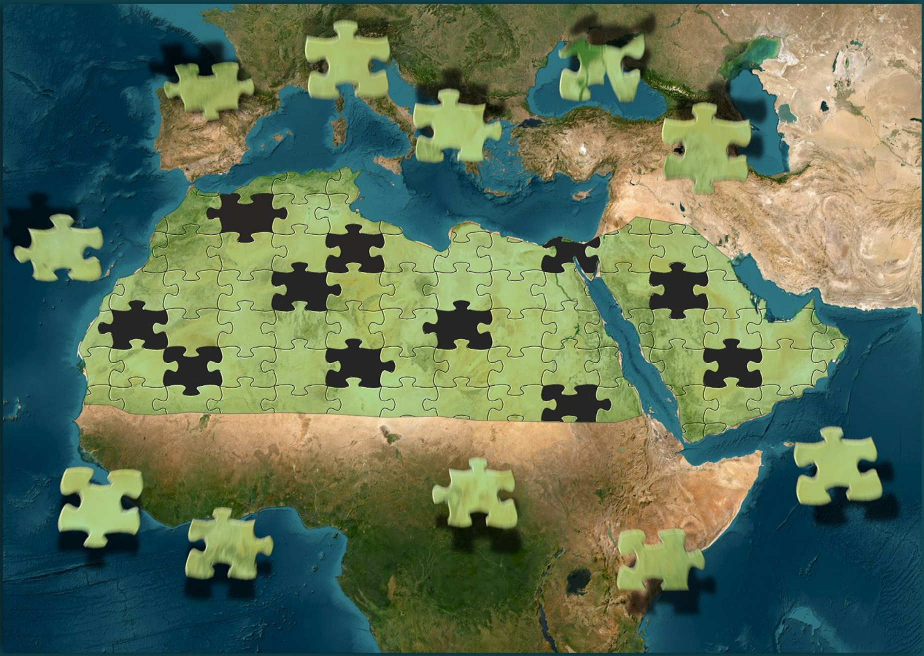
Deserts unveiled

Exploring the biodiversity of the Saharo-Arabian desert vegetation



Mohamed Zakaria Hatim

Propositions

1. The concept of desert as a homogeneous ecosystem is a myth.
   (this thesis)
2. Understanding desert ecosystem complexity requires the combination of traditional phytosociology with advanced statistics.
   (this thesis)
3. Increased measurement precision hinders scientific generalization.
4. Classification systems perpetuate the illusion of natural boundaries.
5. The pursuit of happiness as a societal goal undermines collective well-being.
6. Sandboarding will become a popular sport in European mountains.

Propositions belonging to the thesis, entitled

Deserts unveiled: Exploring the biodiversity of the Saharo-Arabian desert vegetation

Mohamed Zakaria Hatim

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Deserts unveiled: Exploring the biodiversity of the Saharo-Arabian desert vegetation

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Centaurea eryngioides species growing in the desert of Sinai, Egypt (Photo by Mohamed Zakaria Hatim, 2010, Winner of JVS & AVS picture competition)

To the beings who taught me that one can grow and flourish even in the harshest circumstances: I hope I have told your story well enough and helped to shine a light on your quiet strength.

1

General Introduction

1.1 Introduction to deserts

The exploitation of our planet's resources and the resulting deterioration of biodiversity are pressing global issues that demand urgent attention. Kumari et al. (2021) highlight how rapid population growth has led to increased food demand, prompting agricultural expansion at the expense of wildlife and biodiversity. Additional factors such as habitat fragmentation, pollution, invasive species, and climate change further exacerbate this problem. Moranta et al. (2021) argue that the continuous expansion of the physical economy, driven by the capitalist model, has resulted in unprecedented environmental degradation and species extinction.

Within this context of the global ecological crisis, desert ecosystems emerge as particularly vulnerable. Characterized by minimal precipitation, high evaporation rates, nutrient-poor sandy soils, and limited drought-resistant species, deserts exhibit extremely low productivity. These harsh conditions significantly reduce the self-regulation capacity of desert ecosystems, making them especially sensitive to disturbances. Human activities such as overgrazing, mining, industrial development, and changes in water usage further increase the fragility of these ecosystems, highlighting the urgent need for comprehensive conservation efforts (Kinney, 1995).

However, it is crucial to realize and recognize that deserts, including those in North Africa and the Middle East, are not merely barren lands. They hold significant ecological and biodiversity value, hosting various unique plant species adapted to extreme conditions. Recent studies in areas such as Rawdhat Abalworood and Albaha have highlighted the unique flora in these regions, emphasizing their crucial role in maintaining ecological balance and providing essential ecosystem services (Alghanem & Alhaithloul, 2023; Al-Khulaidi & Al-Namazi, 2022).

Recent research underscores the importance of conducting taxonomical and plant ecology studies in the deserts of North Africa and the Middle East to mitigate biodiversity loss and desertification. Studies in the semi-arid lands of North Africa have revealed significant plant diversity linked to soil properties, highlighting the need for detailed taxonomical research to understand these ecosystems better and to develop targeted conservation efforts (Souahi et al., 2022). An investigation of the flora and soil biodiversity in the arid rangelands of eastern Morocco has underscored the rich plant diversity and the critical role of taxonomical studies in maintaining ecosystem health (Hachmi et al., 2023).

This dissertation focuses on the Saharo-Arabian region, including the Sinai Peninsula and the Arabian Peninsula. This region, the largest hot arid area in the world (Fig. 1), is of particular interest due to its distinct geographical and climatic attributes within arid landscapes (White, 1983). The Sinai Peninsula, characterized by its mountainous terrain and coastal proximity, experiences a unique blend of Mediterranean and desert climates. This combination leads to significant variations in temperature and precipitation patterns, creating microclimates that support diverse plant and animal species adapted to extreme conditions (Danin & Orshan, 1990).

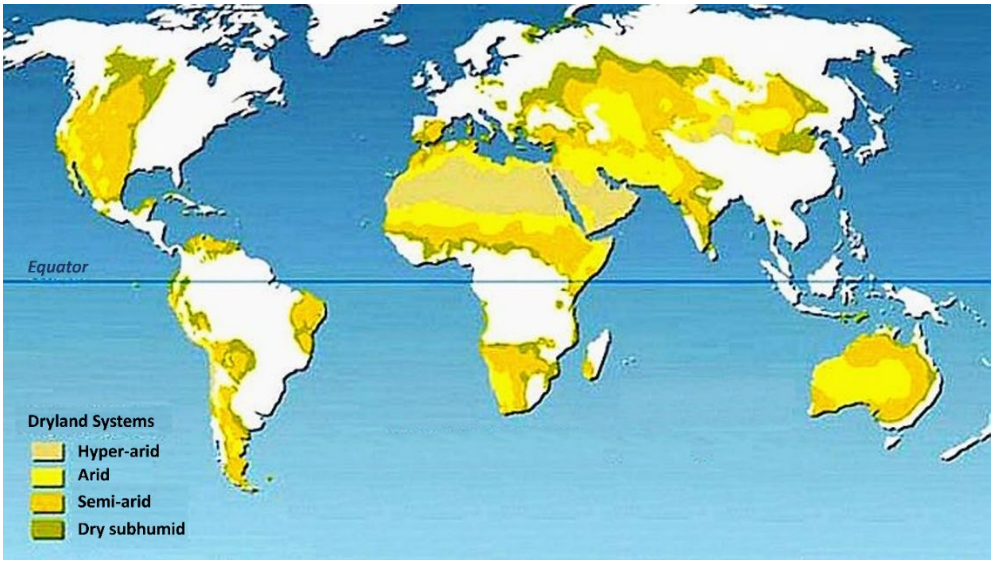

Figure 1. Global Distribution of dryland systems. The map illustrates the global distribution of dryland systems, categorized into hyper-arid, arid, semiarid, and dry subhumid regions. Drylands make up 41.3% of the global terrestrial area. Source: Millennium Ecosystem Assessment.

The Arabian Peninsula exhibits extreme aridity, with vast deserts like the Rub' al Khali (Empty Quarter), that receive minimal rainfall and have high evaporation rates. This region's climate is heavily influenced by its geographical location, which subjects it to persistent high-pressure systems that inhibit precipitation. The harsh climatic conditions have led to the evolution of specialized flora and fauna adapted to survive in such an environment (Ghazanfar, 1991).

The vegetation in these regions not only represents adaptation and endurance but also reflects complex ecological interactions and evolutionary processes. The relationships among various plant species and their environments demonstrate evolutionary, adaptive, and survival strategies refined over millennia, enabling these species to thrive in extreme temperatures, water scarcity, and nutrient-poor soils (Ward, 2009; Smith et al., 1997). For instance, perennial plants in the Ouargla region of Algeria have developed physiological, morphological, and reproductive adaptation parameters to thrive in the intense heat, minimal precipitation, and nutrient-poor soils of the hyper-arid Saharan environment (Noureddine & Chehma, 2009).

