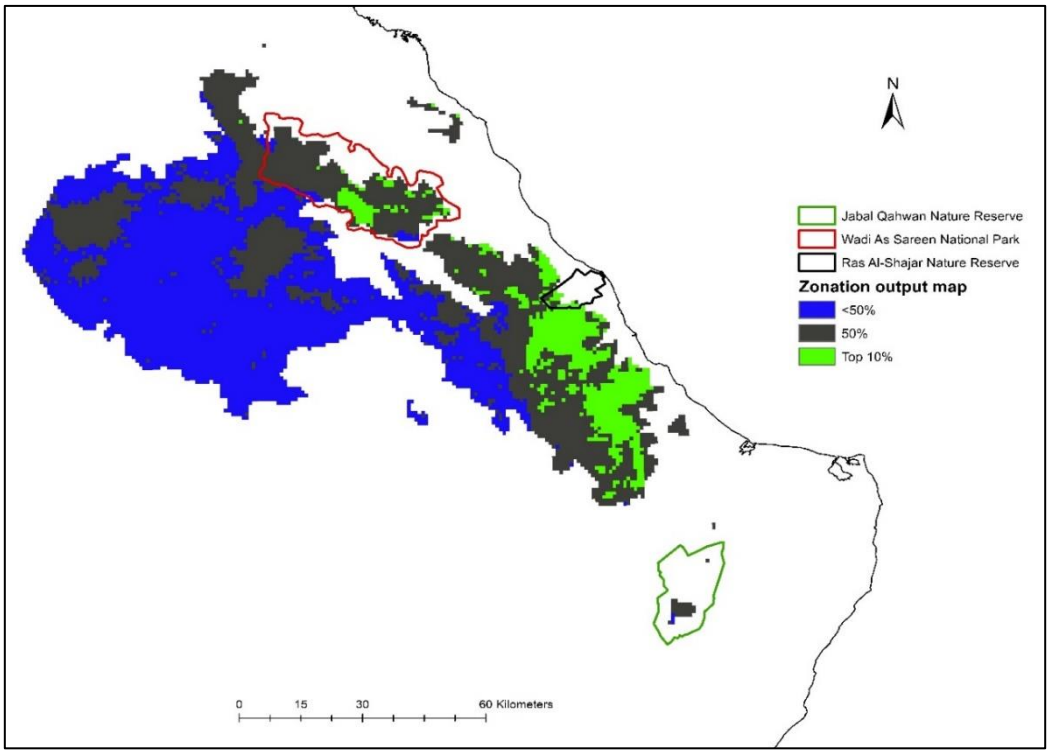


Figure 6.10. The Zonation output map for the high priority conservation areas over the three protected areas in the Eastern Hajar Mountains.

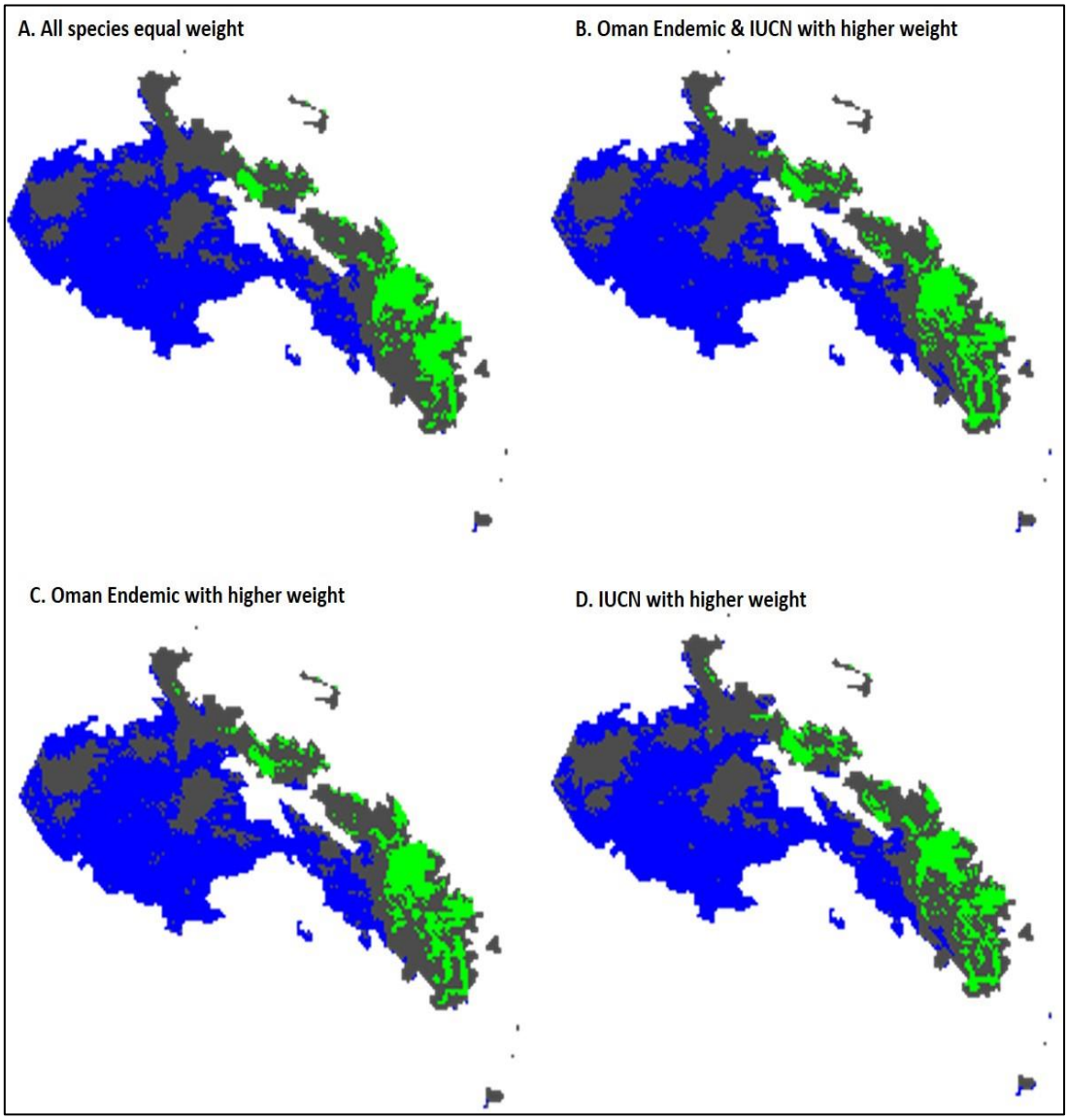


Figure 6.11. Priority conservation maps showing the top 10% (green), and top 50% (grey) priority areas identified by Zonation in the Eastern Hajar Mountains, Oman.

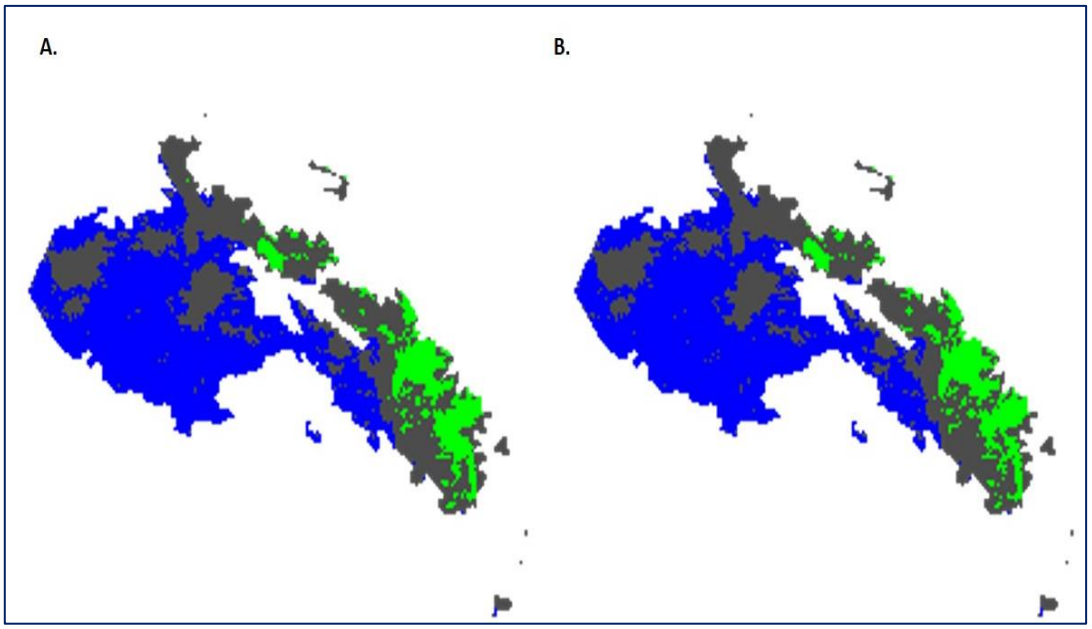


Figure 6.12. Priority conservation maps showing the top 10% (green), and top 50% (grey), A. with including the range- restricted species, and B) excluding the range- restricted species in the Eastern Hajar Mountains, Oman

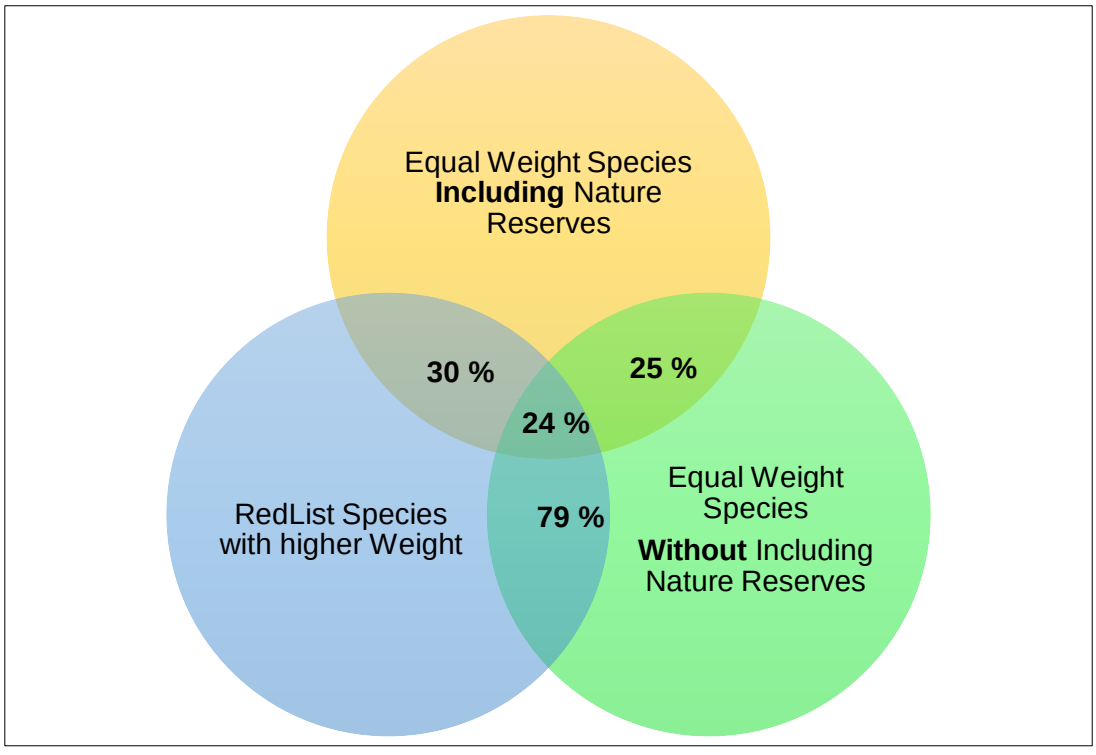


Figure 6.13. The percentage overlap between the three prioritisation scenarios used in the Zonation analysis; orange shading represents the Zonation analysis which gives equal weight for species including the nature reserves in the area, green shading represents the Zonation analysis which also gives equal weight for species but excluding the nature reserves and blue shading represents the Zonation analysis which gives higher weight for the red-list species and equal weight for the rest species.

CHAPTER 7

CONSERVATION ASSESSMENT AND PRIORITISATION USING IMPORTANT PLANT AREAS: EASTERN HAJAR MOUNTAINS, OMAN

7 CHAPTER 7: CONSERVATION ASSESSMENT AND PRIORITISATION USING IMPORTANT PLANT AREAS: EASTERN HAJAR MOUNTAINS, OMAN

7.1 ABSTRACT

Protection of 70% of the most important areas for plant diversity by 2020 is the goal of the Global Strategy for Plant Conservation (GSPC); these areas are identified according to common criteria, representing the most important sites for plant diversity. This chapter designates the Eastern Hajar Mountains as an important plant area (IPA) in the Arabian Peninsula using the newly revised IPA criteria, which also allowed for identifying sites as KBAs through the application of the new thresholds.

I compared the results of the IPAs (a criteria-based selection approach) for the identification of the important plant areas with those of a complementarity-based approach to assess the compatibility of the IPA as an approach to conserve the prioritised area and the possibility of integrating both approaches. The results were compared in terms of plant richness and area cover. The average area overlap between the two approaches was about 85%. The proposed area selected by the combined IPAs with the top 50% of that proposed by the complementarity approach was almost identical, with the same potential for species richness to be conserved. On a national scale, the inclusion of the complementarity-based approach in the IPAs selection process may help in locating the most critical areas for plants.

7.2 INTRODUCTION

7.2.1 Oman new spatial, strategic plan

The Oman national spatial strategy (ONSS) is in the process of being developed for the whole country. This strategy is the first in the country's history and will provide a comprehensive spatial framework for directing, organising and implementing urban and rural development in Oman for the next 20 years. It will be developed in close collaboration with all kinds of private and governmental stakeholders, and the first step will be to collect all types of information related to social, economic and land use on extensive data. For the plant data, the IUCN Arabian plant specialist group (APSG), which was initiated in response to the global strategy for plant conservation (GSPC) has been asked to collaborate with Oman botanic garden (OBG) to prepare a map of Important plant areas (IPAs) for the whole country so that it can be used as a part of the ONSS development. This is a critical time to be involved and be part of this process, as the country is suffering from poor coordination of planning between authorities: the involvement of plant diversity experts is usually minimal and always provided far too late in the process. Providing correct and accurate plant data will be of great value at this critical time of planning.

It is crucial to ensure plant priority sites are included in national strategic plans. Therefore, the identification of IPAs for the Eastern Hajar Mountains will provide a basis for conservation activities and future research on plants and site prioritisation in Oman. In Oman and many other countries, protected areas have been, to date, selected on an *ad-hoc* basis, and are often based on charismatic megafauna, without detailed investigation of all biodiversity (Pressey, 1994, Pressey, 1999, Margules et al., 2002, Mills et al., 2012). The identification of IPAs can assist and improve the coverage of important biodiversity within the existing protected areas, propose new areas for protection and assist with the prioritisation and placement of other conservation activities.

7.2.2 Spatial conservation prioritisation

Numerous approaches are available for selecting priority sites for conservation, most of which can be categorised as either the scoring/criteria-based or complementarity-based (Moilanen et al., 2009b, Lehtomäki and Moilanen, 2013). A set of selection criteria are used to identify priority sites in the scoring-based approach (Gaston et al., 2001, Abellán et al., 2005). Important plant areas (IPAs) (Anderson, 2002b), Important bird areas (IBAs) (Heath et al., 2000), hotspots (Myers et al., 2000) and key biodiversity areas (KBA) (Eken et al., 2004) are the best-known examples of this approach. A scoring-based methodology is usually used for identifying important sites for a single taxon, although the complementarity approach can also be used. Prioritising sites for multiple taxa is usually done using complementarity-based approaches through an optimisation process (i.e. systematic conservation planning, SCP) (Margules and Pressey, 2000, Cowling et al., 2003). A complementarity-based approach (Zonation) has been carried out in the previous chapter (Chapter 6).

7.2.2.1 Important Plant Areas (IPAs)

The IPA program was developed by Plantlife International in the early 2000s in response to the Global Strategy for Plant Conservation (GSPC) (Plantlife International, 2004). The IPA methodology has been used extensively across Europe, North Africa and the Middle East.

The lack of knowledge in the species and habitat data, in many regions outside Europe, has led to development of a modified set of the original IPA criteria, which are suitable for regional use; however the formal IPA criteria was never altered (Al-Abbasi et al., 2010, Radford et al., 2011). Recent advances in knowledge, the significant effort in Red Listing, and the huge experience gained from

implementation of the IPA criteria in many regions have led to the development of a revised set of IPA criteria that are globally applicable (Darbyshire et al., 2017b).

Plantlife International (2004) define IPAs as "*natural or seminatural sites exhibiting exceptional botanical richness and/or supporting an outstanding assemblage of rare, threatened and/or endemic plant species and/or vegetation of high botanic value*." Identifying and protecting the most important sites for plant diversity is the ultimate aim of the important plant area (IPA) program, a component for the framework of the UN Convention on Biological Diversity (CBD) and the Global Strategy for Plant Conservation (GSPC) (Anderson, 2002b). Target 5 of the GSPC stated, ''At least 75% of the most important areas for plant diversity of each ecological region is protected with effective management in place for conserving plants and their genetic diversity by the year 2020," referring directly to the identification of IPAs in delivering this target (CBD, 2012).

IPAs can be identified according to common criteria, based on the presence of threatened species, botanical richness and threatened habitats. The site should meet one or more of the IPA criteria to qualify as an IPA (Appendix 7.1). The number, size and range of an IPA are decided at a national level according to the restrictions of the existing criteria and knowledge, resources and experience of national IPA groups within each country. Two main stages are followed in identifying an IPA: first, identify all potential IPAs within a country and, then, select the most important sites, taking into account that they have an effective network of sites. IPAs do not imply any legal status of the areas identified and are considered as a conservation tool that helps deliver plant data to more extensive conservation schemes, which can then be used in conservation advocacy, planning and legislation.

The three main criteria used to categorise sites as IPAs are as follows: criterion A, the presence of threatened species; B, unusual species-richness and C, the presence of threatened habitats (Appendix 7.1). The new criteria are now aligned with the KBA global criteria to facilitate the alignment of areas chosen using the two approaches (Darbyshire et al., 2017a). A site is qualified as an IPA if it satisfies even one of the three criteria and meets an associated threshold (thresholds are normally quantitative, e.g. site known, thought or inferred to contain ≥ 1% of the global population, for criteria Ai).

The main aim of the sub-criteria under criterion A is to capture species that have been nationally (Ai), or regionally A(ii) assessed as globally threatened under the IUCN red list. Sub-criteria A(iii) and A(iv) entail the highly restricted (HRE) and range-restricted endemics (RRE), which have formally not been assessed under the IUCN red list criteria and are likely to be threatened (Darbyshire et al., 2017a).

Sites with exceptional plant richness are captured under criterion B and assessed under three sub-criteria (Appendix 7.1). A high number of species within a defined habitat are considered under sub-criterion B(i) and sites with an exceptional number of high conservation value species under criteria B(ii). The newly added sub-criterion B(iii) is intended to capture sites with cultural, social and economic importance for people. While criteria B is applied to sites with exceptional species richness regardless of the threats, criterion C aims to capture threatened habitats and can also be assessed against the three sub-criteria (C(i): globally threatened, C(ii): regionally threatened and C(iii): nationally threatened habitats).