These adaptations, as elucidated further on, include the development of deep root systems to access water from deeper soil layers, small, thick, or waxy leaves to minimize water loss through transpiration, and CAM (Crassulacean Acid Metabolism) photosynthesis in some species. Morphologically, many plants possess features that protect them from herbivores and reduce heat absorption, such as spines or thick, tough leaves. Reproductive adaptations include producing seeds that can remain dormant for extended periods until more favourable conditions arise.

This research aims to advance our knowledge of the desert vegetation in these regions through in-depth exploration of their ecological and vegetation characteristics and distribution. Such knowledge is essential for supporting efforts to mitigate biodiversity loss and desertification, and is pivotal for developing effective conservation strategies and addressing the ecological challenges posed by climate change and human activities (Davis, 2016).

1.2 Background

Deserts are predominantly found in specific latitudinal belts and regions due to distinct climatic and geographical factors. Most of the world deserts are located in two main latitudinal zones: subtropical and mid-latitude. Subtropical deserts, which include prominent examples such as the Sahara Desert in North Africa, the Arabian Desert in the Arabian Peninsula, the Kalahari Desert in Southern Africa, the Great Victoria Desert in Australia, and the Mojave and Sonoran Deserts in North America, are typically situated around the Tropics of Cancer and Capricorn, between approximately 20° to 30° north and south of the equator (Wikle, 2017). These deserts are largely formed due to persistent high-pressure systems in these latitudes, known as subtropical ridges, which inhibit cloud formation and precipitation. As warm air rises near the equator, it cools and releases moisture as rain. The now-dry air then descends around 20° to 30° latitude, creating the prevailing arid conditions (Nicholson, 2011).

Mid-latitude deserts are found at higher latitudes, typically between 30° to 50° north and south of the equator. Examples include the Gobi Desert in Mongolia and China, the Patagonian Desert in Argentina, and the Great Basin Desert in the United States (Kimura & Moriyama, 2019). These deserts are often influenced by the rain shadow effect, where moist air rises and cools as it travels up the windward side of mountains, causing precipitation. When the air descends on the leeward side, it is dry, creating desert conditions. Notable examples of this phenomenon include the Atacama Desert in South America, created by the Andes Mountains, and the Mojave Desert in the United States, influenced by the Sierra Nevada (Dragotă et al., 2011).

In addition to latitudinal placement, deserts can also form in interior continental regions far from any ocean, where moist air masses rarely reach. These interior continental deserts include the Gobi Desert in Central Asia and the Great Basin Desert in the United States (Ahmed et al., 2014). Furthermore, coastal deserts such as the Namib Desert in Namibia and the Atacama Desert in Chile are influenced by cold ocean currents, which cool the air and reduce its ability to hold moisture, leading to deficient rainfall (Tobosque et al., 2022).

The deserts prevalent in North Africa and the Middle East from the Saharo-Arabian phytogeographic region (Takhtajan, 1986) (Fig. 2). These regions exemplify harsh environments characterized by extreme aridity, significant temperature fluctuations, and nutrient-poor soils (Noy-Meir, 1973). Such abiotic conditions make life extremely difficult for plants and animals. Despite these challenges, deserts support a conspicuous variety in plant life, demonstrating remarkable adaptability to their ecological conditions (Ehleringer, 1985).

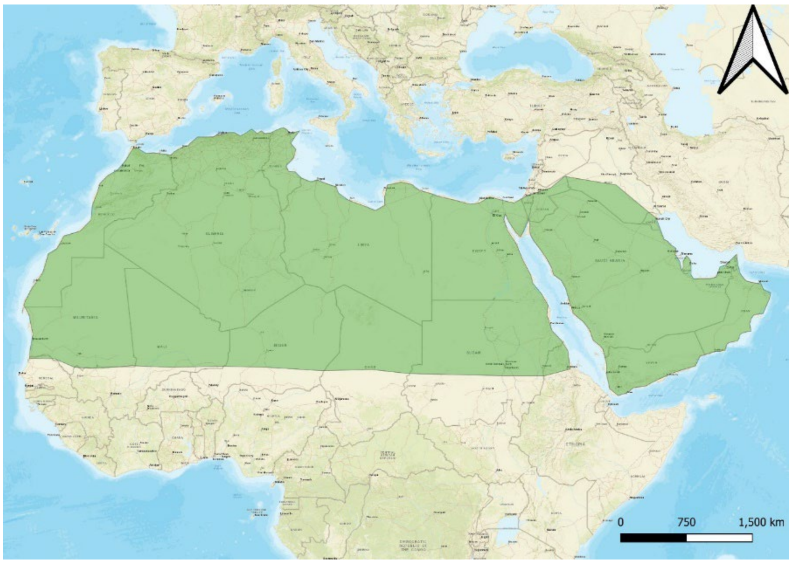

Figure 2. Map illustrating the extent of the Saharo-Arabian region as defined by Takhtajan (1986).

1.2.1 Climatic Conditions of the Saharo-Arabian region

The Saharo-Arabian region is predominantly characterized by extreme aridity, making it one of the harshest environments on Earth. This region spans vast areas of North Africa and the Arabian Peninsula, encompassing diverse desert regions such as the Sahara Desert and the Arabian Desert.

Annual precipitation in the Saharo-Arabian region is very low, often less than 100 mm per year in many areas. This scant rainfall is highly irregular, both spatially and temporally, with some locations experiencing years without any precipitation. The distribution of rainfall is not only uneven but when it does occur; it is often in the form of short, intense storms that can lead to flash flooding. This variability in precipitation significantly influences the distribution of vegetation types and determines other ecological processes in the region, like erosion and sedimentation (Noy-Meir, 1973).

The region exhibits significant temperature fluctuations, contributing to its harsh climatic conditions. Daytime temperatures can rise above 50°C (122°F) during the summer, while nighttime temperatures can drop to near freezing, especially in winter (Goudie, 2002). The Saharo-Arabian region receives intense solar radiation, with high levels of insolation throughout the year. This contributes to the extreme daytime temperatures and a rapid heating of the ground surface (Jury & Vaux, 2005).

High rates of evaporation are a defining feature of the Saharo-Arabian climate. Evaporation often exceeds precipitation, leading to a significant moisture deficit. Potential evaporation rates can be as high as 3,000 mm per year, far surpassing the minimal rainfall. This high evaporation results in extreme dry soil conditions, accumulation of salt in the upper soil layers, and limits the availability of water for plants and animals (Le Houérou, 1980).

The region is also influenced by persistent and strong winds, which contribute to the desiccation of the landscape. These winds can transport sand and dust over vast distances, forming extensive dune systems (ergs) and impacting soil moisture levels. The wind patterns are responsible for the formation of various desert landforms, such as hamadas and regs (see the next paragraph), by eroding and depositing materials across the landscape (Cooke et al., 2006).

1.2.2 Geology and landforms

The deserts of Saharo-Arabian region (Fig. 3), including the Sahara and Arabian deserts, are characterized by diverse and complex geological features, ranging from lowlands to high mountains. The Sahara Desert spans approximately 9.2 million square kilometres and primarily comprises sand dunes, gravel plains, rocky plateaus, and dry valleys. One of the prominent geological formations in the Sahara is the Tsondab Sandstone Formation, found in the central Namib Desert. This formation includes eolian (wind-blown) dune deposits as well as fluvial (river) and playa (dry lake) sediments, indicating a combination of desert and water-related geological processes that have shaped the landscape over time (Ward, 1988).

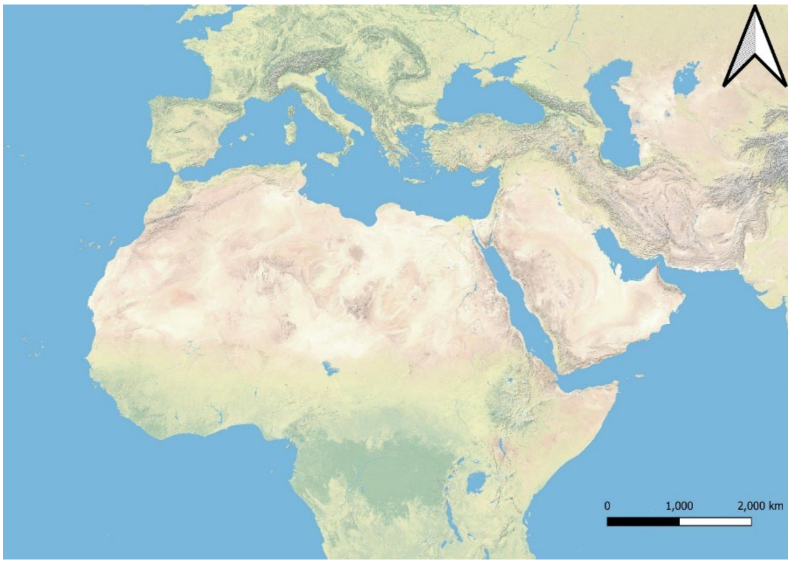

Figure 3. A map showing the geological features of Saharo-Arabian deserts. Source: Esri.