Applying criterion C in Oman will be difficult at this stage of analysis as there is no complete threatened habitat classification map for Oman or the Arabian Peninsula. A document is being prepared by plant specialists from the Centre for Middle Eastern Plants (CMEP) and OBG; which is considered as the first document to

classify and map Oman vegetation habitats and their threats based on their extensive field experience and knowledge accumulated through the last 20 years. Further detailed analysis will be required to finalise and populate this vegetation map in order to be used in conservation assessment and planning. Also, the recent work to classify the vegetation of the Eastern Hajar Mountains into plant communities has contributed to the description of plant habitats and thus the IPA assessment procedures (Al Harthy and Grenyer, 2019). Therefore, approximate applications of criteria B and C were carried out in this analysis.

The IPA approach has been used to prioritise sites for conservation in Europe, Africa and the Middle East. Many countries have incorporated the IPA approach into their conservation planning and proved it to be a successful approach (Darbyshire et al., 2017b, Plantlife International, 2018). For example, there are many ongoing conservation and management projects of IPAs in countries such as Turkey, Romania and Macedonia. Also, the Plantlife conservation programs of the rare and threatened species in the UK are based on the IPAs. In the South and East Mediterranean, after the first identification of the IPAs, species and habitat monitoring, management plans were developed (Radford and Odé, 2009, Plantlife International, 2018).

IPAs provide a useful tool for identifying gaps in the existing national protected area programs and help conserve planning due to their international significance for plant diversity (Radford et al., 2011). National IPAs also contribute to the delineation of key biodiversity areas (KBAs), a separate but conceptually related initiative that aims to contribute to conserving global biodiversity (Eken et al., 2004). The new main aim of the KBA approach is to bring different site identification approaches under a single standardised approach (IUCN, 2016). The revised IPA criteria will help identify sites as key biodiversity areas (KBA) using the modified associated

thresholds (see Darbyshire et al., 2017), which are based on the original IPA criteria (Anderson, 2002b). Also, the new IPA criteria take into account socio-economically and culturally important plants to facilitate long-term conservation through sustainable use, with the involvement of the local communities living in these areas. Site identification as IPA/KBA merely implies that the site should be managed in ways that ensure the persistence of biodiversity.

The aims of this analysis are to identify the IPAs in the Eastern Hajar Mountains using the newly revised criteria (which can also be defined as KBA with the new IPA criteria). The IPA approach selected in this study is compatible with the government's approach towards identifying the important biodiversity areas for the country. This does not imply that the IPA approach is the best or the only suitable approach for identifying areas of importance for plant diversity using the newly available data. This study adopted a complementarity-based approach (i.e. Zonation) for the same set of species and study area (presented as Chapter 6). Therefore, the priority site selection was carried out using two different types of data. These are the actual collected occurrence points, and the SDMs produced from the previous chapter.

Using the SDMs as a basis for selecting IPAs in the Eastern Hajar Mountains will create new knowledge, for the country, on how robust is the SDMs in prioritising areas for conservation. Although the collected occurrence points are the gold standard in species location, they only represent and cover part of the entire species ranges, additionally, the herbarium data record only the presence of species and do not reflect true absence. Due to these shortfalls plus the bias in species data collection (see below), IPA delineation using the occurrence data will eventually produce IPAs that are also biased towards data-rich areas and missing potential areas within species ranges. Using accurate SDMs will help to address this lack of

data, and ultimately, producing more reliable priority areas. The priority sites that were produced by the complementary-based approach were, then, compared with the areas identified by the IPA approach to check the compatibility of the IPA approach and the possibility to be integrated within the complementary-based approach.

7.3 METHODOLOGY

7.3.1 Study area

This study was carried out in the Eastern Hajar Mountains on an elevational range from 500m to the highest point in the mountains at about 2200m. More details about the study area can be found in chapters 1 and 2 of this thesis.

7.3.2 Species data

The primary species data used in the analysis included the data collected from the recent study carried out in the Eastern Hajar Mountains as a part of a more extensive study to classify and describe the vegetation of the mountains (Chapter 4) (Al Harthy and Grenyer, 2019). In this study, a total of 110 vegetation plots were randomly selected to cover the elevation of and above 1000 m in the entire Eastern Hajar Mountain range (i.e. an area of about 1900km^2) and to represent the highest possible variation in habitats (wadi, plateau and slope). Within each plot, a species list of perennials and annuals/biennials were recorded. Also, environmental variables such as elevation, aspect, slope and soil characteristics were measured for each plot in the study area. Unidentified species were collected for identification at the Oman botanic garden (OBG) and herbarium vouchers housed in the OBG herbarium.

Plant species data were also extracted from other published and unpublished sources, which included the data from a survey that was carried out by the Centre

for Middle Eastern Plants (CMEP) at the Royal Botanic Garden Edinburgh (RBGE) for the construction of an atlas for the mountains of Oman in 2014 (Miller and Knees, 2014). The ongoing expedition, exploration and documentation by the OBG researchers have also contributed to the species list used here through their field and herbarium databases. The species data were similarly extracted from the national herbarium (NOH) and Sultan Qaboos University herbarium (SQUH) and used in this study. The data extracted from herbarium databases were revised and verified for consistent quality with field sampling data.

The Oman plant red data book was used as the main source to evaluate species' endemism and rarity for the identification of IPA (Patzelt, 2014). IUCN 2001 red list categories were used in the species assessment on a national level in the Oman red data book (Gärdenfors et al., 2001), except for the endemic, near-endemic and regionally endemic species, which were globally assessed (IUCN, 2016).

7.3.3 Flora and vegetation analysis

Available species data (collected from different sources) were aggregated to publish the first plant species checklist for the Eastern Hajar Mountains (Appendix 7.2). The full list was compiled using the data collected from this current research, the three main herbaria in the country, OBG database (in addition to the list provided by Dr Annette Patzelt, the OBG scientific director) and RBGE database. The species then was verified by Annette Patzelt and me. Vegetation descriptions and classifications were carried out as a separate study and presented in a previous separate chapter (Chapter 4). A brief description of the flora and the main plant communities of the mountains will be presented here.

7.3.4 IPA/KBA assessments

A total of 2500 species occurrence points were gathered from three herbaria and this current study to be used in the IPA assessment (Figure 7.1). The data collected

from the three herbaria contributed to only about 14% of the data analysed, although the total primary species occurrences data gathered from the herbaria databases amounted to about 5000 points, half of which were omitted due to, for example, the wrong identification of or missing geographical coordination.

In this assessment, the newly revised 2017 IPA criteria were applied, a first for the Arabian Peninsula or the Middle East (Appendix 7.1, revised criteria by Darbyshire, 2017). The species occurrence data were and are still being used in all the IPA assessments with considerable involvement from regional plant experts. In this analysis and, for the first time, I used the predicted distribution maps from SDM, which were presented previously in Chapter 6, for the application of the new IPA criteria, in addition to the commonly used occurrence data. The predicted SDMs used in the analysis have a high predicted performance with an AUC threshold of ≥ 0.7 (details in Chapter 6). This study used SDMs for IPA assessment to examine if there is a difference in the areas assigned for conservation between the two types of data.

7.3.4.1 Criterion A

For the application of IPA's criterion A, with its associated thresholds, I used the red list species assessment in the red data book of Oman, which was also updated during a recent workshop (Patzelt, 2014). A list of all the range-restricted, rare and threatened species recorded in the Eastern Hajar Mountains is included in Table 7.1. For the sub-criterion A(i) evaluation, I extracted species recorded as globally threatened under IUCN red listing. Then, I assessed each of the vegetation plot, used for the vegetation classification study, against the presence of these globally threatened species (i.e. species with NT, EN, VU and CR IUCN red list criteria). For the sub-criterion A(ii), the regionally threatened species, I used all the species with a conservation status of LC in the IUCN red list and then assessed their presence in

each plot. Endemic and near-endemic species with data deficient (DD) IUCN red list status are assessed under IPA criteria A(iii) (i.e. HRE) and A(iv) (i.e. RRE), respectively. There were no DD species in the Eastern Hajar and thus no IPAs identified under criteria A(iii) or A(iv).

As there are no rules regarding the size and shape of the boundary of the identified IPAs, I manually drew a convex polygon around the maximal extent of the union of the species distributions meeting each of the assessed IPA criteria. I did this separately for the occurrence data and SDMs. These polygons were then used as the basis to identify the approximate locations for the IPAs produced by both methods.

7.3.4.2 Criterion B

Criterion B measures the species richness within a defined habitat or vegetation type (Table 7.3, revised criteria). There is no formal habitat classification for the entire range of the Eastern Hajar Mountains. Therefore, I used the plant communities identified earlier in the current study (Chapter 4) to support the application of criterion B so that each of the four communities will represent a separate, empirical vegetation type. I used the union of the ranges of the indicator species for each community to identify the boundary of each. Also, to support the application of the sub-criteria, the species richness map for the complete species of the Eastern Hajar and the richness map of the red list species (Figure 6.6) were used to calculate the species richness in each of the defined plant communities (for richness map, refer to Chapter 6).

I calculated the number of species out of the total number of species within each of the plant communities to examine if the whole community qualifies under criterion B(i). Also, I calculated the number of the red list species out of the total in each community to assess the qualification of the community under criterion B(ii). The

community should have up to 10% of the mountains' flora to qualify under B(i) and ≥ 3% of species of high conservation value (i.e. red list species) under criteria B(ii). I did not assess the species under sub-criterion B (iii) (culturally and economically important species) due to the lack in this kind of documentation for the whole country. Nevertheless, many of these species fall under the other two sub-criteria of criterion B. As I mentioned earlier, criterion C (threatened habitat) cannot be used due to the absence of formal habitat assessments in the country; therefore, it has not been carried out in this analysis.

The delineation of the IPA boundaries was carried out using the ArcGIS software (ArcMap 10.5.1). A map for each of the IPA criteria was produced using the species occurrence data and the SDMs. The area of each of the IPAs was measured in relation to the total study area.

7.3.5 Alignment of the IPA with KBA

As this is the first analysis in the Arabian Peninsula, applying the newly proposed IPA criteria, the alignment of the revised IPA criteria with the KBA ones was briefly discussed to examine how this will apply to the Eastern Hajar Mountains. The proposed IPAs will be examined to assess if they qualify as a KBA area.

7.3.6 Comparison between IPA and Zonation

Focusing on the suitability of criteria-based approaches, such as the IPA as a source for spatial conservation planning in the Eastern Hajar Mountains, the proposed IPAs were compared with the complementarity-based approach, Zonation, which has been presented in Chapter 6 in this thesis. Since an IPA can be defined on a single criterion, the individual areas identified by each of the proposed IPAs (polygons) were intersected with the Zonation output map on a range from the top 5% to the top 100% in five increments to identify areas that satisfied both the approaches. Also, I combined eight IPAs into one and then overlapped that with the

conservation targets to examine the differences between them and the areas identified by Zonation. The area covered by each of the ten specified conservation targets (5–100%) was also calculated. The analysis was carried out using the ArcGIS software (i.e. ArcMap 10.5.1).

7.4 RESULTS

7.4.1 Flora and vegetation

A total of 433 species were recorded from the entire elevational range, representing 31% of the total flora of the country (i.e. covering about 5% of the total country area) (Appendix 7.2, the checklist) (Miller and Knees, 2014, Patzelt, 2015c, Al Harthy et al., in review). The species names follow the latest updates in the Plants of the World online database that was published by Kew Gardens in 2015 (Plants of the World Online, 2019). The species list is the first completely compiled and documented checklist for the Eastern Hajar Mountains. The number of species is likely to increase with continued identification and verification of the current collections. The potential of discovering species new to science from the Eastern Hajar Mountains is still high, as observed from the current study, such as the possibility of a new *Salvia* species record (verification in progress, Al Harthy, in prep.). Twenty-eight of the species found in the Eastern Hajar were identified as range-restricted, ten as national endemics, five near-endemic and thirteen regional endemics in addition to eight rare and threatened species (Patzelt, 2014, Patzelt, 2015c).

The habitat of the Eastern Hajar ranges from well-vegetated wet wadi systems to sparsely vegetated drier rocky slopes and a desert steppe at higher elevations. Four plant communities were identified above 1000 m elevation (details in Chapter 4). In addition to the detailed classification of the plant communities above 1000 m (i.e.

from this study, Chapter 4), a description of the plant communities below 1000m was extracted from Patzelt (2015c), to provide a general overview of the mountains' vegetation. A list of the plant communities is provided in Table 7.2.

7.4.2 IPA identification

7.4.2.1 Criteria A

Six species, in the Eastern Hajar, met sub-criterion A(i) (Table 7.3), three of which were recorded inside the studied plots and the rest from other species data, but still used in the assessment. Between this and the occurrences data, I would suggest an IPA that covers the distribution range of the species that met criterion A(i) (Table 7.3; Figure 7.2). Although I have suggested only one large polygon for the IPA using the occurrence data, this can be split into two or more areas depending on the final number of IPAs proposed for the Eastern Hajar Mountains. I have identified five IPA areas using the SDMs that meet criterion A(i). Two of these areas were almost identified in the same location of the occurrence data IPA while the other three in a completely different location, on a lower elevation that covers an elevational range from 500 m to about 1400m (Figure 7.2).

I recorded twenty-two species to assess sites in the study area under sub-criterion A(ii). Using the occurrence data, I found that the area identified as an IPA covers almost the same location as the IPA identified under criterion A(i). When I used the SDMs for assessing sites under this criterion, I identified two IPAs that also nearly represent the same location as the occurrence data IPA (Figure 7.3).

7.4.2.2 Criterion B

For sub-criteria B(i) and B(ii), I used the four plant communities identified in Chapter 4 to define the vegetation type, which is required for assessing the sites under these criteria. Using the occurrence point data, all four plant communities met both

criterion B(i) and criterion B(ii). Therefore, I was able to identify four IPAs that cover the same area as the plant communities (Figure 7.4). Using the SDMs to define the vegetation types (or the plant communities), I identified more areas than the original plant communities, as the predicted distribution of the indicator species covered a wider range of the mountains. I identified seven IPAs based on criterion B(i) and the same areas under sub-criterion B(ii) (Figure 7.4). As mentioned earlier, I was able to identify more sites that qualify to be a potential IPA using the SDM-based selection.

The maps presented in figures 7.2–7.4 show that the number of IPAs suggested using SDMs is always higher than the number of those proposed using the occurrence data. The number of the IPAs produced or proposed using the occurrence data ranged from one to four IPAs while between 2–7 IPAs using SDM maps.

Overall, a total of eight IPAs were proposed for the Eastern Hajar Mountains (Figure 7.5), four of which (i.e. IPA 3, 4, 5 and 6) were identified based only the SDMs under both criteria A and B; the rest was a combination of the SDM and the occurrence data.

7.4.3 Alignment of the IPA with KBA

Sites are labelled as KBAs if the species in the area meet either the vulnerability or irreplaceability criteria (criterion A). Six species triggered the identification of the sites as KBA under criteria A (i.e. KBA vulnerability criterion) (Table 7.3). For example, *Campylanthus hajarensis*, *Dionysia mira, Lindenbergia arabica, Schweinfurthia imbricata, Desmidorchis arabica* and *Ceratonia oreothauma* are six globally threatened species that triggered the identification of the Eastern Hajar Mountains as an IPA under criterion A(i) and as a KBA. These species triggered the KBA criterion A upon aligning them on regionally-based KBA criteria. Table 7.3 shows the detailed alignment of the IPA's newly revised criteria on the Eastern Hajar

Mountains with the KBA criteria. With the revised IPA criteria from 2017, individual IPAs will automatically meet the threshold to become KBAs.

7.4.4 IPAs and Zonation

The eight proposed IPAs cover a total of about 5838km^2, comprising approximately 59% of the mountains area above 500m and about 1.9% of Oman's total area (Figure 3). IPAs 1 and 2 represent the largest areas among the eight IPAs with an area of 1232 km^2 and 1985 km^2 , respectively (Table 7.4). When overlapping the area identified by each of the eight IPAs with different conservation targets from Zonation, it is clear that as the conservation target for the overall study area protection increased, its inclusion within the IPA decreased (Figure 7.6). The example map in Figure 7.7 represents a negative relationship between the conservation target and the amount of this target inside each of the proposed IPAs. If we take IPA2, as an example, the area of each of the conservation target included within this IPA decreased from about 78% at 5% conservation target to about 25% at 100% conservation target. This relationship means that if we increase the conservation target for the whole study area, the representation of this target inside any of the eight IPAs decreased, Figure 7.8 is included for more explanation of the relationship between the conservation targets and the IPAs (same concept as Figure 7.6).

Each of the eight proposed IPAs represents a minimum of 10% (out of the total richness) of species richness in the study area, as defined using sub-criterion B(i) (Appendix 7.1 for Details of criteria thresholds), with no consideration of the area of the IPA. For example, IPA2 with an area of 20% (largest proposed IPA) of the total study area and IPA7 with only 5% of the total study area, represent about 87% and 18%, of the total plant richness, respectively, and the number will vary according to each of the IPAs proposed. Combining the eight IPAs, which represent about 50%

of the study area, will allow for 96% plant richness conservation. Unexpectedly, conservation of the same percentage of richness (96%) using Zonation will require protection of 50% of the study area (the same total area of the combined IPAs). A minimum of 50% of species richness is retained with 10% area protection using Zonation.

Examining the location of this area and how it is overlapped with the area identified when protecting 50% of the area using Zonation approach revealed an almost identical location of the top high conservation areas (Figure 7.8). The area for the combined IPAs included within each of the conservation targets ranged from 98% overlap at 5% of Zonation conservation targets, with divergence down to 60% overlap when 100%, respectively, (Figure 7.9).

The average overlap between the two approaches, using the combined IPA, on the top 50% and bottom 50% was 90% and 70%, respectively, with an average overlap of about 85% (Figure 7.10). The locations of the selected areas using both the approaches were almost identical on the top 50% protection. Both approaches identified the mid- and high-elevation mountain ranges as the top priority sites. These elevational ranges are known to have the highest plant richness (Lomolino, 2001, Hrivnák et al., 2014, Ghafari et al., 2018).

7.5 DISCUSSION

7.5.1 Species data

The data I collected in the current study and the putative analysis of other published and unpublished data in addition to the expert-based botanical knowledge represents the best data available for this analysis in Oman. Collecting species data for this analysis (i.e. from the three national herbaria) revealed the scarce and uneven distribution of species data, which appeared to be clumped in areas such as

the high elevation of mountains, and areas that do not look promising or interesting for plant data collection by scientists. This observation highlighted the need for a full inventory of species and habitat data distribution to avoid a possible drawback in conservation planning and to be able to make the most of conservation tools.

Nevertheless, the species data collected during this study facilitated and contributed to the spatial prioritisation analysis using both the criteria-based approach and complementarity-based approach. This analysis highlighted the importance of data availability for better use of conservation tools and, eventually, robust conservation decisions.

The use of SDMs as the base for IPA selection revealed 3 IPAs that were not selected when using the species occurrence data (specifically, IPAs 3–6). IPAs 3, 4 and 5 are located, partly, in Al Dakhliya (Samil) and mainly in Al Sharqiya region (Dima Wa Al Taiyyin, Ibra, Al Mudhaiby and Jaalan Bani Bu Hassan). These areas were the ones that were highlighted as completely lacking species occurrence information (Figure 7.1). These areas also appeared in most of the SDMs and consequently in selecting the IPAs. Due to this result, the use of the SDM as a basis for the priority area selection proved to be a robust tool, that included all the potential locations of the species ranges which could be missing from using the occurrence data only. This result emphasises, again, the need for a species inventory in these highlighted areas for complete data in this part of the country. Extending this procedure of data analysis may help identify data-deficient areas if applied for the whole country, which will help direct the sampling efforts by institutes such as the Oman botanic garden and others towards those areas.

It should be noted that the identification of the IPAs, using Zonation, in the Eastern Hajar Mountains was the first attempt in the area and, completely, depended on species distribution models which have not yet been validated on independent data.

Therefore, cautious interpretation of applying Zonation to the predicted ranges should be undertaken, and in particular when advocating conservation action in areas which are largely comprised of extrapolated range data unsupported by primary specimen collection.

7.5.2 IPA/KBA identification

The newly revised IPA criteria and their associated thresholds allow the flow of the data between the different conservation schemes for selecting priority areas. Nevertheless, the amount of data and fieldwork required to accomplish these areas such as the Eastern Hajar Mountains and Oman is generally vast. In order to apply the new thresholds, data collection grounded on site-based inventories, species distribution mapping and global IUCN red list assessments will be required mainly for applying criteria A and B. Identification and classification of the vegetation habitat and the threats to these habitats is required for application of criteria C.

The KBA criteria require the application of a strictly global assessment, omitting national conservation priority sites that can be of a global significance for a particular species or habitat (Melovski et al., 2012). Therefore, there is a need for a holistic approach that is tailored for national plant assessment and prioritisation. The revised IPA criteria are flexible in the sense that they can be applied for both national and global scales with rich or sparse plant data and countries with variable plant diversity. The KBA approach requires more comprehensive plant data, including species distribution, population size, habitat types and threats measured for both species and habitats.

The revised IPA approach is a pragmatic yet sufficiently rigorous approach that does not require an abundant species and habitat data. The sites can be identified as IPAs by being among the ‘best or richest’ sites assessed under the revised criteria. For Oman, most of the KBA criteria cannot be applied due to the lack of distribution

maps for many species, although the presence of the red list data can improve this assessment. As Oman is currently developing its national spatial strategy plan, the identification of the IPAs under a national scale is crucial at this stage. Therefore, identifying sites as a KBA will not much affect the selection procedures at this time for Oman; however, this is possible with the new revised IPA criteria. Furthermore, the process of identifying IPAs for the whole country is of two stages: first, identifying all the potential IPAs and, second, selecting the most important sites as the authorised committee.

Consequently, using the newly revised IPAs criteria, any identified IPA will automatically become eligible to be designated as a KBA (i.e. a plant based KBA) if it meets the KBA thresholds. In this study, I have demonstrated that the application of the revised IPA criteria for the Eastern Hajar Mountains is possible but has some shortcomings. The availability of species distribution maps along with global IUCN red list assessments made the application of IPA criterion A possible; however, it was not possible to apply IPA criteria C due to the absence of habitat threat maps. Also, the IPA criteria account for alternative measures (i.e. national and regional) where a global IUCN red list assessment is absent. Otherwise, this information would be omitted using the KBA approach, as it does not allow for these alternatives.

Although the KBA approach defines globally significant sites for biodiversity, it does not delineate the actions that need to be taken for this diversity to persist or take into account the social and economic constraints usually associated with conservation planning (Game et al., 2013, Christopher et al., 2015, Clinton et al., 2015, Di Marco et al., 2016, IUCN, 2016). IPA is a powerful tool for plant conservation for sites that may become targets for conservation actions, particularly after the recent modification of the criteria and the inclusion of plants of social and economic

importance to people in the areas being assessed. Future research studies to define socially and economically important plants for the Eastern Hajar Mountains are recommended.

7.5.3 IPA and Zonation

The criteria-based approach (IPA) used for the prioritising areas of high conservation values generated consistent results when compared with the complementarity-based approach (Zonation), although the IPA procedures cannot, by nature, take into account complementarity. The complementarity-based approach provides more flexible results for area selection due to the flexibility in changing conservation targets according to the conservation requirements. Although the IPAs yielded good results and was able to identify the same area as the Zonation on the top 50% target; this was only possible if we combined all the proposed IPAs as one area, which make it harder for conservation planners to select between these areas. Also, using Zonation and with a minimum of 10% area protection, we will be able to protect 50% of the species richness, a result that will be challenging to acquire using the IPAs approach. The systematic prioritisation area selection (Zonation) approach entails the systematic collection of data, which is lacking in many areas within Oman, but confidently the results from this analysis will help to highlight and to encourage more systematic data collection.

The comparison between the threshold-based approach and the complementarity-based approach proved that the IPA approach could identify sites for plant diversity. For example, a site of low global importance (e.g. low irreplaceability) can still be identified as an IPA; such as the sites that were triggered by species with widespread distribution but regional scarcity. Also, the criterion-based approach can be efficient when identifying priority sites in conjunction with other sites. There have been major advancements in spatial prioritisation methodologies and also in the

availability of the plant data, although more work still needs to be done. Spatial prioritisation-based approaches can be used to set targets for a wide range of biodiversity features such as threatened species, range-restricted species and ecological integrity of areas.

In conclusion, the identification of priority sites for conservation using the IPA approach and/or the complementarity approach proved to be useful for identifying and prioritising a largely congruent set of conservation areas in the Eastern Hajar Mountains. The approach may be of use elsewhere in Oman, as combining the criteria-based approach with the complementarity-based one appears to be an effective tool. The emphasis in integrating these two approaches, where possible, rather than separating them will provide conservation planners and scientists with a different tool to achieve a conservation target. The comparison of these two approaches to defining IPAs on a national scale demonstrates that the inclusion of the systematic conservation approach in the IPA process may help complete the set of proposed IPAs and guide further investigations in selected areas based on sound scientific information.

Table 7.1. Range-restricted species from the Eastern Hajar Mountains and their global IUCN Red List status; category of threat are CR: Critically Endangered , EN: Endangered, VU: Vulnerable, NT: Near Threatened, LC: Least Concern.

Species	**IUCN Red List Assessment**
Oman Endemic taxa	
1. *Campylanthus hajarensis* Hjertson, Henrot & Thulin	EN
2. *Dionysia mira* (Jaub. & Spach) Wendelbo	EN
3. *Iphiona horrida* Boiss.	LC
4. *Launaea omanensis* N.Kilian	LC
5. *Polygala mascatensis* Boiss.	LC
6. *Pycnocycla prostrata* Hedge & Lamond	LC
7. *Searsia aucheri* (Boiss.) Moffett	LC
8. *Teucrium stocksianum* Boiss. subsp. *stenophyllum* R.A.King	LC
9. *Verbascum akhdarense* (Murb.) Hub.-Mor.	LC
10. *Ziziphus hajarensis* Duling, Ghaz. & Prend.	LC
Oman Near Endemic taxa: *species occur in one geographical entity, but in two countries*	
1. *Convolvulus ulicinus* Boiss.	LC
2. *Lavandula subnuda* Benth.	LC
3. *Lindenbergia arabica* (S.Moore) Hartl	NT
4. *Schweinfurthia imbricata* A.G.Mill., M.Short & D.A.Sutton	NT
5. *Verbascum omanense* Hub.-Mor.	LC
Regionally Endemic taxa: species *restricted to the Arabian Peninsula, occurring in at least two different countries and in more than one geographical entity*	
1. *Adenosciadium arabicum* H.Wolff	LC
2. *Desmidorchis arabica* (N.E.Br.) Meve & Liede	VU
3. *Ceratonia oreothauma* Hillc., G.P.Lewis & Verdc.	VU
4. *Dipcadi biflorum* Ghaz.	LC
5. *Echinops erinaceus* Kit Tan	LC
6. *Farsetia linearis* Decne. ex Boiss.	LC
7. *Halothamnus bottae* Jaub. & Spach	LC
8. *Herniaria maskatensis* Bornm.	LC
9. *Ochradenus arabicus* Chaudhary, Hillc. & A.G.Mill.	LC
10. *Ochradenus aucheri* Boiss. subsp. *aucheri* A.G.Mill.	LC
11. *Pteropyrum scoparium* Jaub. & Spach	LC
12. *Pulicaria glutinosa* Jaub. & Spach	LC

Species	IUCN Red List Assessment
13. *Zygophyllum qatarense* Hadidi	LC
Nationally Rare and Threatened taxa: species which are not range-restricted but are rare and threatened	
1. *Caudanthera edulis* (Edgew.) Meve & Liede	CR
2. *Balanites aegyptiaca* (L.) Delile	CR
3. *Cladium mariscus* (L.) Pohl	VU
4. *Epipactis veratrifolia* Boiss. & Hohen.	VU
5. *Maerua oblongifolia* (Forssk.) A.Rich	EN
6. *Pycnocycla aucheriana* Decne. ex Boiss.	VU
7. *Rydingia persica* (Burm.f.) Scheen & V.A.Albert.	EN
8. *Schoenus nigricans* L.	VU

Table 7.2. . plant communities recorded in the Eastern Hajar Mountains and their elevation range.

PLANT COMMUNITIES	Source
Colline and sub-montane zone: C*ommiphora wightii-Grewia erythraea* shrubland (100–500m)	Patzelt, 2015
Montane zone: transitional shrubland with *Searsia aucheri* (500–1200m)	Patzelt, 2015
Echiochilon persicum-H*elianthemum kahiricum* community (1000-1600m)	Al Harthy & Grenyer, 2019
Searsia aucheri -Acacia tortilis community (1000-1700m)	Al Harthy & Grenyer, 2019
Prunus arabica- C*eratonia oreothauma* community (1200-2000m)	Al Harthy & Grenyer, 2019
Ebenus stellata-C*onvolvulus ulicinus* community (1500-2197m)	Al Harthy & Grenyer, 2019

Table 7.3. Revised IPAs criteria assessment for the Eastern Hajar Mountains with their alignment with the global KBAs criteria (using the combined IPAs).

Revised criteria	**Alignment with KBA criteria**	
A: THREATENED SPECIES		
A (I) **SITE CONTAINS ONE OR MORE GLOBALLY THREATENED SPECIES**	**A1**	• Site contains> 1% of the global distribution of *Dionysia mira* • Site contains> 1% of the global distribution of *Campylanthus hajarensis* • Site contains> 1% of the global distribution of *Lindenbergia arabica* • Site contains> 1% of the global distribution of *Schweinfurthia imbricata* • Site contains> 1% of the global distribution of *Desmidorchis arabica* • Site contains> 1% of the global distribution of *Ceratonia oreothauma*
A (II) **SITE CONTAINS ONE OR MORE REGIONALLY THREATENED SPECIES**	**A1** potential match with national/ regional KBA criteria	• Site contains > 1% of the global distribution of 22 species that are recorded in the Red Data book of Oman under LC conservation status (check table 1)
(B) BOTANICAL RICHNESS		
B(I) SITE CONTAINS A HIGH NUMBER OF SPECIES WITHIN A DEFINED HABITAT OR VEGETATION TYPES	**B3** only provides key data for global KBA assessment	• Sites contain unique communities which have a mixture of Irano-Turanian floristic elements (e.g. *Prunus arabicus* and *Dionysia mira*) and African Palaeotropical floristic elements: example of the relict *Ceratonia oreothauma* and *Acacia gerardii* (i.e. Xeromorphic, montane steppe-woodland)
B(II) SITE CONTAINS AN EXCEPTIONAL NUMBER OF SPECIES OF HIGH CONSERVATION IMPORTANCE	**B2** only provides key data for global KBA assessment	• Site contains> 3% of the national endemic species: *Iphiona horrida, Launaea omanensis, Polygala maskatensis, Pycnocycla prostrata, Searsia aucheri, Teucrium stocksianum* subsp. *Stenophyllum, Verbascum akhdarense, Ziziphus hajarensis.* • Site contain > 3% of the regional endemic species: *Convolvulus ulicinus, Lindenbergia arabica, Schweinfurthia imbricata, Verbascum omanense, Adenosciadium arabicum, Cleome austroarabica* subsp. *Muscatensis, Dipcadi biflorum, Echinops erinaceus,*

Revised criteria	Alignment with KBA criteria	
		Echiochilon callianthum, Farsetia linearis, Ochradenus arabicus, Ochradenus aucheri, Pteropyrum scoparium, Pulicaria glutinosa. • Site contains> 3% of the rare and threatened species: *Caralluma mouretii, Balanites aegyptiaca, Cladium mariscus, Epipactis veratrifolia, Maerua oblongifolia, Pycnocycla aucheriana,* Rydingia persica, *Schoenus nigricans.*

Table 7.4. Area of each of the eight IPAs proposed for the Eastern Hajar Mountains.

IPAS	AREA (KM2)	% IPA AREA OF THE TOTAL STUDY SITE
IPA 1	1232	12
IPA 2	1985	20
IPA 3	232	2
IPA 4	633	6
IPA 5	758	8
IPA 6	87	1
IPA 7	536	5
IPA 8	375	4

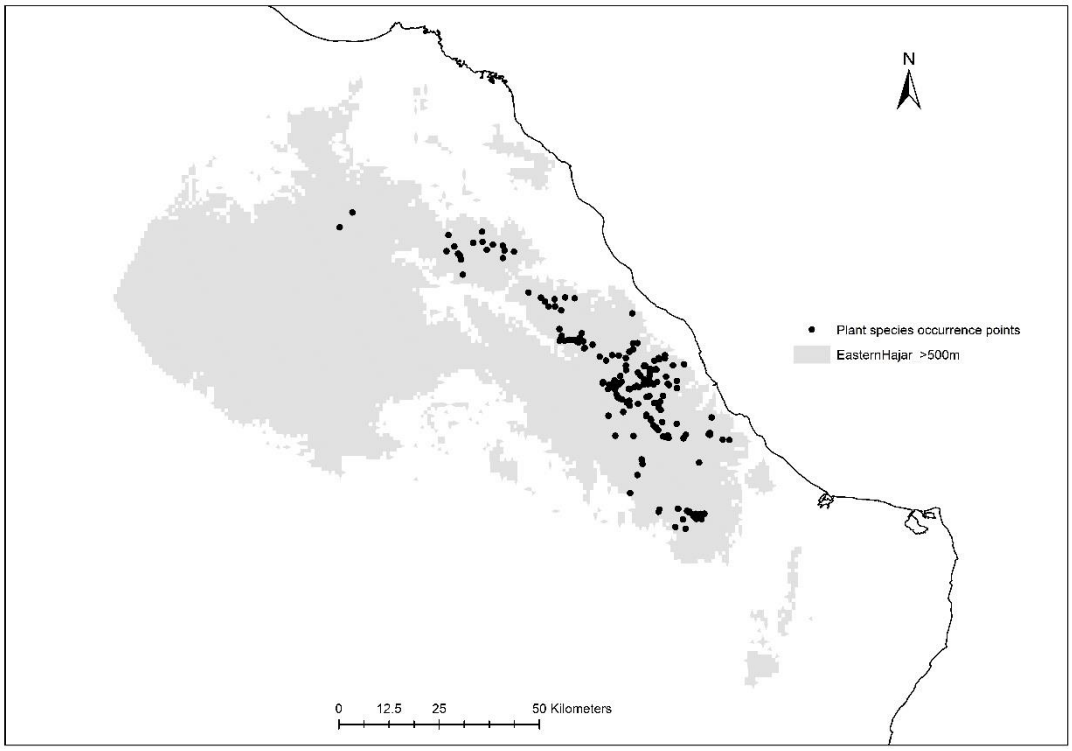


Figure 7.1. Plant species occurrences above 500m in the Eastern Hajar Mountains, Oman, representing data collected from the three herbaria in the country and the newly collected data from the current study.

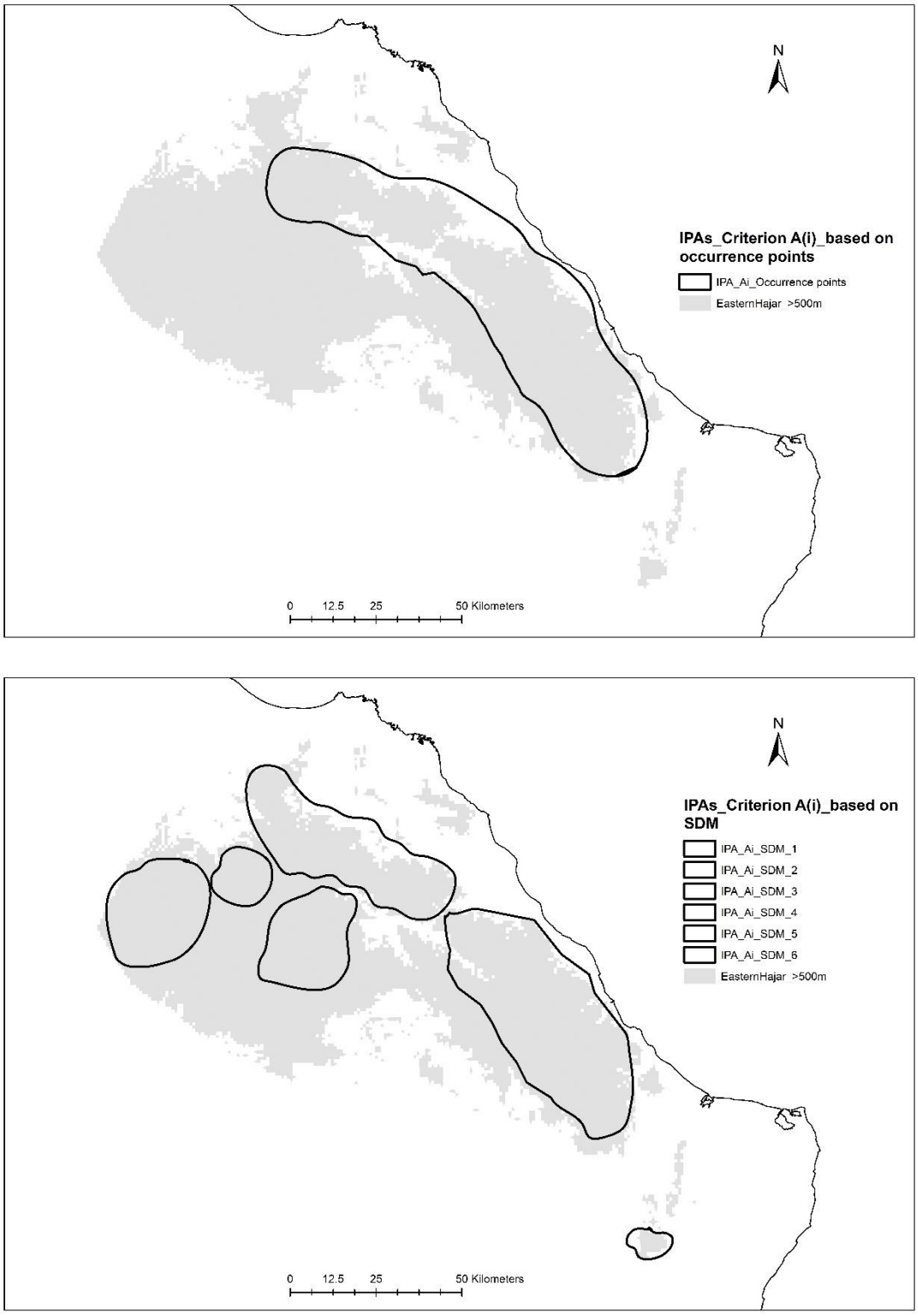
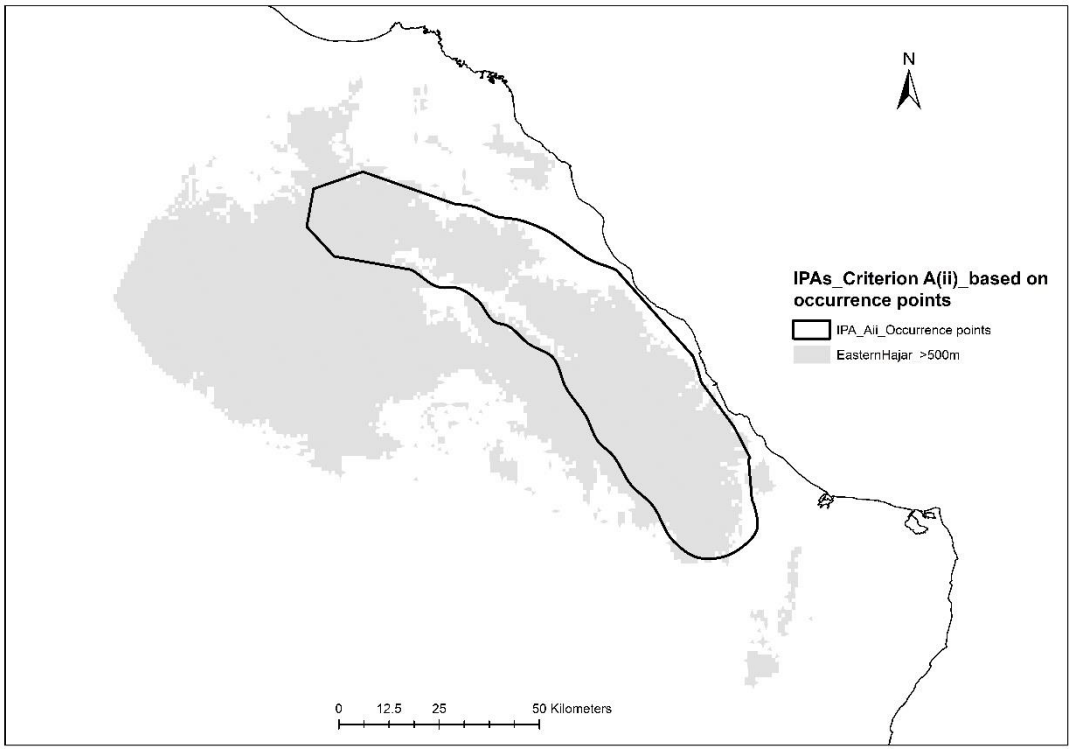