In the Arabian Peninsula, the geology is equally varied. The Arabian Shield, a region of Precambrian crystalline rocks, dominates the western part of the peninsula. This shield includes several distinct geological formations, such as the Pan-African orogeny near Wadi Um Relan in the Eastern Desert of Egypt. This region's geological history is marked by significant tectonic activities that have influenced the current landscape (Taylor et al., 2017). Additionally, the East Gilf Kebir basalt in Southwestern Egypt provides insights into the paleo-tectonic positions of Northeast Africa during the Cretaceous-Paleocene period, revealing a far south tropical paleo-latitude compared to present-day (Lotfy & Odah, 2015).

Gypsum crusts are another notable geological feature found in the deserts of North Africa and the Middle East. These crusts, which can be classified into shallow-water evaporites, subsurface crusts, and surface crusts, exhibit distinct diagenetic features and characteristic textures and structures (Watson, 1988).

Various landforms characterise the Saharo-Arabian region deserts, each influencing the type of vegetation that can thrive in these arid environments. Understanding these landforms is crucial for explaining the ecological and botanical diversity of these regions (Le Houérou, 1985).

One prominent landform is the hamada (Fig. 4), a desert landscape characterized by a barren, hard, rocky plateau with little to no sand. Hamadas are typically composed of large expanses of exposed bedrock or compacted gravels and are often the result of wind erosion stripping away finer particles. Vegetation in hamadas is sparse due to the lack of soil, with only drought-resistant plants surviving in cracks and crevices where some moisture can be retained (Evenari et al., 1987).

Figure 4. Hamada landform in the Sahara Desert, Morocco. Photograph by Dago Bert, 2023.

In contrast, ergs (Fig. 5) are vast expanses of sand dunes formed by the accumulation of wind-blown sand. These "sand seas" can cover hundreds of square kilometres and are highly dynamic, with dunes constantly shifting due to wind activity. The vegetation in ergs is extremely sparse, usually limited to specialized plants that can anchor themselves in the sand and tolerate extreme aridity, such as certain types of grasses and shrubs that stabilize the dunes (Faour et al., 2016). Parts of the ergs are entirely bare of plants.

Regs (Fig. 6), also known as desert pavements, are areas covered with a surface layer of closely packed, interlocking rock fragments of pebble and gravel size. These regions result

Figure 5. Erg landform in the Sahara Desert, Algeria, Source: https://kudatotam.ru/.

from the deflation of finer particles by wind, leaving behind a surface of coarse materials. Regs typically exhibit higher vegetation diversity due to their more stable substrate and better moisture retention, with plants adapting to shallow soils and reduced water infiltration, including species with extensive root systems that can reach deep underground moisture (Ballantine et al., 2005).

Figure 6. Reg landform in the Sahara Desert, Mauritania. Photograph by Ji Elle, 2010.

Another significant landform is the wadi (Fig. 7), a dry riverbed that only contains water during periods of heavy rain. Wadis vary greatly in size and are often characterized by steep sides and a flat bottom. The soil can be relatively sandy, rocky or even clayey. Vegetation in Wadis can be surprisingly lush compared to surrounding desert areas, as these regions can collect and retain more water, allowing for the growth of various shrubs, grasses, and even small trees (Bar-Matthews, 2014).

Figure 7. Wadi landform in Wadi Shawka, UAE. Photograph by Alexander Mcnabb, 2020.

Playas (Fig. 8), or dry lake beds, are flat-bottomed depressions found in deserts that occasionally hold water after infrequent rainstorms. The soil in playas is often highly saline, and as the water evaporates, it leaves behind salt flats. Vegetation in playas is specialized to tolerate high salinity, with halophytic plants being the most common (El-Ghani et al., 2017).

Figure 8. Playa landform in Sahara desert, Morocco. Photograph by Tupatu, 2022.

Each landform has several associated vegetation types and presents unique challenges and opportunities for plant life, contributing to the overall biodiversity and ecological complexity of desert regions in North Africa and the Middle East.

1.2.3 Vegetation and Flora

The vegetation in the Saharo-Arabian region is primarily composed of xerophytic plants, which have evolved a range of adaptations to survive in harsh, water-scarce environments.

These adaptations enable plants to thrive despite the extreme aridity and nutrient-poor soils that characterize the region. Xerophytes include a variety of shrubs, grasses, and herbaceous plants. These plants have developed several physiological and morphological adaptations to minimize water loss and maximize water uptake. Many xerophytic plants have extensive root systems that penetrate deep into the soil to access groundwater. For example, *Vachellia* (= *Acacia*) species can extend their roots over 30 meters deep to reach subsurface moisture (Fahn & Cutler, 1992).

To reduce transpiration, many xerophytes have small, narrow leaves or modified leaf structures such as spines or scales. This adaptation is common in genera like *Artemisia* (including *Seriphidium*) and *Euphorbia*. It minimizes water loss, while essential photosynthetic functions can still be performed (Gutterman, 2002).

Some other xerophytes, so-called succulents, have specialized water storage tissues. This adaptation allows them to maintain physiological processes during prolonged dry periods. The genus *Euphorbia*, for instance, includes many species that can store significant amounts of water in their stems and leaves (Nobel, 1988). One notable example is *Aloe armatissima* (Fig. 9), found in the Al-Shafa Highlands in Taif, Western Saudi Arabia. This species has thick, fleshy leaves that can store significant amounts of water, enabling it to maintain physiological processes during prolonged dry periods (Alsherif & Fadl, 2016). Another example includes *Centaurothamnus maximus*, a succulent known for its ability to store water in its tissues, helping it survive in the harsh conditions of the Saharo-Arabian deserts(Alsherif & Fadl, 2016).

Figure 9. Aloe armatissima, a succulent species in Western Saudi Arabia. Photograph by S. Collenette, 2014.

Halophytic plants are prevalent in saline areas, such as playas and salt flats. These plants have adapted to thrive in high-salinity soils where most other plant species would not survive.

Some halophytes, such as *Suaeda vermiculata* (Fig. 10), have specialized glands that excrete excess salt, allowing them to manage the high saline content in their tissues (Labidi et al., 2010). Other halophytic plants, such as *Sporobolus alterniflorus* and *Aizoon pubescens*, often accumulate organic solutes and ions in their cells to balance the osmotic pressure and prevent water loss due to the high external salt concentrations (Flowers & Colmer, 2008).

Figure 10. Suaeda vermiculata, a common halophyte in the Saharo-Arabian region. Photograph by Ruth Ripley, 2013.

Plants in the Saharo-Arabian region fulfil essential ecological roles, contributing to the stability and functioning of desert ecosystems. For instance, *Atriplex halimus* (Fig. 11) helps prevent soil erosion by stabilizing the soil with its root systems, particularly in areas prone to wind erosion (Haddi et al., 2003). Also, the plants contribute to nutrient cycling by decomposing organic matter and releasing nutrients into the soil, supporting other plant and microbial life. Another aspect is that the vegetation can create microclimates by providing shade and reducing surface temperatures, benefiting both plant and animal species in the area (Ward, 2009).

1.2.4 Human and Environmental Impact

Human activities and environmental changes have significantly impacted the deserts of North Africa and the Middle East, leading to biodiversity loss, desertification, and socio-economic challenges. The rapid urbanization, economic growth, and industrial activities in these regions have contributed to environmental degradation. For instance, the increase in non-renewable energy consumption has exacerbated air pollution and contributed to the ecological footprint, further straining the fragile desert ecosystems (Nathaniel et al., 2020). Moreover, the intensive agricultural practices and the introduction of new technologies, although aimed at boosting food security, have often led to the over-extraction of water resources and soil degradation, thereby accelerating desertification (Ziadat et al., 2021).

Figure 11. Atriplex halimus, a deep-rooting plant decreasing soil erosion in arid zones in Saharo-Arabian region. Source: freenatureimages.eu.

Climate change further compounds these issues, with increasing temperatures and decreasing precipitation expected to worsen the aridity of the region. The Middle East and North Africa (MENA) region is projected to experience more frequent and severe heat waves, leading to enhanced water scarcity and higher energy demands for cooling, which in turn increases carbon emissions (Lange, 2020). Additionally, desertification driven by climatic factors and human activities has led to significant losses in agricultural productivity and biodiversity, threatening food security and livelihoods (Bayram & Öztürk, 2020).