Figure 7.2. Newly revised IPA criteria assessment using both the occurrence data (top) and SDMs data (bottom) for the Eastern Hajar Mountains in Oman; sub-criterion A (i).



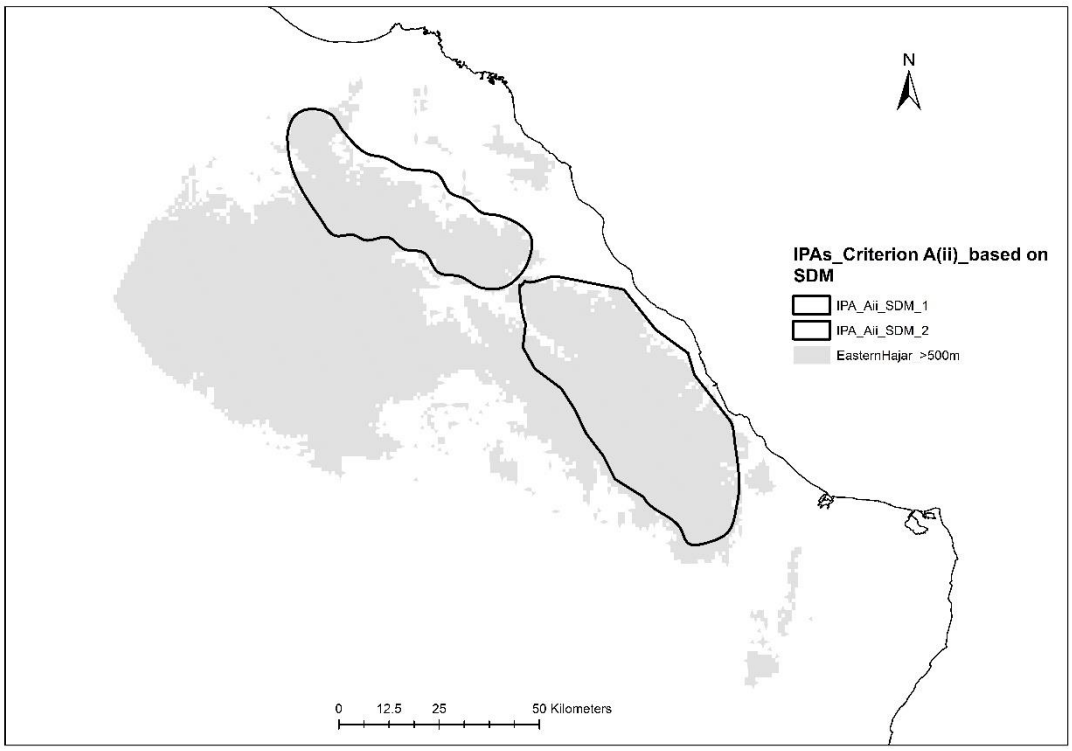


Figure 7.3. Newly revised IPA criteria assessment using both the occurrence data (top) and SDMs data (bottom) for the Eastern Hajar Mountains in Oman; sub-criterion A (ii).

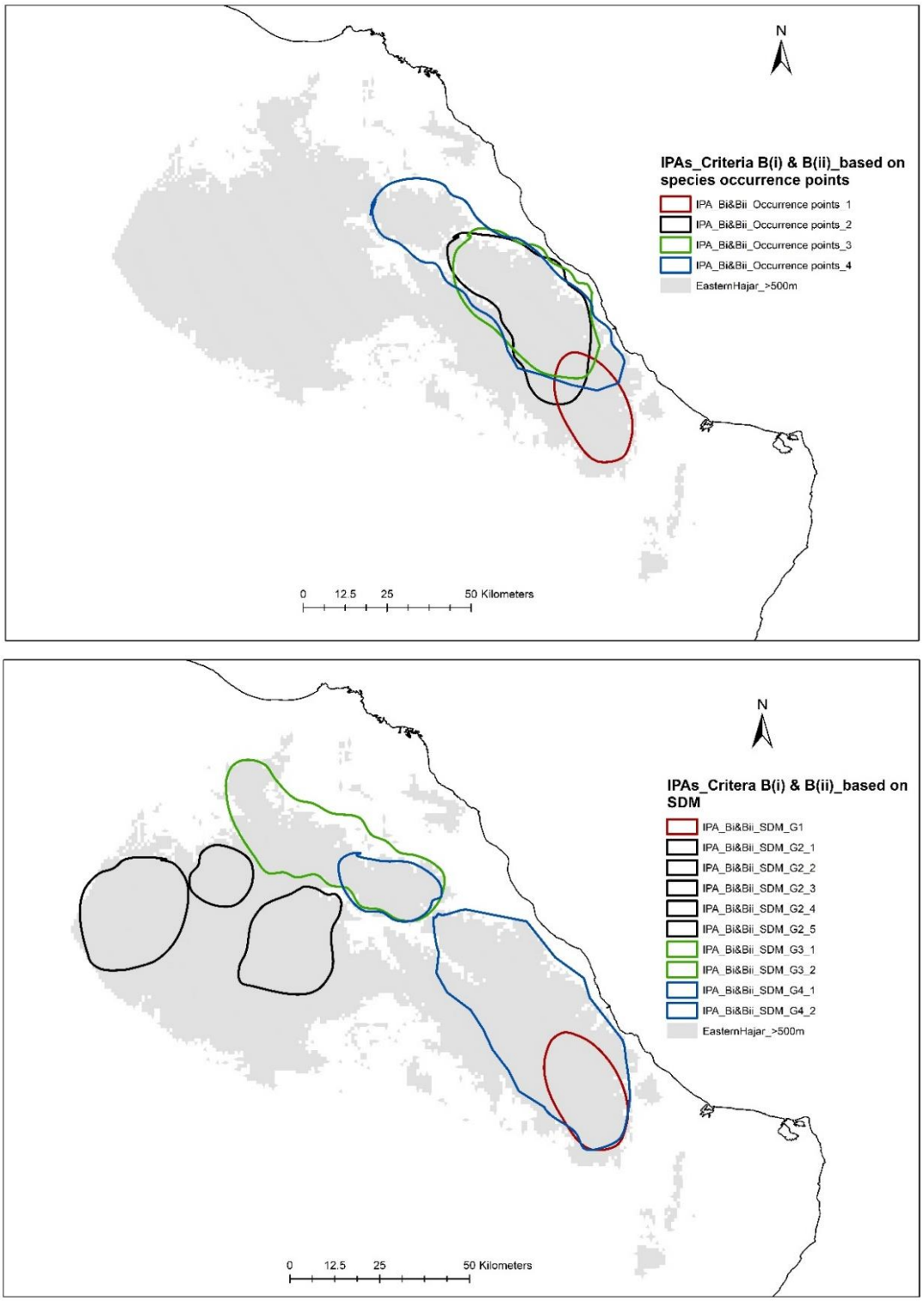


Figure 7.4. Newly revised IPA criteria assessment using both the occurrence data (top) and SDM data (bottom) for the Eastern Hajar Mountains in Oman; sub-criterion B(i) and B(ii).

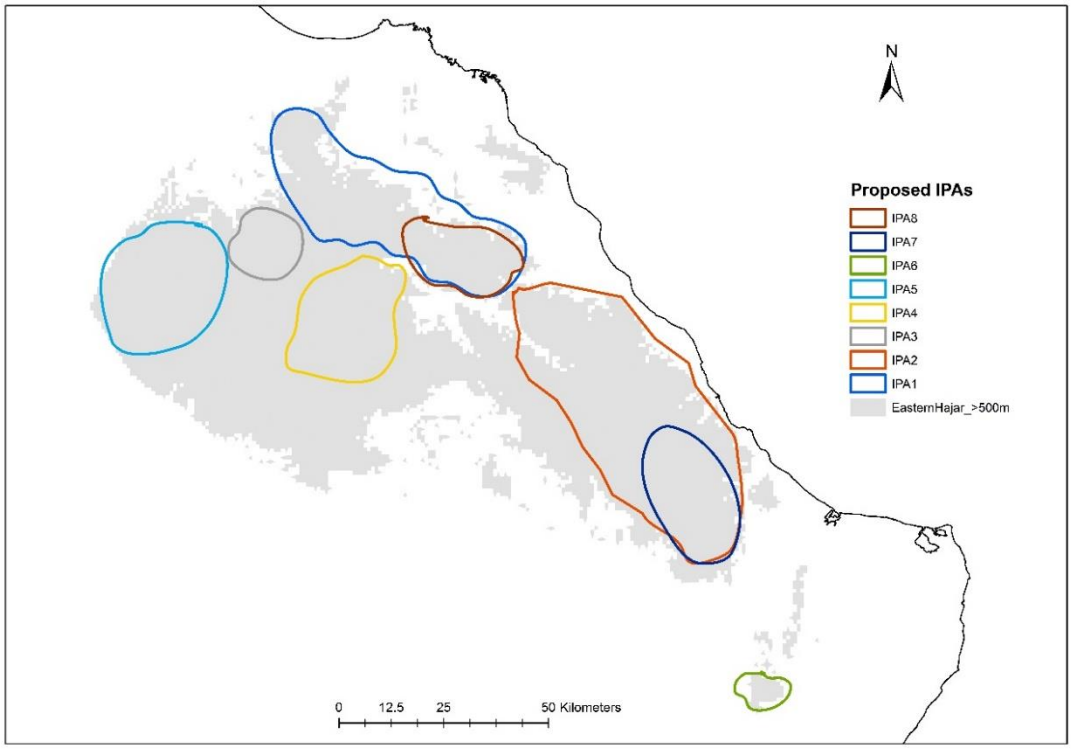


Figure 7.5. The 8 IPAs proposed using both the occurrence data and the SDMs for the Eastern Hajar Mountains, Oman.

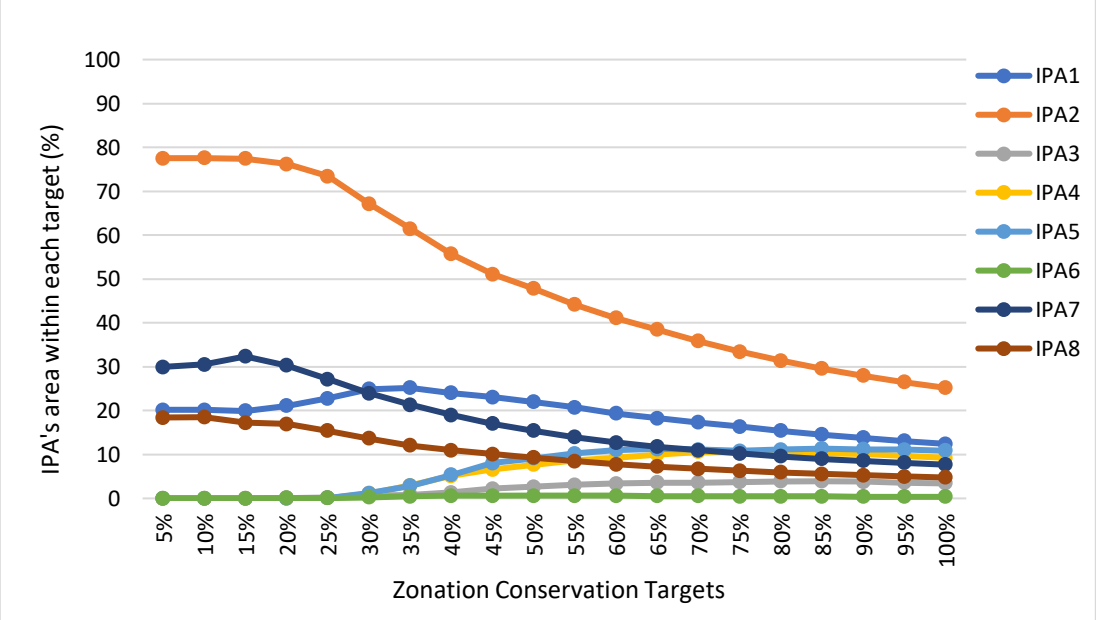


Figure 7.6. Priority conservation areas selected by Zonation, and the proportion of each conservation target inside the 8 proposed IPAs in the Eastern Hajar Mountains, Oman.

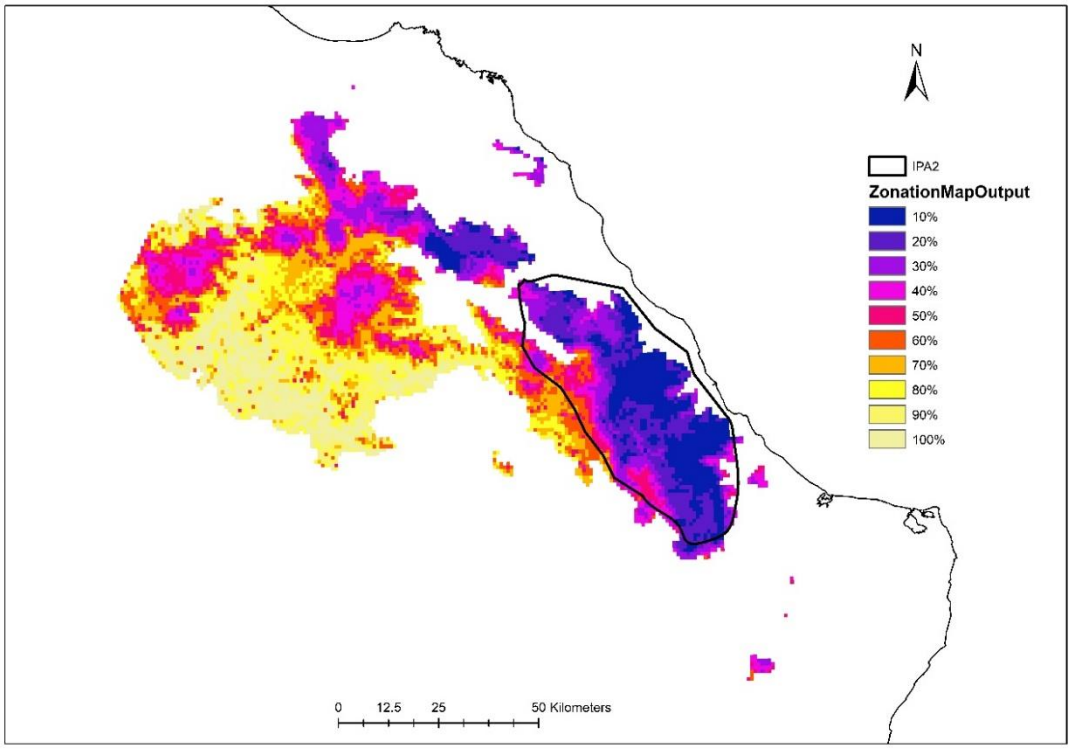


Figure 7.7. The overlap between IPA1 and the different conservation targets from Zonation.

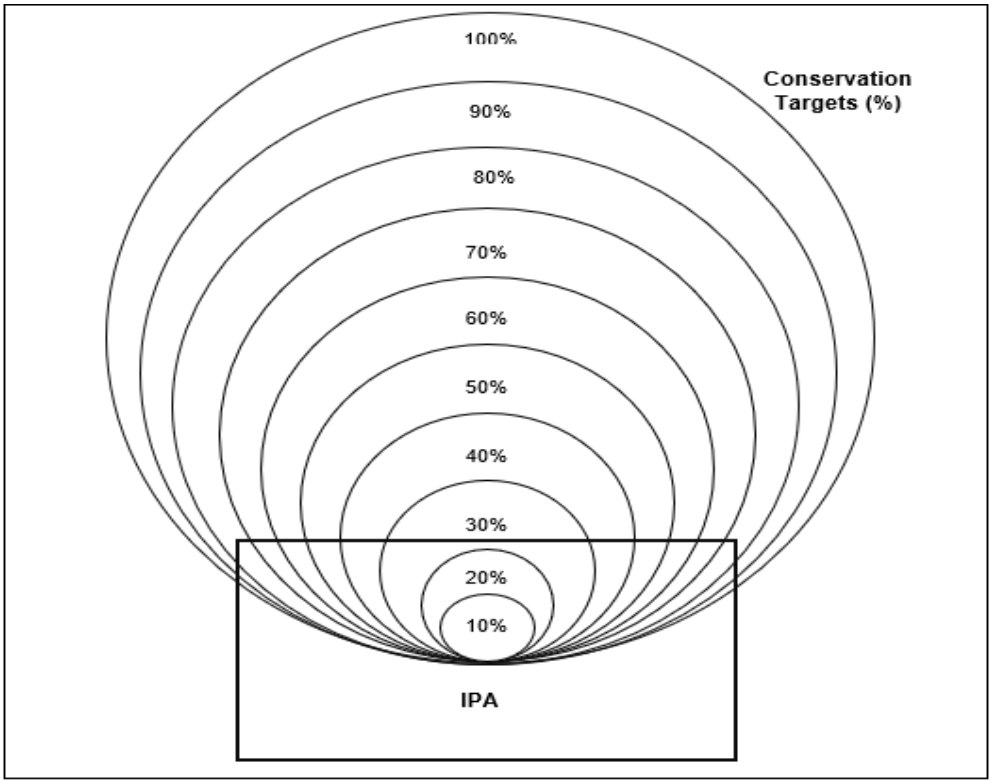


Figure 7.8. A graph explaining the overlap between the Zonation conservation targets and the representation of this target inside the proposed IPAs, in the Eastern Hajar Mountains, Oman.

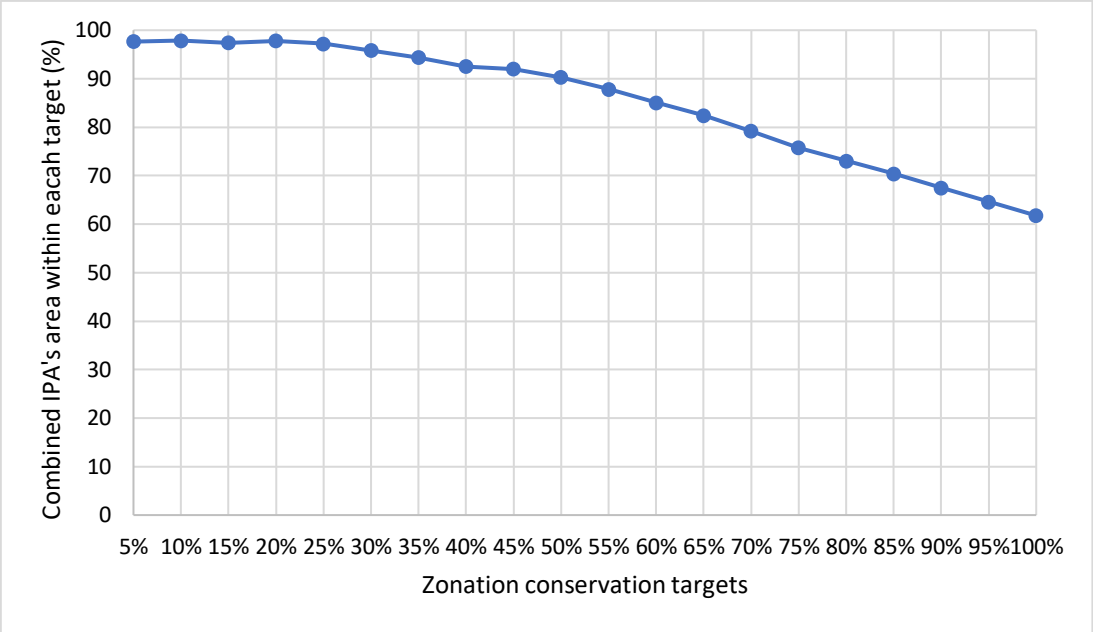


Figure 7.9. Priority conservation areas selected by Zonation (see Chapter 6), and the proportion of each conservation target inside the combined IPA in the Eastern Hajar Mountains, Oman.

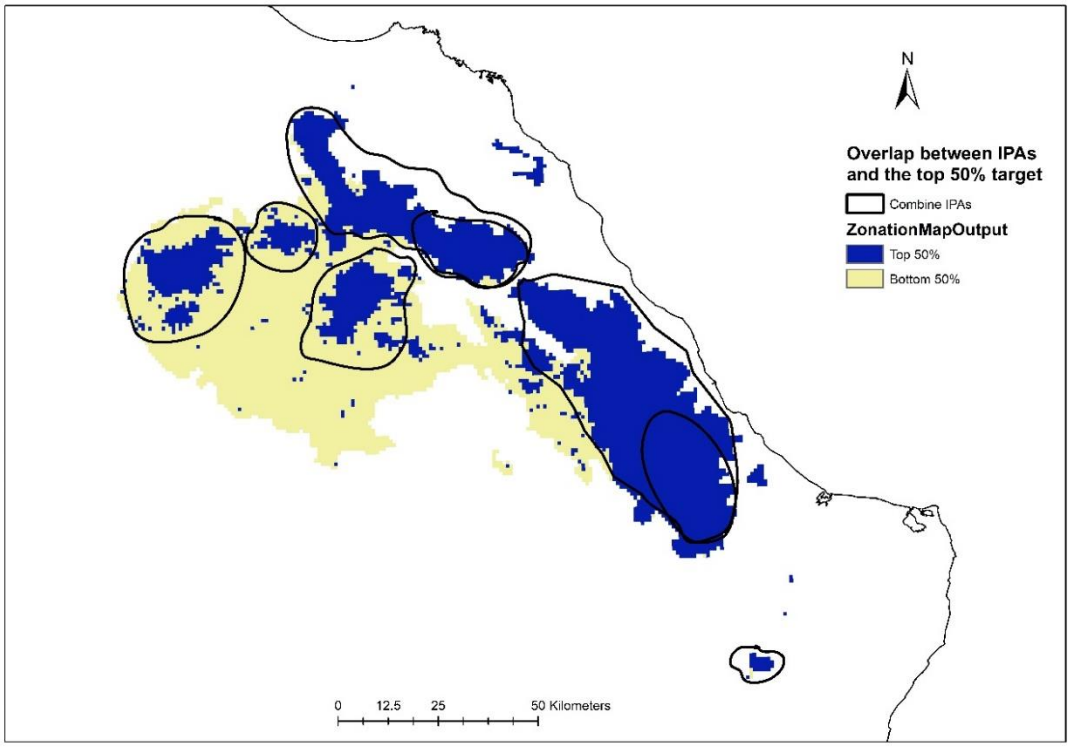


Figure 7.10. The overlap between the combined IPA and the top 50% priority conservation areas selected by Zonation in the Eastern Hajar Mountains, Oman.

CHAPTER 8

CONCLUSION

8 CONCLUSION

8.1 THESIS SUMMARY

The overall aim of this thesis was to classify, model, and evaluate the vegetation of the Eastern Hajar Mountains in Oman. The data collected to attain the objectives of this research was to be used for making better and more robust conservation planning decisions.

This chapter presents a brief discussion and conclusion for each of the research aims discussed in the Introduction chapter (Chapter 1). In addition, broader issues of the lack of knowledge and background in conservation planning at a personal level are raised, and potential future research projects are outlined. The more detailed and in-depth discussion has been included in each of these chapters. Four secondary aims were evolved in order to achieve the overarching aims of the research, as outlined below.

8.1.1 AIM 1: Classify the vegetation of the Eastern Hajar Mountains into plant communities and relate the distribution of these communities to a set of environmental variables, such as climate and soil type.

This aim was achieved through a comprehensive plot-based data collection and classifying the vegetation into plant communities using TWINSPAN before relating their composition and distribution to a set of environmental variables by adopting the DCA and CCA ordination methodology. This work was published in the *Journal of Arid Environments* (Al Harthy and Grenyer, 2019) and presented in chapter 4 in this thesis.

The analysis resulted in four well-defined plant communities that were spatially structured by climatic factors with strong elevational gradients. It is noteworthy that the high- elevation community (The *Ebenus stellata-Convolvulus ulicinus* community

(HEEC)) was always distinctly identified using all different datasets, with more ambiguous plant communities distribution identified at lower elevations (see Figures 4.3 & 4.4). Grazing and development (mainly road construction) represent the two threats posed to the vegetation in the Eastern Hajar Mountains. Although the amount of development is not measured in this study, an increase in the road network and the construction of a new building in the mountains was observed and documented over the duration of the study. Although the mountains were heavily grazed in most of the plots studied, the grazing was not found to have any effect on plant community distribution, which was mainly affected by other environmental variables.

8.1.2 AIM 2: Quantify the soil seed bank and compare it with the above-ground vegetation.

Soil seed bank studies are essential to gaining an understanding on how the area will respond to future changes and protection, and the persistent soil seed bank might increase the likelihood of the persistence of a population on a site. Therefore, the knowledge of the soil seed bank in these mountains is a useful tool for the purpose of different conservation activities.

Hundreds of soil samples were collected from the vegetation plots that were initially designed for the vegetation classification study in order to quantify the soil seed bank composition as well as density in the Eastern Hajar Mountains (Chapter 5). A very low species richness and diversity were recorded in the seed bank with only 21 species in common between the seed bank and the above-ground vegetation, out of the 208 species recorded in the later. The low germination of the soil seed bank, coupled with the low similarity between the seed bank and the above-ground vegetation, was hard to explain unequivocally, given that several biotic and abiotic factors can influence this result. Also, caution should be exercised in dealing with

the results of this experiment due to the wide range of experimental variabilities that may affect the seed germination in a green-house which were documented in many other studies.

8.1.3 Aim 3: Predict the current distribution of the perennial plant species of the Eastern Hajar Mountains.

Five modelling techniques were used to predict the current distribution of the species in the unsurveyed sites within the Eastern Hajar Mountains (Chapter 6). All of the five modelling methods generally performed well, as about 97% of the species were predicted better than normal with an AUC of ≥ 0.5 and 48% of the species with an AUC with ≥ 0.7. Although the performance was fairly good for all modelling methods, no single method could be identified that was good for all species.

The ensemble method proved to be the best method to be used due to its exceptional modelling performance for all species with an AUC of ≥ 0.9. Therefore, I will propose the ensemble method to be used in this area and which also could be applied to other areas within Oman, in light of the scarcity of species distribution data for many species across the country. The resulting Species Distribution Maps (SDMs) were used to realise the fourth aim of prioritising areas for conservation in the Eastern Hajar Mountains. Chapters 6 and 7 discussed the spatial area prioritisation using Zonation in detail and made a comparison with the IPA approach for conservation area selection.

8.1.4 Aim 4: Spatial conservation prioritisation.

The IPA approach identifies areas for conservation, primarily based on the presence of endemic species and threatened habitats. This approach is completely contingent on the availability of Red List species assessment and on the presence of habitat evaluation, which is mostly missing for many areas and countries. Therefore, using the newly revised IPA approach for identifying areas for conservation in the Eastern

Hajar Mountains proved to be a useful tool due to the availability of the Red List data for Oman, despite the missing habitat data.

Two IPAs were identified on these mountains based on the three main criteria used in the IPA assessment. Zonation was also used for prioritising areas for conservation as a more complementary-based approach (Chapter 6). Although these two approaches incorporated the use of different prioritisation methodologies, they both identified almost the same high conservation areas. In addition, both approaches identified areas that are beyond the scope of the protected areas. Thus, it can be surmised that using either approach for conservation area prioritisation is a useful tool with some difference in the size of the area defined and imparts greater flexibility in area selection under the Zonation approach.

8.2 FUTURE RESEARCH

The work presented here can be developed into comprehensive studies in order to complement the current study. It can also be used to help propose new future research projects for ensuring a better understanding of the species and plant community distribution, which can then be used for more robust conservation planning.

For the vegetation classification studies in the Eastern Hajar Mountains, a more inclusive data collection that covers the entire elevational gradient of the mountains will be a more prudent approach. The entire elevational gradient study will allow for a complete plant community classification, which, in turn, will support their placement into a formal syntaxonomical classification. In addition, this study allows for better understanding and explanation of the plant diversity pattern in the Eastern Hajar Mountains. Similarly, a broader consideration of the distribution of plant communities and of species diversity facilitates robust conservation planning.

Therefore, extending the scope of the current study to cover the lower elevation of the mountains will increase its value and pave the way for better conservation decisions.

Socioeconomic studies are urgently required for the Eastern Hajar Mountains due to the extensive pressure exerted on vegetation due to overgrazing and development. For example, understanding and incorporating the land-use history and habitat conditions of these lands will affect the spatial area prioritisation for conservation.

One of the most important considerations for any future vegetation study in these types of arid mountains is that of climate change. The shift on the mountain's species ranges caused by climate change will most probably affect the selection and planning for any conservation area in the mountains. Therefore, species distribution modelling will need to be developed under the different climate change scenarios, especially in the wake of the expected future dryness of the Hajar Mountains to account for future changes.

These are only a few possible types of research in which this thesis could be further developed and expanded.

8.3 PERSONAL REFLECTIONS

On a personal level, coming purely from field-based botany background to work on conservation research was a challenging task. Conservation is a broad field that requires skills in many areas. The following are the main challenges that I needed to overcome in order to develop a better understanding of what is required to work on conservation research and think as a conservationist.

One of the first things that I needed to learn was to understand the way in which I used to function as a pure researcher and try and link it to management and policy. This inescapably required changes in the manner that I think about how to perform

good conservation research that will eventually have influence and contribute to my conservation decisions. I also needed to put more thought into the bigger picture from a conservationist perspective, as opposed to near-sighted, focusing on a specific project or research.

My research also required a lot of collaboration with many institutes on a personal communication level as well as on an organisational and official communication level. Networking is an important skill that I needed to develop and improve from the start of the project, which consequently pushed me to learn how to be excellent in my communication with people. These communication skills were developed through many meetings with experts and officials to explain my project and its importance in order to procure data and also be able to join, for example, very restricted helicopter trips with Royal Forces. Furthermore, the development of communication skill empowered me to attend some of the related workshops to help me demonstrate my research and how it can be used in a conservation planning process.

Analytical thinking skills and being able to explain the complication of the multidisciplinary activities required for conservation research was a major skill that I also developed during this research. To begin with, being a botanist was a very useful background that helped me to easily pick up many of the subjects and skills that I needed to finish this study. For example, statistics is one of the major skills that I started to focus more upon in order to deal with my own data, as well as other data used in this research. Continuous development of statistics skills will always be a key valuable addition to my skills if I will continue to work on these types of researches.

Utilising different software packages in order to run a robust data analysis for conservation research was definitely the most challenging, intensifying and time-

consuming task that I needed to undertake as part of this research. Many of the specific tools and software that I learned during my current work started from scratch. These include software such as the TWINSPAN for vegetation classification, PC-ORD for ordination, learning how to write codes in R program to run the species distribution modelling (SDMs) as well as learning software for spatial prioritisation analysis, like Zonation.

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APPENDICES

APPENDICES

Appendix 3.1. Field work challenges in the Eastern Hajar Mountains.

Fieldwork Challenges

Challenges during vegetation survey and soil sampling:

- *Plot locations identification:* It was not easy to locate plots using the pre-selected points according to the GIS map. Therefore, rules such as walking in a specific direction from a specific starting point were followed when the points in the map could not be located in a precise manner. The unbiased site location was carefully looked after using the maps and enforcing strict rules in locating them.
- *Species identification*: It was quite difficult to identify many of the species as most of these were missing parts useful for identification, which made it difficult for immediate identification in the field. Thus, species vouchers were collected and brought back to the OBG herbarium for further identification and verification.
- *Soil sampling*: It was not always possible to collect five soil samples from each plot due to the logistical challenge of carrying back the soil samples to the soil lab, especially in the hiking and helicopter trips. Therefore, fewer soil samples were collected from a few studied plots.
- *Collection time*: The area was under prolonged drought, especially over the last ten years, which affected the presence of many of the plant species in the mountains. Therefore, many of the previously recorded species were not found during the period of this research (i.e. mainly the annual/ biennial species). The collection time for this project was extended over 3-4 years in order to capture most of the species occurring in these mountains. Four years of fieldwork was a long time for the project, which caused a delay in data analysis and results.

Physical challenges during the fieldwork

Carrying out a research project in the arid area of the Eastern Hajar Mountains is full of physical challenges and other predicaments:

- Dry, hot and desert climate of the mountains will intensify the risk of heat and cold hits.

- The sheer physical and mental challenge of walking and climbing for long distances under the harsh environment of the Eastern Hajar Mountains.
- Finding a shelter from the sun, especially during the hiking trip.
- Managing and leading a team from different backgrounds in one of the most challenging environments.
- Logistics of carrying back the collected plant and soil materials.
- Being mentally sharp and skilled in dealing with any emergency that the team may potentially face during any field trip, specifically the long field trips and the hiking trip; and being able to encourage them to complete all of them.
- Dealing with minor accidents such as, small injuries and fatigue from carrying out fieldwork.
- Ensuring safety of the entire team and their ability to complete a field trip.

A day in the field

- In the days before the trip, the cars, the field equipment, the food and water for the trip were checked and prepared.
- In addition, cars were selected, checked and filled with enough petrol to ensure safety of driving in the mountains.
- Usually, the field day started at around 6:00 in the morning and travelling to the mountains took around 3 hours' drive.
- After arriving at the study location, the vegetation plot is located using the preselected locations in the map (see chapter 4).
- After locating the plot, the data collection and soil sampling were carried out as described in the methods.
- If the trip is more than one day long, a safe location was selected to set up the camp and it was ensured that all the water and foodstuff are safely kept in a locked place away from the animals in the area.

- Labelling of the soil samples and plant species vouchers was ensured before moving to the next plot.
- Packing of the field equipment and moving to the next location.

Appendix 4.1. **DCA AND CCA DIAGRAMS FOR THE LEVEL 4 DIVISION (COVER AND PRESENCE/ABSENCE DATA) OF TWINSPAN CLASSIFICATION (USING ALL SPECIES AND PERENNIAL SPECIES ONLY DATASETS):**

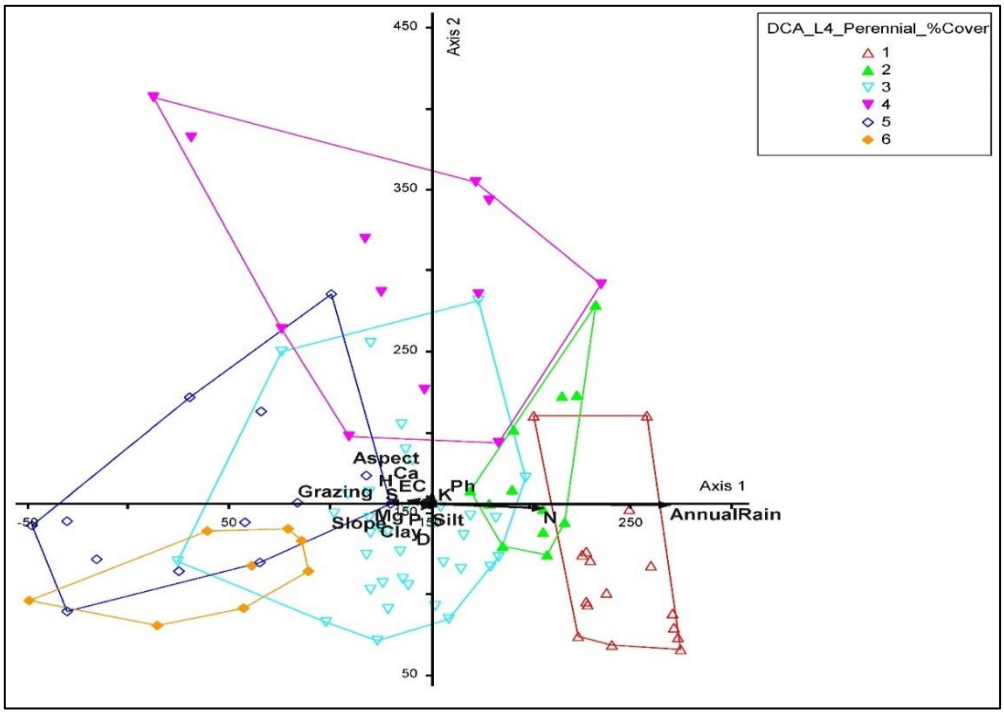


Figure 1. DCA ordination using perennial species cover data from Level 4 TWINSPAN classification.