The socio-economic impacts of these environmental changes are profound. The increasing prevalence of dust storms, a direct consequence of desertification and land degradation, poses severe health risks, including respiratory and cardiovascular diseases, further stressing the healthcare systems in these regions (Soleimani et al., 2020).

Efforts to mitigate these impacts include adopting sustainable land and water management practices, promoting renewable energy, and improving agricultural techniques tailored to the arid environment. Such measures are crucial to enhancing resilience against climate change and ensuring sustainable development in these vulnerable regions (Lefers et al., 2020).

1.4 Land-use needs and challenges

In a modern context marked by climate change and declining biodiversity, examining and understanding desert flora in North Africa and the Middle East are paramount challenges. The implications of such research extend beyond academic enrichment. The insights gained from the current thesis can inform and shape ecological conservation strategies, enhance climate resilience plans, and refine sustainable land use protocols in arid and semi-arid regions. These insights are vital for developing methods to mitigate the adverse effects of ecological changes and human activities, thereby protecting these essential ecosystems from ongoing environmental degradation. This study aims to uncover new patterns and adaptive strategies to address the increasing environmental challenges facing these uniquely diverse and resilient ecosystems.

Numerous studies, including those by Ward (2009) and Maestre et al. (2012), have extensively examined the diverse ecological, floristic, and environmental patterns in desert regions, addressing both biotic interactions and abiotic adaptations. However, Schenk & Jackson (2002) highlight significant knowledge gaps, particularly in aligning syntaxonomical classifications with internationally recognized naming conventions and comprehensively mapping and studying vegetation across varied landscapes, such as the Sinai.

These gaps necessitate a renewed, vigorous approach to exploring and reassessing desert ecosystems (Levin, 1999). It is essential to recognize that these regions, as Noy-Meir (1973) described, are not simple, uniform areas but complex, dynamic systems with many ecological and environmental nuances. Therefore, a meticulous, multifaceted investigation is required to fully understand the intricate interplay of life and environment within these landscapes (Grime, 1977).

The urgent need for detailed and innovative examination is further emphasized by increasing environmental challenges, including climate change, land degradation, and resulting biodiversity loss (Chapin III, 1993). The intricate relationship between changing weather conditions and human impacts on the environment calls for re-evaluating and integrating existing knowledge to develop a comprehensive understanding of desert ecology (Begon et al., 2006).

Present environmental demands, along with ongoing discrepancies in the classification and understanding of desert plants, underscore the necessity for a thorough reassessment and integration of various ecological, floristic, and environmental patterns and processes (Ehleringer, 1985). This refined exploration is critical for closing existing knowledge gaps and advancing ecological science, conservation strategies, and environmental management (Whitford, 2002), ultimately aiding in mitigating ecological degradation and preserving biodiversity within these unique ecosystems (Smith et al., 1997).

1.5 Objectives and structure of this thesis

This thesis is organized into four chapters, each discussing a specific aspect, scale and region of desert vegetation in North Africa and the Middle East. Chapters 2 and 3 present a detailed vegetation study in two different regions: the Sinai and the Hijaz mountain ranges in Saudi Arabia. Chapter 4 uses these and many other studies to construct an overview of the desert vegetation in the whole Saharo-Arabian region. These three chapters provide schemes of vegetation diversity at different scales, with underlying factors, that can be used for nature conservation and land-use policy and planning. Chapter 5 provides an example of the application of the data by predicting future vegetation patterns due to climate change.

Chapter 2 offers an in-depth phytosociological overview of the desert vegetation in Sinai, a recognized global hotspot for flora. The objectives are to categorize, describe and explain the distinct vegetation communities and their distribution. A robust database was constructed utilizing vegetation plot data from existing literature and own field surveys. Several advanced analytical methods, including the modified TWINSPAN, Hopkins' test, and the Silhouette algorithm, were employed to validate vegetation classification into nine main classes, each representing different aspects of Sinai desert vegetation. Within these, 25 vegetation groups were distinguished, with four principal vegetation groups identified: salt desert, lowland desert, mountain desert, and ruderal desert. The chapter uncovers a significant diversity in life forms, chorotypes, and alpha diversity within these main groups. The findings result in an updated, methodologically advanced classification and description of Sinai's desert vegetation, serving as a reference for future studies, conservation efforts, land use, and addressing global change issues related to the region's unique vegetation.

Chapter 3 delves into a detailed study of the flora and vegetation of the foothills of the Hijaz Mountains and adjacent coastal zones in Saudi Arabia. These areas remain underexplored despite their floristic interest. The study was executed along two transects of vegetation surveys, focusing on coastal and inland areas, complemented by an exhaustive analysis of soil samples. Advanced analytical methods were deployed to validate the derived plant communities, including modified TWINSPAN and the Silhouette algorithm. The exploration resulted in the identification of seven distinct plant communities, each dominated by a different species. They were further classified into three vegetation clusters, with variation in their occurrence ranges largely dictated by latitude and altitude. This investigation unveils the distinctive vegetation of the Hijaz Mountains foothills, providing vital insights and serving as a foundational reference for nature conservation decisions and future in-depth studies in these uniquely floristic regions. As it is a relatively underexplored area, it also supplied important data for the next chapter.

Chapter 4 offers a comprehensive overview of the vegetation of the Saharo-Arabian region, the largest hot desert region in the world. In which, we integrate various syntaxonomical systems, discussing the inherent difficulties in reconciling them with universally accepted nomenclature. This chapter delves into an exhaustive exploration of the varied desert vegetation in another significant region, endeavouring to provide a thorough phytosociological overview to address the existing knowledge gaps. The goals are to meticulously identify and describe the unique vegetation communities and elucidate their specific distributions across different desert types. A comprehensive database has been developed, incorporating vegetation plot data from many sources. The chapter employs sophisticated analytical techniques, such as modified TWINSPAN and the Silhouette algorithm, to authenticate the categorization of the vegetation into distinct classes, revealing various aspects of the region's desert flora. Multiple vegetation groups were discerned within these broad classes, highlighting the immense diversity in life forms and ecological characteristics. This thorough examination offers an enriched, advanced understanding of the region’s desert vegetation. It lays a solid foundation for subsequent research, conservation initiatives, and strategies to mitigate global change impacts in these ecologically significant landscapes. The chapter aims to provide the main steering factors at different scales and identify major patterns of desert vegetation. It forms a framework for future vegetation studies in the whole region. It is also an important basis for identifying hotspots (areas of highly diverse flora and vegetation) and other areas of nature conservation interest.

Chapter 5 returns the focus to the Sinai desert. As detailed mapping of the vegetation is lacking in this region, modelling is used to make suitability maps and predict vegetation trends under a climate change scenario.

Integrating existing publications with new insights derived from extensive vegetation plot databases and advanced methodologies in vegetation science is made to address current research gaps. This synthesis of knowledge will yield a clearer and more detailed overview of desert vegetation in North Africa and the Middle East. The findings from this thesis are anticipated to significantly bolster the foundation for conservation decisions, environmental policies, and advanced studies on desert vegetation in these regions.

2

Phytosociological survey of the desert vegetation of Sinai, Egypt

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2.1 Abstract

Although Sinai is a global hotspot for desert vegetation, there is no well-documented overview of the Sinai vegetation. We aim to provide a phytosociological overview of Sinai desert vegetation based on an extensive database and formal classification. We further aim to describe the vegetation communities and provide information on their distribution. We built a comprehensive database utilizing all available vegetation plot data of the study area from published literature and our field surveys. We determined the database clustering tendency (Hopkins' test analysis) and estimated its optimal number of clusters (Elbow method). We performed a cluster analysis (modified TWINSPAN) and improved the validity of the resulted groups by approximating natural clustering using the Silhouette algorithm. We visualized the results by calculating an NMDS and drawing distribution maps for observed vegetation communities. We distinguished nine classes representing the Sinai desert vegetation: *Salicornietea fruticosae*, *Retametea raetam*, *Haloxylonetea salicornici*, *Retamo-Tamaricetea fluviatilis*, *Acacietea tortilis*, *Artemisietea herbae-albae*, *Anabasietea articulatae*, *Chiliadenetea iphionoidis*, *Stellarietea mediae*. We distinguished 25 vegetation groups, of which seven are new findings, representing four main vegetation groups: salt desert, lowland desert, mountain desert, and ruderal desert. We observed a high diversity in life forms, chorotypes, and alpha diversity of the vegetation among the main groups. Therophytes, chamaephytes, hemicryptophytes and phanerophytes are the dominant life forms. Prevailing chorotypes are the Saharo-Arabian, Mediterranean, Mediterranean-Irano-Turanian and Irano-Turanian-Saharo-Arabian. The salt desert and lowland desert vegetation are species-poor, while mountain desert vegetation is relatively species-rich. The ruderal desert vegetation is the most species-rich. We present a common classification of Sinai desert vegetation based on cutting-edge methods and provide an updated description of desert vegetation groups of Sinai. Our study forms an important basis for decision making in nature conservation, global change issues, and further in-depth studies on Sinai vegetation.

2.2 Introduction

The ability of plants to survive the harsh conditions of deserts has fascinated botanists through times. Because of its being a central region for biodiversity in the Middle East, its geographic location at the connection of three continents, and the climatic changes happening in recent times (Ayyad et al., 2000), Sinai is one of the most important desert regions globally. Thus, it has attracted the attention of geographers and botanists since the seventeenth century (Batanouny, 1985), who contributed with important insights on the flora of Sinai (Forsskål, 1775; Delile, 1813; Fresenius, 1834; Täckholm, 1932). In 1935, for the very first time, Zohary addressed the phytogeographical classification of Sinai flora, which served as a basis for further local and regional studies of the Sinai flora and vegetation (e.g., Migahid et al., 1959; Ahmed, 1983; Danin, 1983; Fayed et al., 2004; Shaltout et al., 2004; Hatim et al., 2016).

Although Zohary (1973) and Danin (1983) made notable attempts to provide an overview of syntaxonomical classification, no study has provided a convincing classification scheme of the desert vegetation of Sinai. Despite being highly comprehensive and providing detailed community descriptions, their proposed classification schemes can hardly be reconciled with the widely recognized International Code of Phytosociological Nomenclature (Theurillat et al., 2021). Furthermore, the scientific reference material (vegetation relevés or equivalents) is missing in the work of Zohary (1973), which means that most of Zohary's syntaxa need to be considered *nomina nuda*, according to the Code (Theurillat et al., 2021).

In the present time of the large-scale decline of biodiversity, excessive land use and exploitation, and climate change, we urgently need an overview of the current status and diversity of ecosystems. Based on an extensive vegetation plot database comprising 1,421 relevés on which we apply approved, cutting-edge methods in vegetation science, our study updates earlier studies, including the work of Hatim et al. (2016; 816 relevés). More precisely, we will answer the following questions: (i) What are the vegetation communities of the Sinai desert vegetation, (ii) where do they occur, (iii) which diversity and ecological patterns, plant-life forms, and geological features characterize the observed vegetation communities, and (iv) can we develop a syntaxonomical scheme summarizing previous and current research? The results of our study may serve as an improved basis for decision making in Sinai nature conservation and environmental policy and further in-depth studies on Sinai vegetation.

2.2.1 Study area

The Sinai Peninsula is a triangular plateau in the northeast of Egypt. Bordered by the Mediterranean sea in the North, it extends south to Ras Muhammad, where the eastern coast of Suez Gulf meets the western coast of Aqaba Gulf. The area of the Sinai Peninsula (61,000 km^2) approximates 6% of that of Egypt. The core of the peninsula is situated near its southern end and consists of high and very rugged igneous and metamorphic rock formations (Fig. 1). The northern two-thirds of the peninsula are characterized by a tremendous northward-draining limestone plateau (El-Tih and Ugma Plateau), which rises from the Mediterranean coast, extends southwards, and terminates in a high escarpment on the northern flanks of the igneous core (Said, 1962). The Sinai Peninsula can be divided into three regions based on their geomorphological features: northern, central, and southern (Fig. 1). The elevation ranges from 0 m to 2,641 m at the highest peak of Saint Catherine mountain (Zahran & Willis, 2009).

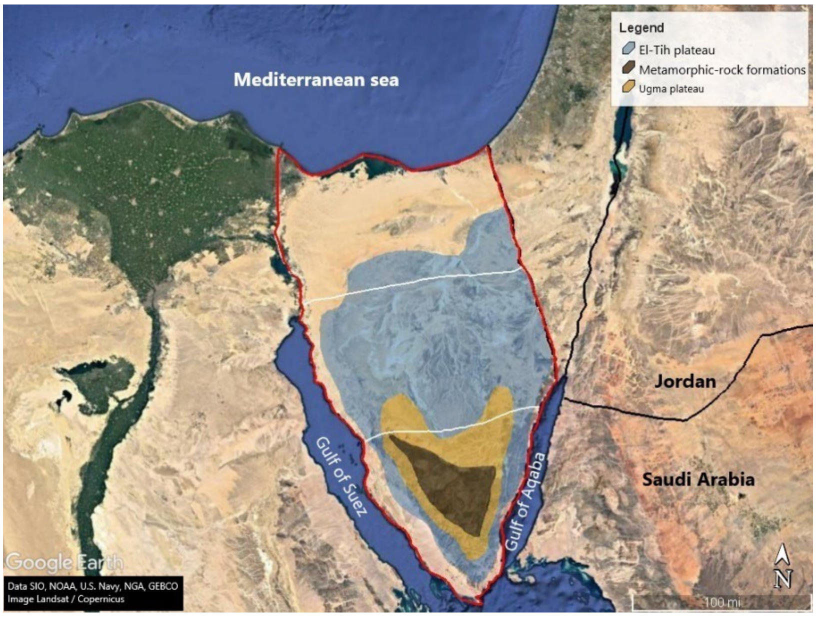

Figure 1. Map of Sinai showing features of the study area. The Sinai region is surrounded by a red line and divided by two white lines into three regions, southern, central and northern Sinai, from the south to the north (prepared from Google Earth).

The Sinai Peninsula lies in the junction of three floristic regions, the Saharo-Sindian, which corresponds to Zohary's (1966) Saharo-Arabian, the Irano-Turanian, and the Mediterranean regions (Zahran & Willis, 2009). Unlike the Saharo-Arabian chorotype, Danin & Plitmann (1987) stated that the Mediterranean chorotype declines from north to south in Sinai. While the Irano-Turanian chorotype is common in the highlands of the Sinai desert, the Sudanian chorotype is common in the lowlands of the Southern Sinai (Danin & Plitmann, 1987).

According to Ayyad et al. (1986), the Sinai Peninsula climatically belongs to the Saharo-Arabian region. It is distinguished into an arid zone in the Northern Sinai and a hyperarid zone in the Central and Southern Sinai. The arid zone is characterized by hot summers, mild winters, and rainfall during winter. According to Emberger (1963), this zone is further distinguished into two provinces: (i) the coastal belt province, which is under the maritime influence of the Mediterranean Sea and has a relatively short dry period with annual rainfall ranging from 100 to 200 mm, and (ii) the inland province, with a relatively long dry period and annual rainfall of 20 to 100 mm. The hyperarid zone includes the central and southern regions of Sinai. It is further divided into two provinces: (i) the hyperarid province with hot summers, mild winters, and winter rainfall, which includes Central Sinai or the El-Tih Plateau, together with the western and eastern coasts of the Gulfs of Aqaba and Suez, and (ii) the hyperarid province with cold winters and hot summers, which occurs around the Sinai mountains (Zahran & Willis, 2009).

Air temperature in Sinai is subject to significant spatial variations. The mean maximum summer temperature ranges from 20 °C at Saint Catherine (Southern Sinai) to more than 50 °C at El-Kuntilla (Central Sinai; Zahran & Willis, 2009). The mean minimum winter temperature ranges from 0 °C at Saint Catherine (Southern Sinai) to 9 °C at Nekhel (Central Sinai), 14 °C at El-Arish (Northern Sinai), 15 °C at El-Tor (Southern Sinai) to 19 °C at Sharm El-Sheikh (Southern Sinai). Due to its distinct landscape and pronounced climatic characteristics, Sinai has diverse ecological regions: salt desert, lowland desert, and mountain desert (Fig. 2).