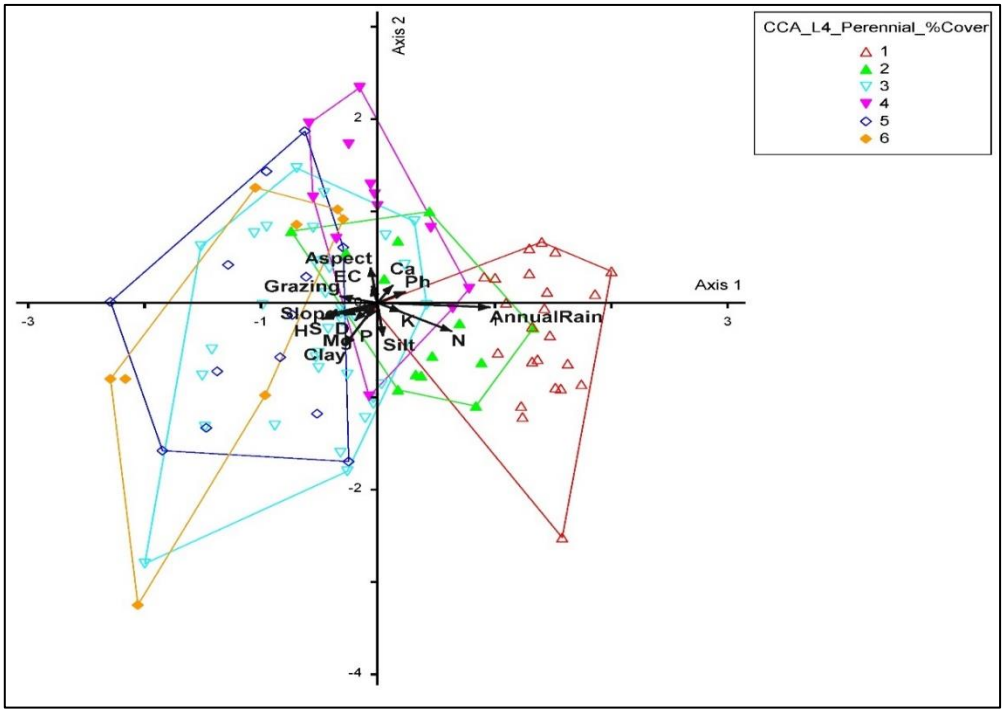


Figure 2. CCA ordination using perennial species cover data from Level 4 TWINSPAN classification.

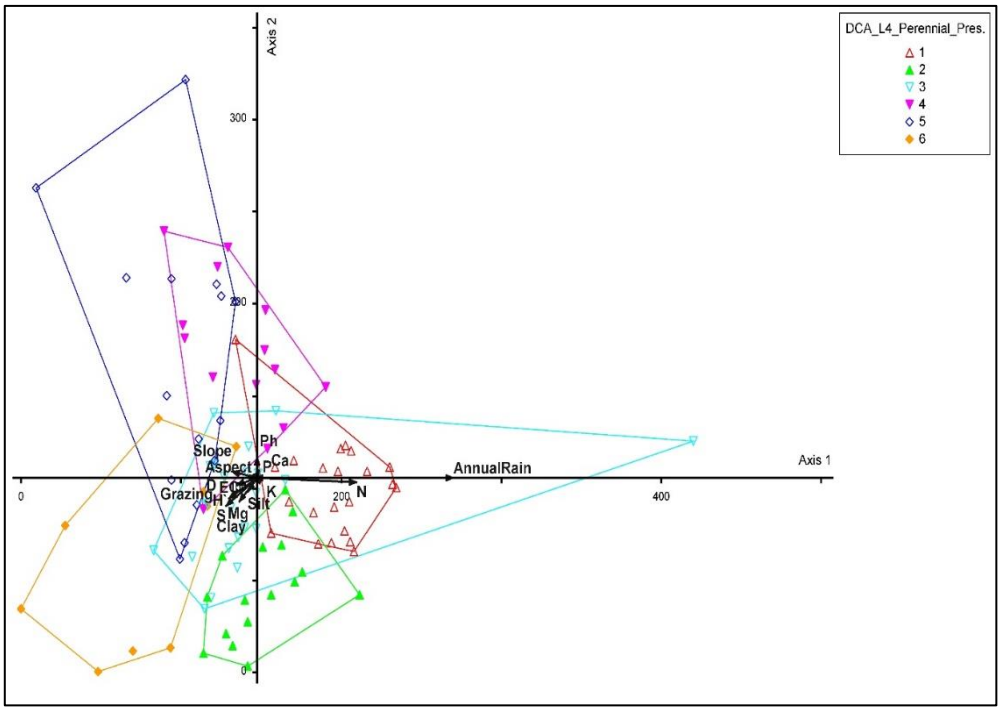


Figure 3. DCA ordination using perennial species presence/absence data from Level 4 TWINSPAN

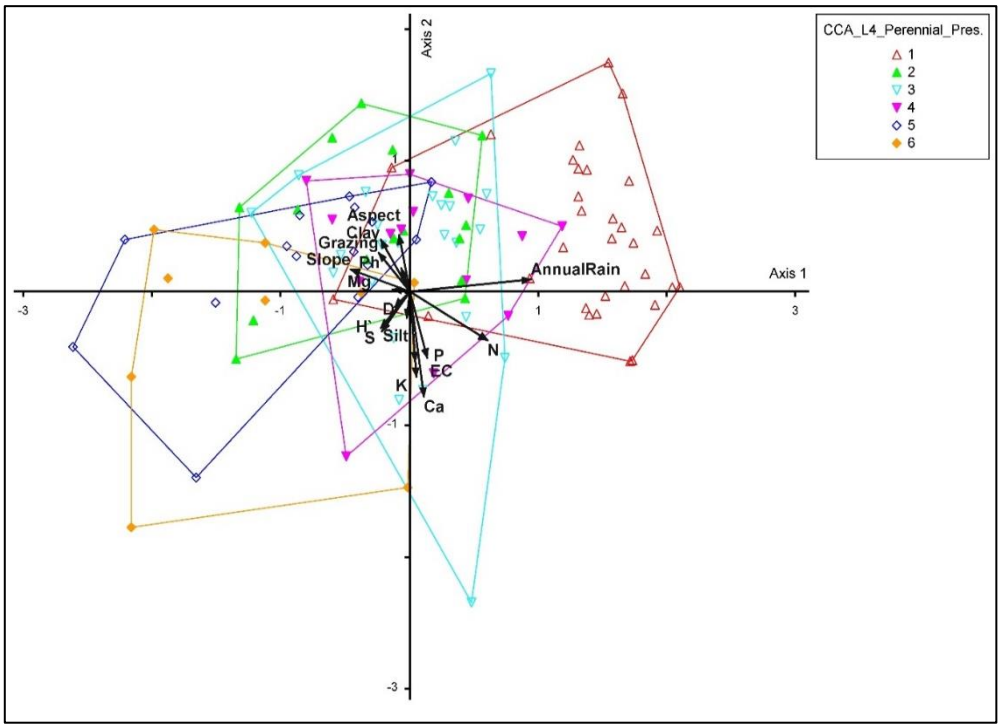


Figure 4. CCA ordination using perennial species presence/absence data from Level 4 TWINSPAN classification.

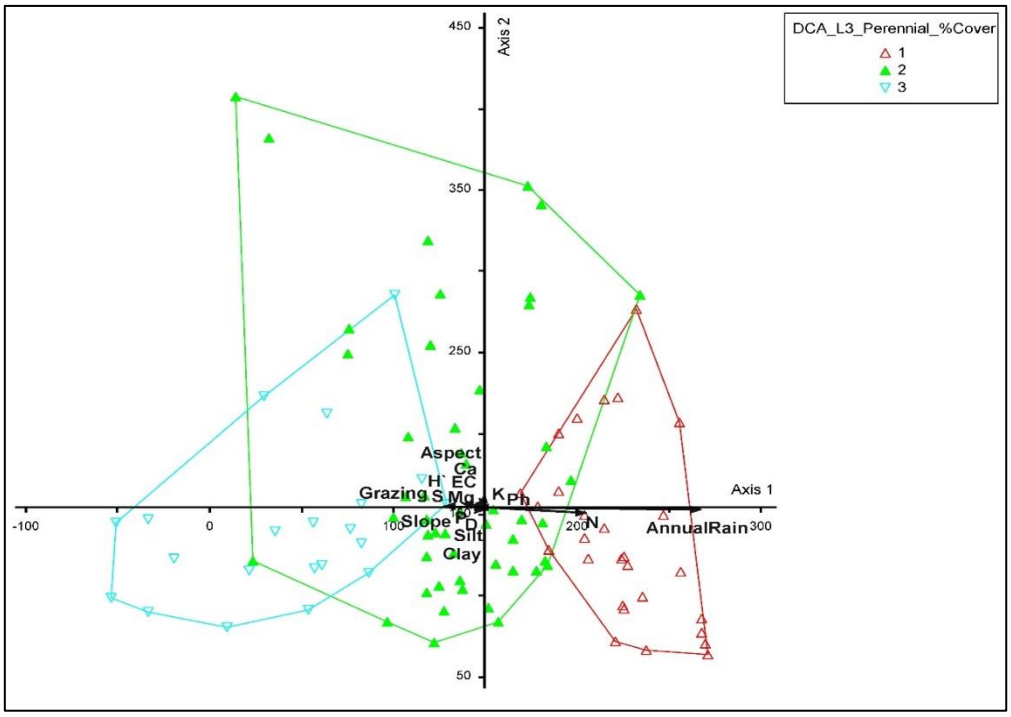


Figure 5. DCA ordination using perennial species cover data from Level 3 TWINSPAN classification.

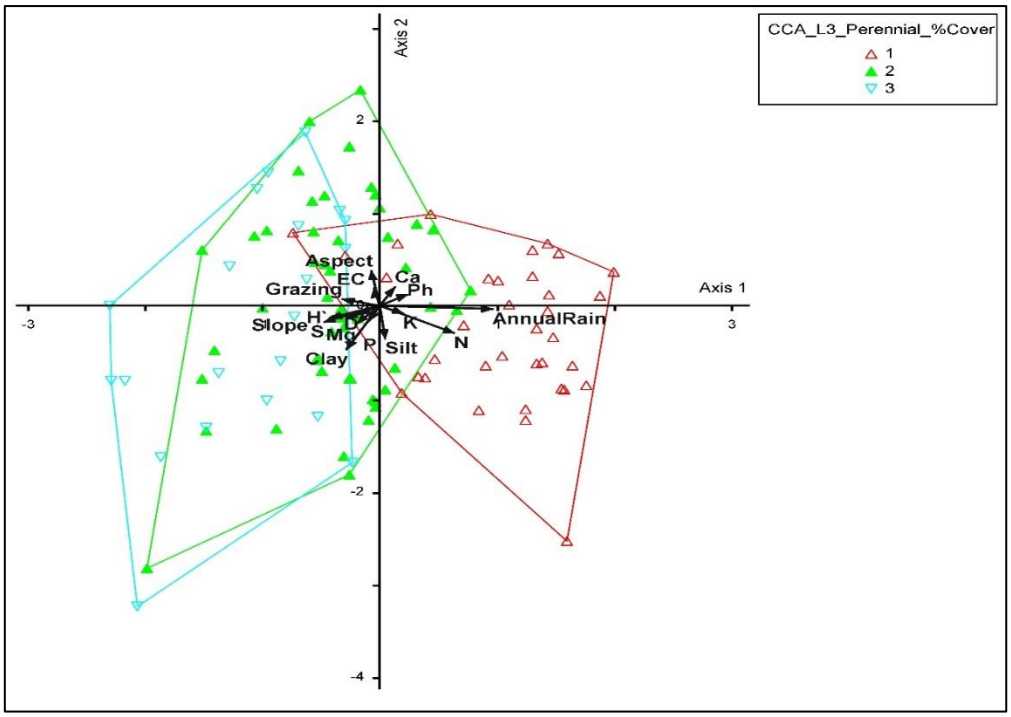


Figure 6. CCA ordination using perennial species cover data from Level 3 TWINSPAN classification.

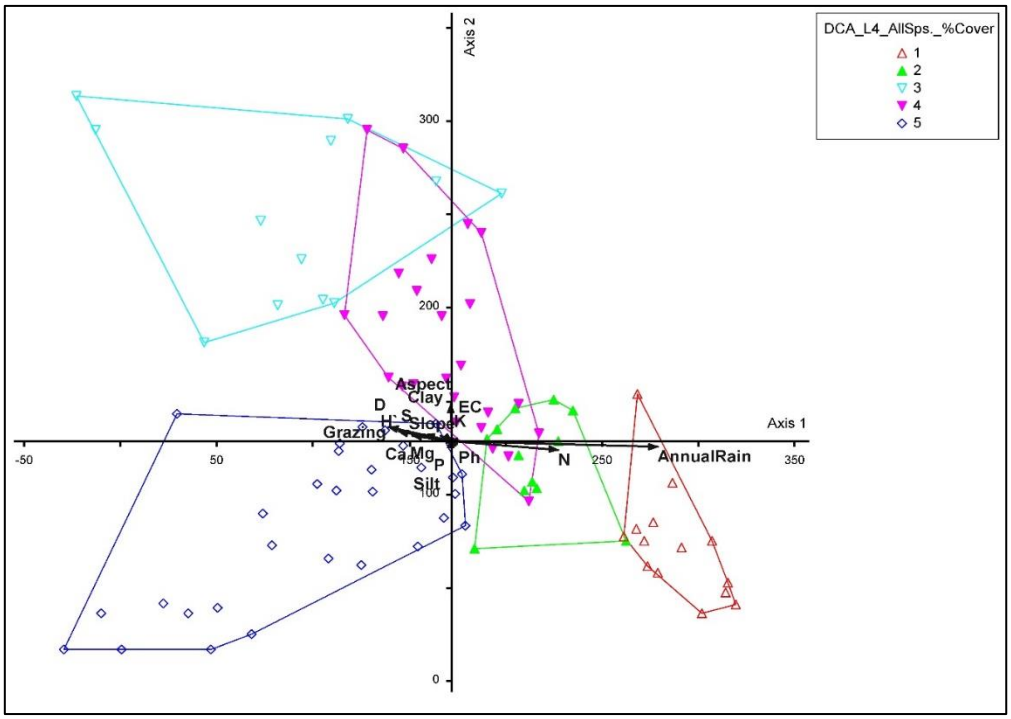


Figure 7. DCA ordination using all species cover data from Level 4 TWINSPAN classification.

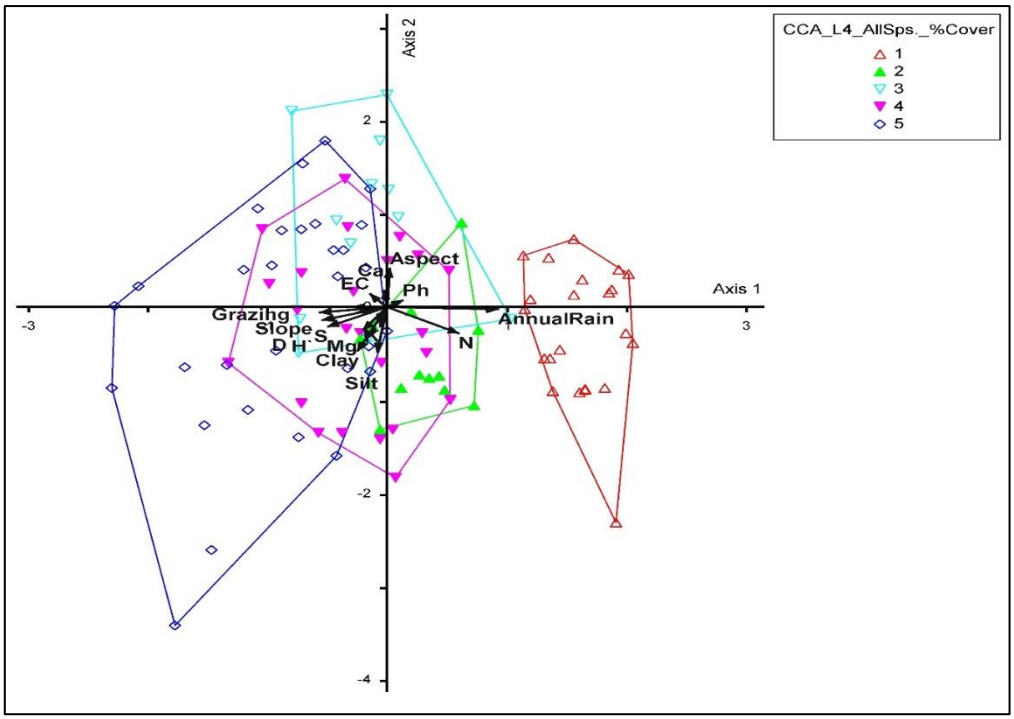


Figure 8. CCA ordination using all species cover data from Level 4 TWINSPAN classification.

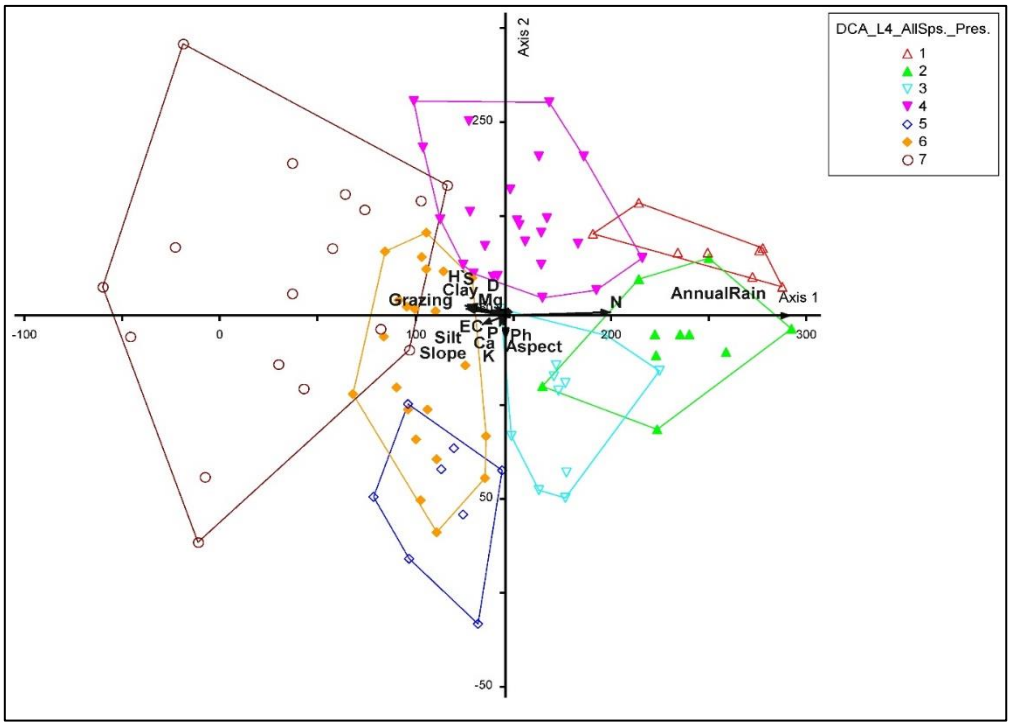


Figure 9. DCA ordination using all species presence/absence data from Level 4 TWINSPAN classification.