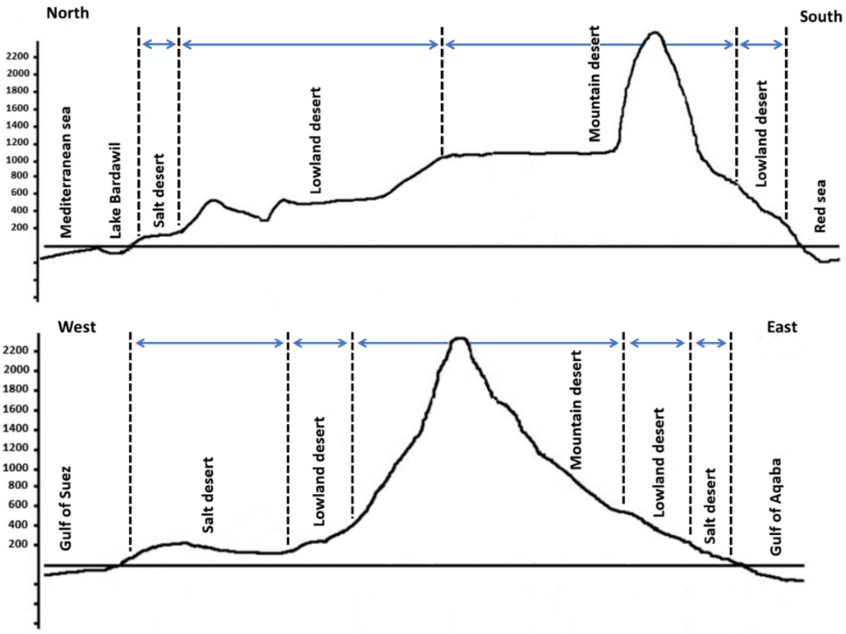

Figure 2. Sectors showing the main ecological regions and altitude (m a.s.l.) along the north–south and west–east directions in Sinai

The prevailing land use in Sinai is farming, especially in the Southern Sinai. According to Shaltout et al. (2019), the edaphic and moisture conditions in the Saint Catherine region (Southern Sinai) create habitats where farmlands can occur. The farmland vegetation can be found in catchment areas of the surrounding mountains or near Bedouin settlements where groundwater is available (El-Hadidi & Hosny, 2000). Sufficient groundwater, together with the natural protection of the locality against winds, provides suitable conditions for cultivation in many wadis in the Southern Sinai (Shaltout et al., 2019). The farms are mainly cultivated with fruit trees and crops (Shaltout et al., 2019). Norfolk et al. (2013) estimated about 600 farms in the Saint Catherine region (Southern Sinai). Bedouins run their farms on the principles of agroforestry, where the smaller orchard trees are widely spaced to grant the light reaching to the cultivated vegetables, thus giving room to the growth of native desert plant species (Norfolk et al., 2013).

2.3 Methods

2.3.1 Data Compilation

We compiled an extensive dataset of all available plot-based vegetation records of Sinai, comprising 1,462 relevés. We omitted single-species relevés with low abundances as it is doubtful that such records represent well-developed plant communities. The resulting dataset comprised 1,421 vegetation records, including 555 taxa (species and subspecies), collected from three main sources: (1) 927 relevés retrieved from the Vegetation database of Sinai in Egypt (Hatim, 2012); stored in the sPlot repository (Bruelheide et al., 2019), (2) 345 relevés from published literature (Abd El-Wahab, 2003; Abd El-Wahab, 1995; Moustafa et al., 2008; Salem & Kamal, 2003; Shaltout et al., 2015), and (3) 149 relevés recorded by the first author in 2017 and 2019. All relevés were made according to the Braun-Blanquet approach (Braun-Blanquet, 1928; Westhoff & Van der Maarel, 1973) and included information on the species abundance. The compiled data reflect the geomorphological variance and habitat diversity of the Sinai desert region to a great extent (electronic appendix). The temporal range of the relevés is from 1959 to 2019, while their altitudes range from 23 to 2450 m.

We stored and managed our data in the Turboveg 3 program (Hennekens & Schaminée, 2001). For each plant species, we updated its taxonomy according to World Flora Online (2021). We compiled information on plant life forms (Raunkiaer, 1934; retrieved from Täckholm, 1974; Boulos, 1999; 2000; 2002; 2005; Danin & Fragman-Sapir, 2016) and chorotypes (retrieved from Takhtajan et al., 1986; Danin, 1986; Danin & Fragman-Sapir, 2016).

2.3.2 Data analysis

We conducted the classification by (a) calculating the clustering tendency to determine if and to which level the dataset has meaningful clusters, (b) approximating the optimal number of clusters, and (c) computing the final cluster analysis.

2.3.2.1 Clustering tendency

To measure to what degree clusters exist in the data, we performed a Hopkins' test (Python, version 3.7.6, electronic appendix), which is a statistical hypothesis test to measure the probability (H) that a given data set is generated by a uniform or continuous data distribution (Hopkins & Skellam, 1954). The Null Hypothesis (H_0) says that data follow a continuous distribution (implying no meaningful clusters), while the alternate hypothesis (H_1) states that data are not uniformly distributed (i.e., the presence of clusters). If H > 0.5, the null hypothesis can be rejected (Hopkins & Skellam, 1954).

2.3.2.2 The optimal number of clusters

We used the Elbow method to estimate the optimal number of clusters (Ketchen & Shook, 1996; Python, version 3.7.6, electronic appendix) by performing multiple cluster analyses with varying, predefined cluster numbers (k). In each analysis, we also calculated the sum of within-cluster variance (W) as the sum of squared Euclidean distances between the plots and the corresponding centroid. Subsequently, we plotted k values against their opposite W values to find the approximate optimal number of clusters indicated by the elbow (breakpoint) of the plotted curve. This breakpoint represents the k value opposite to the lowest W value before the curve becomes almost straight, where the W value approaches zero as the k value comes close to the total number of plots.

2.3.2.3 Classification and related analyses

We classified the data using a hierarchical modified TWINSPAN algorithm (Roleček et al., 2009), with, based on the given data structure, pseudo-species cut levels 0, 5, 25, 50 (JUICE 7.1; Tichý, 2002). We refrained from further hierarchical subdivision when modified TWINSPAN did not result in groups with ecologically meaningful differential species (Tsiripidis et al., 2009). Subsequently, to improve the validity of the groups, we reallocated 194 relevés. We made reallocations only if (i) the constancy values of the differential species of the groups were improved after the reallocation and (ii) the average silhouette values (JUICE, Silhouette function) of relevant groups remained consistent or were enhanced. To visualize the relation between the clusters, we calculated an NMDS (Non-Metric Multidimensional Scaling), using Bray-Curtis distance (CANOCO 5; ter Braak, 1989).

To develop a syntaxonomical overview, we adopted names of syntaxa proposed in the literature, updating them according to the latest version of the International Code of Phytosociological Nomenclature (Theurillat et al., 2021) where needed. Based on vegetation structure and differential, dominant and accompanying species, we allocated each group to a syntaxonomical class and, if possible, further down to the level of orders, alliances, and associations. For some syntaxa, indicated by question marks in the syntaxonomy scheme, we refrained from further allocation towards lower or upper syntaxonomical levels due to the shortage of data about the broader context of the Sinai desert vegetation and its position in the Saharo-Arabian region.

2.4 Results and Discussion

2.4.1 Clustering tendency and the optimal number of clusters

Clustering methods produce clusters by default, even if the data hardly show any variation (dis-continuum). In this case, calculated clusters (groups) would be meaningless (Cross & Jain, 1982). For this reason and to present a mathematically approved approach, we calculated the clustering tendency using Hopkins' statistical hypothesis method. As the result was H = 0.96, we rejected the null hypothesis, meaning the database very likely contains clusters.

The approximated optimal number of clusters based on the Elbow method was 24 (Fig. 3). Since this value (24) is heuristic, we can accept the actual number of clusters (25). The deviation of the actual number of clusters (25) (Fig. 4) from the expected one (24) resulted from the reallocation of the relevés among the groups.

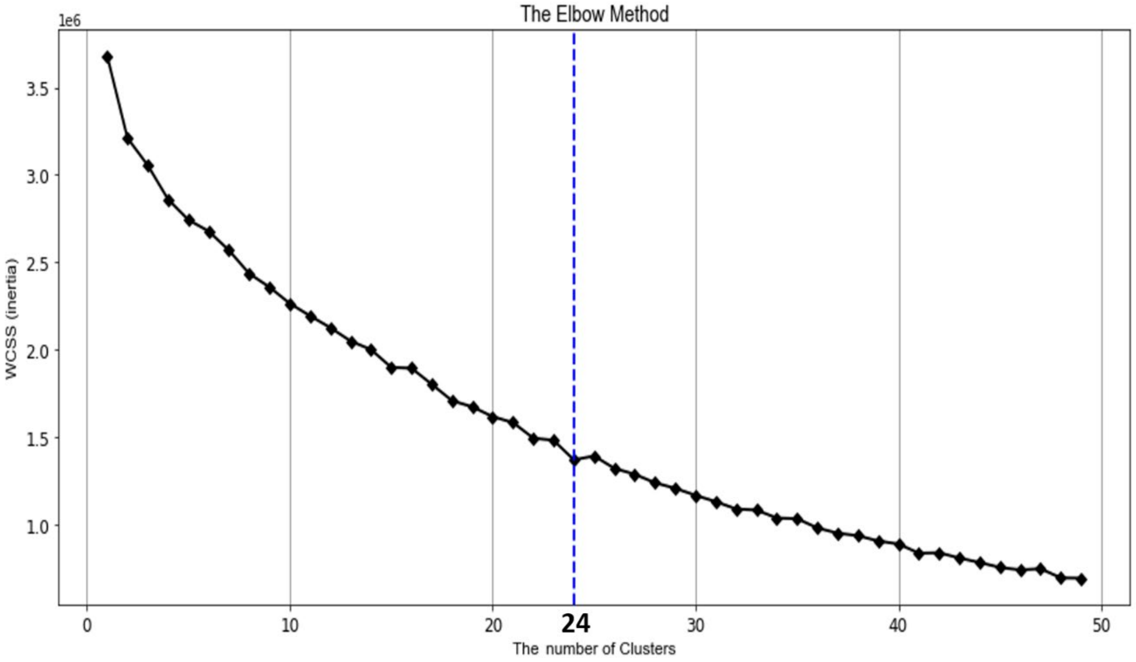

Figure 3. Diagram of the Elbow method showing the expected optimal number of clusters. Within Cluster Sum of Squares (WCSS) values represent the sum of squared Euclidean distances between the plots and the centroid. The lower the value of W, the more meaningful the clusters, and the better the correspondence to an optimal number of clusters. The Elbow is the last breaking point, seen before the flattening of the curve and corresponding to a low WCSS value. In our case, the Elbow corresponds to the number of clusters, 24.

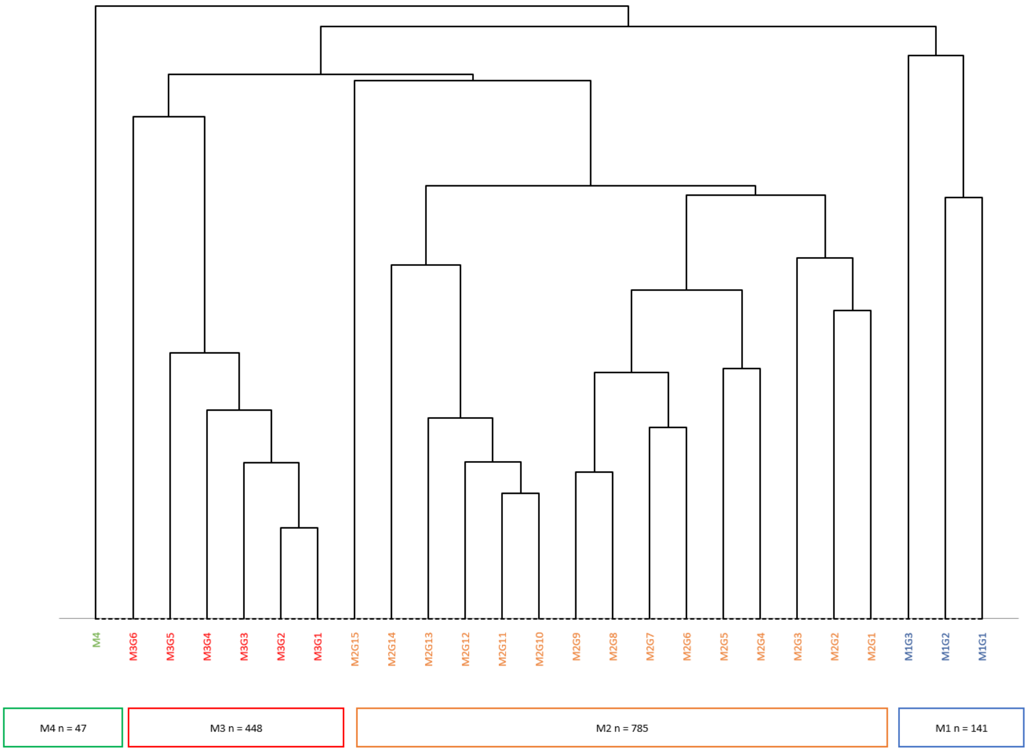

Figure 4. Dendrogram of the final classification based on the agglomerative clustering using Bray–Curtis analysis among the 25 groups. Different colours represent the main groups M1–M4 (blue: salt desert, M1; orange: lowland desert, M2; red: mountain desert, M3; green: ruderal desert, M4). n is the number of relevés in each group.

2.4.2 Classification

After trying different approaches to classify the desert vegetation of Sinai, we found that modified TWINSPAN generated the best results. However, the low species numbers of some plots and substantial differences among species-abundance values make our data set challenging to classify. We overcame these limitations by manually reallocating several relevés based on mathematical Silhouette values analysis and our expert knowledge. The classification resulted in four main groups (M1 – M4), representing salt desert (M1), lowland desert (M2), mountain desert (M3), and ruderal desert (M4) vegetation. M1 – M3 were divided into 3, 15, and 6 groups (G), respectively, while M4 remained undivided. The total number of groups was, as mentioned before, 25. Their hierarchical relationships are indicated in Fig. 4.

Climate inconstancy, geographic isolation, edaphic variation, and high spatial and temporal variability of further abiotic factors substantially impact the distribution of desert vegetation communities and cause greater-than-expected plant diversity (Sandquist, 2014). Our study reflected that in the high diversity of vegetation communities among the different regions and habitats in Sinai.

2.4.2.1 Ordination

The NMDS was calculated on three axes since the stress value was close to 0.1 (Fig. 5, axes 1 and 3, length of axes 1: 2, 3: 1.5, stress value of axes 1: 0.53, 3: 0.17). We chose axes 1 and 3 since they clearly visualize the classification (Fig. 4). M1 to M4 are well separated by their species composition; yet M1, which is prevailed by salt desert vegetation, and M2, which is dominated by lowland desert vegetation, slightly overlap. M4, dominated by ruderal vegetation, is clearly separated from all other groups (Fig. 4 and 5).

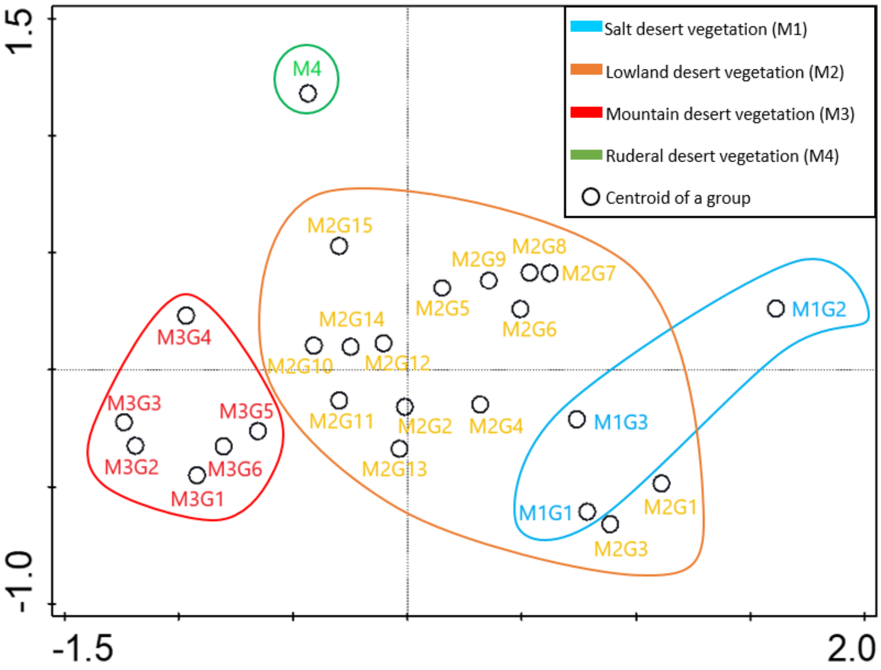

Figure 5. Axes 1 and 3 of the Non-metric Multidimensional Scaling ordination, using Bray–Curtis-based analysis, of the 25 vegetation groups (small black circles represent centroids of the groups) in the Sinai region, based on their floristic composition (length of axes 1:2, 3:1.5; stress values of axes 1:0.53, 3:0.17). The four main groups (M1–4) are indicated in blue (salt desert, M1), orange (lowland desert, M2), red (mountain desert, M3) and green (ruderal desert, M4).

2.4.2.2 Vegetation groups description and classification

Frequency values of the characteristic species of the four main groups (M1 – M4) and the 25 groups are given in Tables 1 to 4. The differential species of the four main groups and the 25 groups are shaded in grey (for a complete synoptic table, see electronic appendix).

The main life forms of Sinai desert vegetation are therophytes, chamaephytes, hemicryptophytes, and phanerophytes shrubs (Fig. 6). The dominant chorotypes are Saharo-Arabian, Mediterranean, Mediterranean-Irano-Turanian and Irano-Turanian-Saharo-Arabian (Fig. 7). We described each main group and the 25 groups below, indicating plant life forms, habitats (ecology), chorotypes, differential species, and geographical distribution.

Table 1. Shortened synoptic table of the classified vegetation relevés of the four main groups (M1-4). The table shows the number of relevés, mean number of species, the list of plant species, and their percent frequencies for each main group. Only differential species (with frequencies ≥ 30%) are included, and their values cells are shaded. The dominant species of each main group is also shaded.