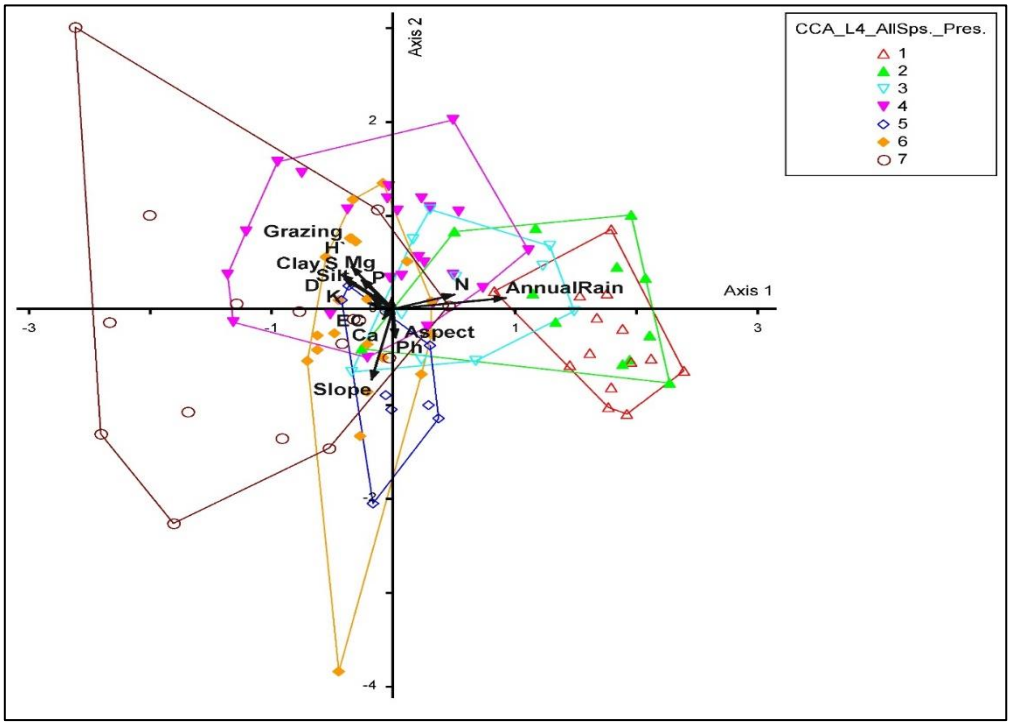


Figure 10. CCA ordination using all species presence/absence data from Level 4 classification.

APPENDIX 4.2. SUMMARY RESULTS OF THE MULTI-RESPONSE PERMUTATION PROCEDURE (MRPP) *statistics of the vegetation groups on the Eastern Hajar Mountains using the third level group results from TWINSPAN. Results are given for multiple pairwise comparisons of the squared Euclidean distance (A= change-corrected within-group agreement; T= difference between the observed and expected deltas); all groups were signficantly different with p value <0.0001), group numbers referred to the plant communities described by TWINSPAN; 1= Ebenus stellata-Convolvulus ulicinus* community, *2= Prunus arabica -Ceratonia oreothauma* community *y, 3= Searsia aucheri -Acacia tortilis c* community, *4= Echiochilon persicum-Helianthemum kahiricum* community.

Groups compared	T	A
2 vs. 4	-17.7295	0.147235
2 vs. 3	-14.638	0.101511
2 vs. 1	-18.0485	0.117247
4 vs. 3	-10.2522	0.092151
4 vs. 1	-22.9028	0.175423
3 vs. 1	-23.5887	0.145884

APPENDIX 6.1. THE SPECIES PREDICTION ACCURACY (AUC VALUES) USING THE FIVE DIFFERENT MODELLING METHODS USED IN SDM ANALYSIS, EM (ENSEMBLE MODEL), GAM, GLM, CTA, RF AND MAXENT.

Species	EM	GAM	GLM	CTA	RF	MAXENT
Acacia gerrardii* ssp. *negevensis	0.9	0.7	0.8	0.7	0.8	0.6
Vachellia tortilis	1.0	0.5	0.5	0.5	0.6	0.5
Acridocarpus orientalis	1.0	0.7	0.8	0.7	0.8	0.7
Aerva javanica	1.0	0.7	0.8	0.7	0.8	0.6
Andrachne aspera	1.0	0.5	0.7	0.6	0.6	0.7
Andrachne telephioides	1.0	0.8	0.9	0.9	0.9	0.9
Argyrolobium crotalarioides	1.0	0.5	0.6	0.7	0.9	0.9
Argyrolobium roseum	0.9	0.5	0.6	0.5	0.5	0.7
Asparagus capitatus* ssp. *gracilis	0.9	0.6	0.7	0.6	0.7	0.7
Astragalus fasciculifolius* ssp. *arbusculinus	1.0	0.6	0.8	0.8	0.8	0.8
Barleria hochstetteri	1.0	0.5	0.6	0.5	0.5	0.5
Blepharis ciliaris	1.0	0.5	0.5	0.7	0.6	0.9
Boerhavia elegans	1.0	0.6	0.7	0.6	0.6	0.8
Boerhavia mista	1.0	0.5	0.5	0.5	0.5	0.6
Capparis spinosa	1.0	0.5	0.4	0.5	0.6	0.4
Desmidorchis arabica	1.0	0.6	0.5	0.5	0.6	0.8
Cenchrus ciliaris	1.0	0.5	0.1	0.5	0.5	0.8
Ceratonia oreothauma	1.0	0.7	0.7	0.8	0.9	0.9
Chrozophora oblongifolia	1.0	0.7	0.8	0.7	0.8	0.8
Chrysopogon aucheri	1.0	0.5	0.6	0.7	0.6	0.7
Commiphora kua	1.0	0.5	0.6	0.6	0.6	0.6
Commiphora wightii	1.0	0.5	0.4	0.5	0.5	0.5
Convolvulus acanthocladus	1.0	0.5	0.5	0.5	0.4	0.4
Convolvulus ulicinus	0.9	0.6	0.6	0.6	0.6	0.5
Convolvulus virgatus	1.0	0.6	0.8	0.7	0.7	0.7
Crotalaria aegyptiaca	1.0	0.5	0.5	0.4	0.6	0.7
Cucumis prophetarum	1.0	0.6	0.7	0.6	0.7	0.6
Cymbopogon schoenanthus	1.0	0.8	0.9	0.8	0.9	0.7
Cynodon dactylon	1.0	0.6	0.8	0.7	0.8	0.6
Cyperus rubicundus	1.0	0.7	0.8	0.8	0.9	0.7
Daphne mucronata	1.0	0.7	0.5	0.5	0.7	0.0
Digitaria nodosa	1.0	0.5	0.5	0.4	0.5	0.5
Dipcadi erythraeum	1.0	0.5	0.6	0.5	0.7	0.6
Dodonaea viscosa	1.0	0.7	0.7	0.7	0.8	0.8
Dyerophytum indicum	1.0	0.5	0.6	0.6	0.6	0.6
Ebenus stellata	1.0	0.5	0.7	0.7	0.8	0.8
Echinops erinaceus	1.0	0.6	0.8	0.7	0.7	0.7
Echiochilon persicum	1.0	0.5	0.5	0.8	0.9	0.8
Ephedra pachyclada* ssp. *pachyclada	1.0	0.5	0.5	0.5	0.7	0.5
Eragrostis papposa	0.9	0.6	0.7	0.7	0.8	0.8

Euphorbia larica	1.0	0.6	0.7	0.7	0.8	0.7
Euryops arabicus	1.0	0.9	0.8	0.8	1.0	0.9
Zygophyllum bruguieri	0.9	0.6	0.7	0.7	0.7	0.6
Zygophyllum indicum	1.0	0.6	0.6	0.5	0.7	0.8
Farsetia aegyptia	1.0	0.5	0.5	0.5	0.6	0.6
Farsetia linearis	1.0	0.7	0.7	0.7	0.8	0.6
Ficus johannis* ssp. *johannis	0.9	0.5	0.6	0.6	0.6	0.6
Forsskaolea tenacissima	1.0	0.5	0.5	0.5	0.8	0.7
Glossonema varians	1.0	0.6	0.8	0.7	0.8	0.8
Grewia erythraea	1.0	0.5	0.6	0.5	0.6	0.6
Helianthemum kahiricum	1.0	0.6	0.7	0.8	0.8	0.8
Helianthemum lippii	1.0	0.5	0.6	0.4	0.7	0.7
Helichrysum glumaceum	0.9	0.8	0.8	0.7	0.8	0.7
Heliotropium calcareum	1.0	0.6	0.8	0.7	0.8	0.7
Heliotropium rariflorum	1.0	0.5	0.6	0.5	0.5	0.4
Heteropogon contortus	1.0	0.5	0.5	0.5	0.5	0.5
Indigofera arabica	1.0	0.5	0.5	0.8	0.8	0.8
Indigofera articulata	1.0	0.6	0.7	0.6	0.7	0.6
Iphiona scabra	1.0	0.6	0.6	0.6	0.7	0.7
Jurinea berardioides	1.0	0.5	0.6	0.5	0.6	0.5
Kohautia retrorsa	1.0	0.6	0.8	0.7	0.8	0.7
Launaea bornmuelleri	0.9	0.5	0.7	0.7	0.8	0.8
Launaea capitata	1.0	0.5	0.8	0.7	0.7	0.8
Launaea omanensis	1.0	0.6	0.6	0.6	0.7	0.6
Lavandula subnuda	1.0	0.5	0.5	0.5	0.5	0.3
Leucas inflata	1.0	0.8	0.7	0.7	0.9	1.0
Lonicera hypoleuca	1.0	0.6	0.8	0.7	0.8	0.8
Lycium shawii	1.0	0.4	0.5	0.4	0.2	0.6
Melhania ovata	1.0	0.6	0.7	0.6	0.8	0.7
Morettia parviflora	1.0	0.6	0.7	0.6	0.7	0.7
Morettia philaeana	1.0	0.6	0.6	0.5	0.8	0.7
Moringa peregrina	1.0	0.5	0.5	0.5	0.5	0.5
Ochradenus arabicus	1.0	0.5	0.6	0.8	0.9	0.9
Ochradenus aucheri	1.0	0.7	0.8	0.8	0.9	0.7
Olea europaea* ssp. *cuspidata	1.0	0.6	0.6	0.5	0.9	0.7
Paronychia arabica	1.0	0.5	0.6	0.6	0.6	0.7
Pergularia tomentosa	1.0	0.6	0.7	0.7	0.7	0.6
Periploca aphylla	1.0	0.5	0.5	0.5	0.6	0.8
Phagnalon schweinfurthii	1.0	0.5	0.7	0.6	0.7	0.6
Physorhynchus chamaerapistrum	1.0	0.6	0.7	0.7	0.8	0.7
Plocama aucheri	1.0	0.5	0.5	0.5	0.8	0.6
Plocama calycoptera	0.8	0.5	0.6	0.5	0.4	0.7
Polygala mascatensis	1.0	0.6	0.6	0.6	0.7	0.7
Prunus arabica	1.0	0.6	0.7	0.6	0.7	0.6
Pulicaria glutinosa* ssp. *glutinosa	1.0	0.6	0.6	0.5	0.6	0.5

Pycnocycla prostrata	1.0	0.5	0.5	0.8	1.0	0.0
Ruellia scindica	1.0	0.7	0.7	0.7	0.8	0.7
Sageretia thea	1.0	0.6	0.7	0.7	0.7	0.8
Salvia aegyptiaca	1.0	0.6	0.5	0.6	0.7	0.8
Sarcostemma viminale	1.0	0.6	0.8	0.7	0.8	0.8
Searsia aucheri	1.0	0.6	0.7	0.7	0.7	0.6
Sideroxylon mascatense	1.0	0.5	0.8	0.7	0.7	0.8
Solanum americanum	1.0	0.6	0.7	0.7	0.7	0.7
Solanum incanum	1.0	0.6	0.6	0.7	0.8	0.9
Taverniera cuneifolia	1.0	0.6	0.7	0.7	0.7	0.7
Tephrosia purpurea* subsp. *apollinea	1.0	0.6	0.6	0.7	0.9	0.7
Tetrapogon villosus	1.0	0.6	0.7	0.6	0.8	0.8
Teucrium stocksianum* ssp. *stenophyllum	1.0	0.5	0.5	0.7	0.7	0.8
Trichodesma africanum	0.9	0.6	0.6	0.6	0.7	0.6
Tripogon africanus	1.0	0.6	0.7	0.6	0.7	0.6
Verbascum akdarense	1.0	0.5	0.6	0.6	0.6	0.7
Zataria multiflora	1.0	0.6	0.7	0.6	0.7	0.7
Ziziphus hajarensis	1.0	0.6	0.6	0.5	0.9	0.9
Ziziphus spina-christi	0.9	0.6	0.7	0.6	0.7	0.6

APPENDIX 7.1. SUMMARY OF THE REVISED IPA CRITERIA AND SUB-CRITERIA (SOURCE: DARBYSHIRE ET AL., *2017)*

Sub-criterion	Threshold
(A) Threatened species A(i) Site contains one or more globally threatened species	Site known, thought or inferred to contain ≥1% of the global population AND/OR ≥5% of the national population OR the 5 ‘‘best sites’’ for that species nationally, whichever is most appropriate
A(ii) Site contains one or more regionally threatened species	Site known, thought or inferred to contain ≥5% of the national population, OR the 5 ‘‘best sites’’ for that species nationally, whichever is most appropriate
A(iii) Site contains one or more highly restricted endemic species that are potentially threatened	Site known, thought or inferred to contain ≥1% of the global population AND/OR ≥5% of the national population, OR the 5 ‘‘best sites’’ for that species nationally, whichever is most appropriate
A(iv) Site contains one or more range restricted endemic species that are potentially threatened	Site known, thought or inferred to contain ≥1% of the global population AND/OR ≥5% of the national population, OR the 5 ‘‘best sites’’ for that species nationally, whichever is most appropriate
(B) Botanical richness B(i) Site contains a high number of species within defined habitat or vegetation types	For each habitat or vegetation type: up to 10% of the national resource can be selected within the whole national IPA network OR the 5 ‘‘best sites’’ nationally, whichever is the most appropriate
B(ii) Site contains an exceptional number of species of high conservation importance	Site known to contain ≥3% of the selected national list of species of conservation importance OR the 15 richest sites nationally, whichever is most appropriate
B(iii) Site contains an exceptional number of socially, economically or culturally valuable species	Site known to contain ≥3% of the selected national list of socially, economically or culturally valuable species OR the 15 richest sites nationally, whichever is most appropriate
(C) Threatened habitat C(i) Site contains globally threatened or restricted habitat/vegetation type	Site known, thought or inferred to contain ≥5% of the national resource (area) of the threatened habitat type OR site is among the best quality examples required to collectively prioritise 20–60% of the national resource OR the 5 ‘‘best sites’’ for that habitat nationally, whichever is the most appropriate
C(ii) Site contains regionally threatened or restricted habitat/vegetation type	Site known, thought or inferred to contain ≥5% of the national resource (area) of the threatened habitat type OR site is among the best quality examples required to collectively prioritise 20–60% of the national resource

Sub-criterion	Threshold
	OR the 5 "best sites" for that habitat nationally, whichever is the most appropriate
C(iii) Site contains nationally threatened or restricted habitat/vegetation type, AND/OR habitats that have severely declined in extent nationally	Site known, thought or inferred to contain ≥10% of the national resource (area) of the threatened habitat type OR site is among the best quality examples required to collectively prioritise up to 20% of the national resource OR the 5 "best sites" for that habitat nationally, whichever is most appropriate

APPENDIX 7.2: CHECKLIST OF PLANT TAXA FROM EASTERN HAJAR, OMAN. FAMILY DELIMITATION FOLLOWS APG III (ANGIOSPERM PHYLOGENY GROUP, 2009) (BREMER ET AL., 2009); AND THE NAMES FOLLOW THE PLANTS OF THE WORLD ONLINE DATABASE (PLANTS OF THE WORLD ONLINE, 2019).

Family	Species
Acanthaceae	
	Barleria hochstetteri Nees
	Blepharis ciliaris (L.) B.L.Burtt.
	Ruellia discifolia Oliv.
	Ruellia sindica Ghafoor & Heine
Aizoaceae	
	Aizoon canariense L.
	Zaleya pentandra (L.) C.Jeffrey
Amaranthaceae	
	Achyranthes aspera L.
	Aerva javanica (Burm.f.) Juss. ex Schult.
	Amaranthus graecizans L.
	Amaranthus hybridus L.
	Amaranthus viridis L.
	Anabasis setifera Moq.
	Caroxylon imbricatum (Forssk.) Moq.
	Chenopodium album L.
	Chenopodium murale L.
	Cornulaca monacantha Delile
	Digera muricata (L.) Mart.
	Halothamnus bottae Jaub. & Spach
	Kaviria rubescens (Franch.) Akhani
	Pupalia lappacea (L.) Juss.
	Sevada schimperi Moq.
	Suaeda aegyptiaca (Hasselq.) Zohary
Anacardiaceae	
	Adenosciadium arabicum H.Wolff
	Ammi majus L.
	Ducrosia anethifolia (DC.) Boiss.
	Pycnocycla aucheriana Decne. ex Boiss. var. *aucheriana*
	Pycnocycla prostrata Hedge & Lamond
	Searsia aucheri Boiss. (Boiss.) Moffett
Apiaceae	

Tricholaser ovatilobum (Dunn & R.O.Williams) Alava

Apocynaceae

Calotropis procera (Aiton) W.T.Aiton

Caralluma mouretii A.Chev.

Cynanchum viminale (L.) L.

Cynanchum viminale subsp. *stipitaceum* (Forssk.) Meve & Liede

Desmidorchis arabica (N.E.Br.) Meve & Liede

Glossonema varians (Stocks) Benth. ex Hook.f.

Leptadenia pyrotechnica (Forssk.) Decne.

Nerium oleander L.

Oxystelma esculentum (L.f.) Sm.

Periploca aphylla Decne.

Periploca sp.nov.

Rhazya stricta Decne.

Arecaceae

Nannorrhops ritchiana (Griff.) Aitch.

Aristolochiaceae

Aristolochia bracteolata Lam.

Apocynaceae

Pergularia tomentosa L.

Asparagaceae

Asparagus capitatus subsp. *gracilis* Browicz

Dipcadi biflorum Ghaz.

Dipcadi erythraeum Webb & Berthel.

Asteraceae

Anthemis odontostephana Boiss.

Atractylis arabica Rech.f.

Atractylis cancellata L.

Centaurea pseudosinaica Czerep.

Cyanthillium cinereum (L.) H.Rob.

Dicoma schimperi (DC.) Baill. ex O.Hoffm.

Echinops erinaceus Kit Tan

Eclipta prostrata (L.) L.

Euryops arabicus Steud. ex Jaub. & Spach

Filago desertorum Pomel

Helichrysum glumaceum DC.

Iphiona aucheri (Boiss.) Anderb.

Iphiona horrida Boiss.

Jurinea berardioides (Boiss.) O.Hoffm.

Launaea bornmuelleri (Hausskn. ex Bornm.) Bornm.

Launaea intybacea Beauverd

Launaea omanensis N.Kilian

Notobasis syriaca Cass.

Osteospermum vaillantii (Decne.)

Phagnalon schweinfurthii Sch.Bip. ex Schweinf.

Pluchea arabica (Boiss.) Qaiser & Lack

Pulicaria arabica Cass.

Pulicaria glutinosa Jaub. & Spach subsp. *glutinosa*

Reichardia tingitana Roth

Senecio breviflorus (Kadereit) Greuter

Urospermum picroides (L.) Scop. ex F.W.Schmidt

Vernonia arabica F.G.Davies

Volutaria lippii Cass.

Xanthium strumarium L.

Zoegea purpurea Fresen.

Boraginaceae

Arnebia hispidissima (Sieber ex Lehm.) A.DC.

Echiochilon callianthum Lönn

Echiochilon persicum (Burm.f.) I.M.Johnst.

Euploca rariflora (Stocks) Diane & Hilger

Euploca strigosa (Willd.) Diana & Hilger

Heliotropium bacciferum Forssk.

Heliotropium calcareum Stocks

Lappula sp. A. sensu R.R. Mill. ined.

Lappula spinocarpos (Forssk.) Asch. ex Kunze

Microparacaryum intermedium (Fresen.) Hilger & Podlech

Trichodesma africanum (L.) Sm.

Trichodesma ehrenbergii Schweinf.

Trichodesma stocksii Boiss.

Brassicaceae

Diplotaxis harra (Forssk.) Boiss.

Eruca vesicaria (L.) Cav.

Farsetia aegyptia Turra

Farsetia linearis Decne. ex Boiss.

Farsetia stylosa R.Br.

Morettia parviflora Boiss.

Morettia philaeana (Delile) DC.

Notoceras bicorne (Aiton) Amo

Physorhynchus chamaerapistrum (Boiss.) Boiss.

Sisymbrium erysimoides Desf.

Sisymbrium irio L.

Burseraceae

Commiphora kua (R.Br. ex Royle) Vollesen

Commiphora myrrha (T.Nees) Engl.

Commiphora wightii (Arn.) Bhandari

Campanulaceae

Campanula erinus L.

Capparidaceae

Capparis cartilaginea Decne.

Capparis spinosa var. mucronifolia (Boiss.) Hedge & Lamond ex R.R.Stewart

Cleome pallida Kotschy

Maerua crassifolia Forssk.

Maerua oblongifolia (Forssk.) A.Rich

Caprifoliaceae

Lomelosia olivieri (Coult.) Greuter & Burdet

Lonicera hypoleuca Decne.

Caryophyllaceae

Cometes surattensis Burm.f.

Dianthus crinitus Sm.

Gymnocarpos decander Forssk.

Gymnocarpos sclerocephalus (Decne.) Dahlgren & Thulin

Gypsophila bellidifolia Boiss.

Herniaria hirsuta L.

Herniaria maskatensis Bornm.

Paronychia arabica (L.) DC.

Polycarpaea robbairea (Kuntz) Greuter & Burdet

Polycarpaea spicata Wight ex Arn.

Polycarpon succulentum (Del.) J.Gay

Silene austroiranica Rech.f., Aellen & Esfand.

Silene chirensis A.Rich.

Silene conoidea L.

Silene villosa Forssk.

Spergularia flaccida (Madden) I.M.Turner

Sphaerocoma hookeri subsp. aucheri (Boiss.) Kool & Thulin

Telephium sphaerospermum Boiss.

Celastraceae

Gymnosporia sp.

Cistaceae

Helianthemum kahiricum Delile

Helianthemum lippii (L.) Dum.Cours.

Cleomaceae

Cleome amblyocarpa Barratte & Murb.

Cleome brachycarpa Vahl ex DC.

Cleome droserifolia (Forssk.) Delile

Cleome gynandra L.

Cleome quinquenervia DC.

Cleome rupicola Vicary

Cleome scaposa DC.

Convolvulaceae

Convolvulus acanthocladus Boiss. & Kotschy

Convolvulus arvensis L.

Convolvulus hystrix Vahl

Convolvulus pilosellifolius Desr.

Convolvulus ulicinus Boiss.

Convolvulus virgatus Boiss.

Cuscuta planiflora Ten.

Seddera latifolia Hochst. & Steud.

Crassulaceae

Rosularia adenotricha (Wall. ex Edgew.) C.-A. Jansson

Cucurbitaceae

Citrullus colocynthis (L.) Schrad.

Corallocarpus epigaeus (Rottler) Hook.f.

Cucumis prophetarum L.

Cyperaceae

Cladium mariscus (L.) Pohl

Cyperus aff. wissmannii O.Schwartz

Cyperus laevigatus L.

Cyperus rotundus L.

Eleocharis caduca (Delile) Schult.

Eleocharis geniculata (L.) Roem. & Schult.

Fimbristylis cymosa var. *spathacea* (Roth) T.Koyama

Fimbristylis ferruginea subsp. *sieberiana* (Kunth) Lye

Schoenoplectus litoralis (Schrad.) Palla

Schoenus nigricans L.

Elatinaceae

Bergia polyantha Sond.

Ephedraceae

Ephedra foliata Boiss. ex C.A.Mey.

Ephedra pachyclada Boiss.

Equisetaceae

Equisetum ramosissimum Desf.

Euphorbiaceae

Acalypha indica L.

Chrozophora oblongifolia (Delile) A.Juss. ex Spreng.

Dalechampia scandens var. *cordofana* (Hochst. ex Webb) Müll.Arg.

Euphorbia arabica Hochst. & Steud. ex T.Anderson

*Euphorbia granulat*a Forssk.

Euphorbia helioscopia L.

Euphorbia hirta L.

Euphorbia indica Lam.

Euphorbia larica Boiss.

Euphorbia peplus L.

Ricinus communis L.

Fabaceae

Argyrolobium crotalarioides Jaub. & Spach

Argyrolobium roseum Jaub. & Spach

Astragalus arpilobus subsp. *hauarensis* (Boiss.) Podlech

Astragalus fasciculifolius subsp. *arbusculinus* (Bornm. & Gauba) Tietz

Astragalus termeanus Maasoumi & Podlech

Astragalus tribuloides Delile

Ceratonia oreothauma Hillc., G.P.Lewis & Verdc.

Crotalaria aegyptiaca Benth.

Crotalaria persica (Burm.f.) Merr.

Crotalaria retusa L.

Ebenus stellata Boiss.

Indigofera arabica Jaub. & Spach

Indigofera articulata Gouan

Indigofera cordifolia B.Heyne ex Roth

Indigofera intricata Boiss.

Indigofera oblongifolia Forssk.

Indigofera spinosa Forssk.

Lotus garcinii Ser.

Medicago polymorpha L.

Medicago sativa L.

Melilotus indicus (L.) All.

Prosopis cineraria (L.) Druce

Pseudolotus villosus (Blatt. & Hallb.) Ali & D.D.Sok.

Rhynchosia minima (L.) DC.

Senna holosericea (Fresen.) Greuter

Senna italica Mill.

Taverniera cuneifolia (Roth) Arn.

Tephrosia nubica (Boiss.) Baker

Tephrosia persica Boiss.

Tephrosia purpurea subsp. *apollinea* (Delile) Hosni & El-Karemy

Tephrosia purpurea subsp. *leptostachya* (DC.) Brummitt

V*achellia flava* (Forssk.) Kyal. & Boatwr.

Vachellia gerrardii var. najdensis (Chaudhary) Ragup., Seigler, Ebinger & Maslin

Vachellia nilotica (L.) P.J.H.Hurter & Mabb.

Vachellia tortilis (Forssk.) Galasso & Banfi

Vicia sativa L.

Geraniaceae

Erodium cicutarium (L.) L'Hér.

Erodium laciniatum (Cav.) Willd.

Erodium neuradifolium Delile ex Godr.

Geranium mascatense Boiss.

Geranium trilophum Boiss.

Monsonia heliotropioides (Cav.) Boiss.

Monsonia nivea (Decne.) Webb

Hydrocharitaceae

Najas marina L.

Juncaceae

Juncus rigidus Desf.

Lamiaceae

Lavandula subnuda Benth.

Leucas inflata Benth.

Rydingia persica (Burm. f.) Scheen & V.A.Albert

Salvia aegyptiaca L.

Salvia macrosiphon Boiss.

Salvia sp.

Teucrium stocksianum subsp. *stenophyllum* R.A.King

Zataria multiflora Boiss.

Liliaceae

Gagea sp. aff. *reticulata*

Linaceae

Linum corymbulosum Rchb.

Lythraceae

Ammannia baccifera L.

Lawsonia inermis L.

Malpighiaceae

Acridocarpus orientalis A.Juss.

Malvaceae

Abutilon fruticosum Guill. & Perr.

Abutilon pannosum (G.Forst.) Schltdl.

Corchorus depressus (L.) Peterm.

Corchorus trilocularis L.

Grewia erythraea Schweinf.

Grewia tenax (Forssk.) Fiori

Hibiscus micranthus L.f.

Hibiscus palmatus Forssk.

Hibiscus somalensis Franch.

Malva parviflora L.

Malvastrum coromandelianum (L.) Garcke

Menispermaceae

Cocculus pendulus (J.R.Forst. & G.Forst.) Diels

Moraceae

Ficus carica L.

Ficus johannis Boiss.

Ficus salicifolia (Vahl)

Ficus vasta Forssk.

Moringaceae

Moringa peregrina (Forssk.) Fiori

Myrtaceae

Myrtus communis L.

Nyctaginaceae

Boerhavia diffusa L.

Boerhavia elegans Choisy

Commicarpus boissieri (Heimerl) Cufod.

Commicarpus helenae (Roem. & Schult.) Meikle

Commicarpus mistus Thulin

Commicarpus stenocarpus (Chiov.) Cufod.

Commicarpus stenocarpus (Chiov.) Cufod.

Oleaceae

Olea europaea subsp. *cuspidata* (Wall. & G.Don) Cif.

Ophioglossaceae

Ophioglossum polyphyllum A. Braun ex Schub.

Orchidaceae

Epipactis veratrifolia Boiss. & Hohen.

Orobanchaceae

Lindenbergia arabica (S.Moore) Hartl

Lindenbergia indica (L.) Vatke

Oxalidaceae

Oxalis corniculata L.

Papaveraceae

Fumaria abyssinica Hammar

Phyllanthaceae

Andrachne aspera Spreng.

Andrachne telephioides L.

Phyllanthus amarus Schumach. & Thonn.

Plantaginaceae

Campylanthus hajarensis Hjertson, Henrot & Thulin

Nanorrhinum hastatum (R.Br. ex Benth.) Ghebr.

Plantago afra L.

Plantago amplexicaulis Cav.

Plantago boissieri Hausskn. & Bornm.

Plantago ciliata Desf.

Plantago ovata Forssk.

Schweinfurthia imbricata A.G.Mill., M.Short & D.A.Sutton

Schweinfurthia papilionacea (L.) Boiss.

Plumbaginaceae

Dyerophytum indicum (Gibbs ex Wight) Kuntze

Poaceae

Aristida abnormis Chiov.

Aristida adscensionis L.

Aristida mutabilis Trin. & Rupr.

Brachiaria ovalis Stapf

Brachypodium distachyon (L.) P.Beauv.

Bromus fasciculatus C.Presl

Bromus pectinatus Thunb.

Castellia tuberculosa (Moris) Bor

Cenchrus ciliaris L.

Cenchrus divisus (J.F.Gmel.) Verloove, Govaerts & Buttler

Cenchrus echinatus L.

Cenchrus orientalis (Rich.) Morrone

Cenchrus pennisetiformis Steud.

Cenchrus purpureus (Schumach.) Morrone

Cenchrus setaceus (Forssk.) Morrone

Chloris barbata Sw.

Chloris flagellifera (Nees) P.M.Peterson

Chrysopogon aucheri (Boiss.) Stapf

Chrysopogon plumulosus Hochst.

Cymbopogon commutatus (Steud.) Stapf

Cymbopogon pospischilii (K.Schum.) C.E.Hubb.

Cymbopogon schoenanthus (L.) Spreng.

Cynodon dactylon (L.) Pers.

Dactyloctenium aegyptium (L.) Willd.

Desmidorchis arabica (N.E.Br.) Meve & Liede

Desmostachya bipinnata (L.) Stapf

Dichanthium annulatum (Forssk.) Stapf

Dichanthium foveolatum (Delile) Roberty

Digitaria ciliaris (Retz.) Koeler

Digitaria nodosa Parl.

Echinochloa colonum (L.) Link

Eleusine coracana (L.) Gaertn.

Enneapogon desvauxii P.Beauv.

Enneapogon persicus Boiss.

Eragrostis barrelieri Daveau

Eragrostis cilianensis (All.) Janch.

Eragrostis minor Host

Eragrostis papposa (Roem. & Schult.) Steud.

Eragrostis viscosa (Retz.) Trin.

Fingerhuthia africana Nees ex Lehm.

Heteropogon contortus (L.) P.Beauv. ex Roem. & Schult.

Hyparrhenia hirta (L.) Stapf

Panicum turgidum Forssk.

Phalaris minor Retz.

Phragmites australis (Cav.) Trin. ex Steud. subsp. *australis*

Polypogon monspeliensis (L.) Desf.

Polypogon viridis (Gouan) Breistr.

Saccharum kajkaiense (Melderis) Melderis

Saccharum spontaneum L.

Setaria geminata (Forssk.) Veldkamp

Setaria verticillata (L.) P.Beauv.

Setaria viridis (L.) P.Beauv.

Sporobolus ioclados (Nees ex Trin.) Nees

Sporobolus spicatus (Vahl) Kunth

Sporobolus tenuissimus (Mart. ex Schrank) Kuntze

Stipa mandavillei Freitag

Stipagrostis ciliata (Desf.) De Winter

Stipagrostis hirtigluma (Steud. ex Trin. & Rupr.) De Winter

Stipagrostis paradisea (Edgew.) De Winter

Stipagrostis plumosa (L.) Munro ex T.Anderson

Stipagrostis raddiana (Savi) De Winter

Stipagrostis uniplumis (Licht.) De Winter

Tetrapogon villosus Desf.

Tragus berteronianus Schult.

Tricholaena teneriffae (L.f.) Link

Trichoneura mollis (Kunth) Ekman

Tripidium ravennae (L.) H.Scholz

Tripogon africanus (Coss. & Durieu) H.Scholz & P.König

Tripogon purpurascens Duthie

Urochloa maxima (Jacq.) R.D.Webster

Vicoa divaricata (Cass.) Oliv. & Hiern

Polygalaceae

Polygala dispar Ghaz .

Polygala erioptera DC.

Polygala irregularis Boiss.

Polygala mascatensis Boiss.

Polygonaceae

Pteropyrum scoparium Jaub. & Spach

Rumex conglomeratus Murray

Rumex limoniastrum Jaub. & Spach

Rumex vesicarius L.

Portulacaceae

Portulaca oleracea L.

Potamogetonaceae

Potamogeton nodosus Poir.

Stuckenia pectinata (L.) Börner

Primulaceae

Dionysia mira (Jaub. & Spach.) Wendelbo

Lysimachia linum-stellatum L.

Lysimachia arvensis var. *caerulea* (L.) Turland & Bergmeier

Pteridaceae

Actiniopteris semiflabellata Pic.Serm.

Adiantum capillus-veneris L.

Cosentinia vellea (Aiton) Tod.

Elaphoglossum callifolium (Blime) J.Sm.

Hemionitis pteridioides (Reichard) Christenh.

Onychium divaricatum (Poir.) Alston

Pteris vittata L.

Ranunculaceae

Clematis orientalis L.

Ranunculus muricatus L.

Resedaceae

Ochradenus arabicus Chaudhary, Hillc. & A.G. Mill.

Ochradiscus aucheri (Boiss.) S.Blanco & C.E.Wetzel

Oligomeris linifolia (Vahl ex Hornem.) J.F.Macbr.

Reseda aucheri Boiss.

Reseda muricata C.Presl

Rhamnaceae

Sageretia thea (Osbeck) M.C.Johnst.

Ziziphus hajarensis Duling, Ghaz. & Prend.

Ziziphus nummularia (Burm.f.) Wight & Arn.

Ziziphus spina-christi (L.) Desf.

Rosaceae

Prunus arabica (Olivier) Meikle

Rubiaceae

Callipeltis cucullaris (L.) DC.

Galium setaceum Lam.

Kohautia caespitosa Schnizl.

Kohautia retrorsa (Boiss.) Bremek.

Plocama aucheri (Guill.) M.Backlund & Thulin

Plocama calycoptera (Decne) M.Backlund & Thulin

Plocama hymenostephana (Jaub. & Spach) M.Backlund & Thulin

Rubia infundibularis Hemsl. & Lace

Ruppiaceae

Ruppia maritima L.

Rutaceae

Haplophyllum tuberculatum (Forssk.) Juss.

Salicaceae

Salix acmophylla Boiss.

Salvadoraceae

Salvadora persica L.

Sapindaceae

Dodonaea viscosa (L.) Jacq.

Sapotaceae

Sideroxylon mascatense (A.DC.) T.D.Penn.

Scrophulariaceae

Bacopa monnieri (L.) Wettst.

Misopates orontium (L.) Raf.

Scrophularia arguta Aiton

Verbascum akdarense (Murb.) Hub.-Mor.

Verbascum omanense Hub.-Mor.

Solanaceae

Datura metel L.

Hyoscyamus insanus Stocks

Lycium shawii Roem. & Schult.

Physalis angulata L.

Solanum americanum Mill.

Solanum coagulans Forssk.

Solanum incanum L.

Withania coagulans (Stocks) Dunal

Withania somnifera (L.) Dunal

Sterculiaceae

Melhania muricata Balf.f.

Melhania ovata (Cav.) Spreng.

Tamaricaceae

Tamarix aphylla (L.) H.Karst.

Tamarix senegalensis DC.

Thymelaeaceae

Daphne mucronata Royle

Typhaceae

Typha domingensis Pers.

Urticaceae

Forsskaolea tenacissima L.

Parietaria alsinefolia Delile

Verbenaceae

Phyla nodiflora (L.) Greene

Violaceae

Viola cinerea Boiss.

Xanthorrhoeaceae

Asphodelus fistulosus L.

Zygophyllaceae

Balanites aegyptiaca (L.) Delile

Seetzenia lanata (Willd.) Bullock

Tribulus pentandrus Forssk.

Tribulus terrestris L.

Zygophyllum bruguieri (DC.) Christenh. & Byng

Zygophyllum indicum (Burm.f.) Christenh. & Byng

Zygophyllum paulayanum (J.Wagner & Vierh.) Christenh. & Byng

Zygophyllum qatarense Hadidi

Zygophyllum simplex L.