Main Group	**M1**	**M2**	**M3**	**M4**
Number of relevés	141	785	448	47
Mean species number	5	9	12	17
Tetraena alba	50	2	0	0
Zilla spinosa	8	49	38	4
Fagonia mollis	2	35	35	15
Zygophyllum coccineum	14	32	1	0
Artemisia judaica	1	32	17	9
Haloxylon salicornicum	4	30	1	6
Artemisia herba-alba	1	7	54	0
Alkanna orientalis	0	1	48	0
Teucrium polium	0	5	47	0
Stachys aegyptiaca	0	2	44	0
Phlomis aurea	0	1	42	0
Tanacetum sinaicum	0	1	42	0
Ballota undulata	0	2	32	0
Achillea fragrantissima	0	7	31	2
Chiliadenus montanus	0	1	30	0
Convolvulus arvensis	0	1	1	81
Euphorbia peplus	0	1	4	79
Chenopodium murale	0	1	1	51
Cynodon dactylon	2	2	3	51
Polypogon monspeliensis	0	0	1	47
Malva parviflora	0	2	2	43
Hordeum marinum	0	1	1	43
Oxalis corniculata	0	0	0	38
Tetraena simplex	7	16	0	32
Alhagi graecorum	0	2	1	30

Table 2. Shortened synoptic table of the first main group (M1), showing the resulted three groups (M1G1-3). The table shows the number of relevés, mean number of species, the list of plant species, and their percent frequencies for each group. Only differential species (with frequencies ≥ 30%) are included, and their values cells are shaded. The dominant species of each group is also shaded.

Group	**M1G1**	**M1G2**	**M1G3**
Number of relevés	79	14	48
Mean species number	4	5	6
Tetraena alba	81	36	4
Nitraria retusa	42	21	0
Salvadora persica	0	100	0
Panicum turgidum	11	0	67
Stipagrostis scoparia	13	0	65
Cornulaca monacantha	11	0	54
Convolvulus lanatus	4	0	46
Artemisia monosperma	9	0	40

Table 3. Shortened synoptic table of the second main group (M2), showing the resulted fifteen groups (M2G1-15). The table shows the number of relevés, mean number of species, the list of plant species, and their percent frequencies for each group. Only differential species (with frequencies ≥ 30%) are included, and their values cells are shaded. The dominant species of each group is also shaded.

Group	**M2G1**	**M2G2**	**M2G3**	**M2G4**	**M2G5**	**M2G6**	**M2G7**	**M2G8**	**M2G9**	**M2G10**	**M2G11**	**M2G12**	**M2G13**	**M2G14**	**M2G15**
Number of relevés	67	73	20	44	64	58	29	24	31	77	59	91	106	19	23
Mean species number	3	11	4	6	12	11	16	15	18	9	9	12	5	7	20
Zygophyllum coccineum	100	33	20	16	61	69	14	42	94	1	3	15	5	5	26
Haloxylon salicornicum	24	100	35	39	9	2	3	46	77	10	8	29	41	0	4
Asphodelus fistulosus	0	0	55	2	0	0	0	0	0	0	0	1	0	0	0
Ephedra alata	1	11	30	2	2	0	0	0	0	1	2	3	3	5	0
Acacia tortilis	3	8	5	95	61	34	76	46	68	12	7	3	9	21	13
Cleome droserifolia	4	1	30	9	53	33	17	29	10	5	2	4	0	11	0
Aerva javanica	1	16	15	25	50	10	10	42	26	10	2	29	8	32	0
Capparis aegyptia	0	4	0	0	41	0	0	0	0	6	0	9	1	5	0
Chrozophora oblongifolia	0	3	0	5	34	3	0	0	0	4	0	3	0	11	0
Echinops hussonii	0	1	0	0	30	7	21	0	0	6	2	0	2	5	0
Tetraena simplex	7	5	0	2	9	84	55	54	48	1	0	13	1	0	0
Stipagrostis plumosa	0	5	0	2	5	57	55	8	6	3	12	23	1	0	0
Pulicaria undulata subsp. *undulata*	3	3	0	11	14	52	3	0	39	10	3	24	3	5	22
Citrullus colocynthis	1	10	0	9	25	40	28	29	10	14	12	34	8	5	13
Forsskaolea tenacissima	0	8	0	11	22	50	93	75	39	12	3	30	0	11	0
Indigofera arabica	1	0	0	0	0	3	83	4	0	0	0	0	0	0	0
Iphiona scabra	15	11	0	16	50	48	69	38	45	10	3	13	4	11	0
Fagonia indica var. *indica*	1	0	0	0	0	17	52	25	26	0	0	0	0	0	0
Lotus polyphyllos	0	0	0	0	8	28	52	25	10	0	2	0	0	0	0
Aerva lanata	3	0	0	2	2	24	48	4	3	0	0	0	0	0	0
Diplotaxis harra	0	8	0	2	2	9	45	25	29	4	22	27	3	0	35
Cucumis prophetarum	0	3	0	11	19	12	45	29	13	1	0	8	0	0	0
Erodium oxyrhynchum	0	0	0	0	0	5	41	0	3	0	5	5	0	0	4
Trichodesma africanum	0	4	0	0	16	34	41	17	13	12	3	9	1	11	0
Blepharis edulis	1	0	0	0	11	12	41	0	0	4	2	8	1	5	0
Fagonia glutinosa	7	3	10	2	0	16	31	21	10	1	0	5	3	5	26
Hyoscyamus muticus	0	4	0	11	0	2	7	54	19	3	2	2	6	0	13
Tephrosia purpurea	0	1	0	0	13	7	3	46	13	3	2	1	0	11	0
Lavandula pubescens	0	3	0	5	20	0	14	42	13	4	2	0	0	11	9
Capparis cartilaginea	0	1	0	9	13	16	21	42	35	0	0	0	0	0	0
Fagonia scabra	0	1	0	0	0	29	83	71	100	5	5	1	0	0	0
Atriplex halimus	0	0	5	2	3	2	0	8	58	0	0	4	1	0	0
Caylusea hexagyna	0	11	0	2	6	10	0	46	58	26	22	19	5	5	4
Ochradenus baccatus	4	12	10	20	20	9	17	25	45	17	24	31	17	0	13
Kickxia floribunda	0	0	0	0	0	7	7	13	32	0	0	0	0	0	4
Artemisia judaica	0	19	0	14	25	2	0	0	0	100	73	53	42	21	9
Zilla spinosa	19	21	15	27	39	34	83	67	87	49	93	76	48	37	35
Fagonia mollis	12	34	45	25	28	10	0	4	0	52	86	53	44	37	4
Cleome amblyocarpa	0	0	0	2	3	2	0	0	0	5	44	7	6	0	9
Fagonia arabica	10	18	5	18	3	10	10	17	6	9	37	66	12	11	30
Reseda pruinosa	0	0	0	0	20	9	0	0	0	1	15	37	1	5	0
Retama raetam	3	4	5	14	2	2	0	0	26	26	47	27	94	0	13
Lycium shawii	0	4	0	9	22	0	38	38	32	10	8	14	8	74	9
Tamarix senegalensis	7	0	0	0	9	0	0	4	13	0	3	2	6	0	65
Launaea nudicaulis	0	0	0	0	0	2	10	4	19	4	2	1	3	0	35
Filago desertorum	0	0	0	0	0	0	0	0	0	4	3	1	0	0	35
Anacyclus monanthos subsp. *monanthos*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30
Ifloga spicata subsp. *spicata*	0	1	0	0	2	0	0	0	0	3	0	1	0	0	30
Trigonella stellata	0	5	0	0	0	0	0	0	0	8	3	7	3	0	30

Table 4. Shortened synoptic table of the third main group (M3), showing the resulted six groups (M3G1-6). The table shows the number of relevés, mean number of species, the list of plant species, and their percent frequencies for each group. Only differential species (with frequencies ≥ 30%) are included, and their values cells are shaded. The dominant species of each group is also shaded.

Group	**M3G1**	**M3G2**	**M3G3**	**M3G4**	**M3G5**	**M3G6**
Number of relevés	60	107	62	75	89	55
Mean species number	10	13	10	22	7	11
Stachys aegyptiaca	73	59	31	49	20	31
Ballota undulata	60	39	16	32	10	40
Galium sinaicum	42	26	6	3	3	0
Phlomis aurea	28	93	68	36	6	0
Teucrium polium	65	79	47	49	22	0
Echinops spinosissimus	13	58	29	23	13	0
Origanum syriacum subsp. *sinaicum*	23	48	37	24	1	0
Chiliadenus montanus	40	47	29	31	16	11
Tanacetum sinaicum	48	60	89	29	22	0
Crataegus x sinaica	0	13	50	8	2	0
Nepeta septemcrenata	22	35	37	8	3	0
Mentha longifolia subsp. *typhoides*	2	9	31	19	0	7
Alkanna orientalis	62	75	45	85	6	0
Peganum harmala	2	2	3	57	8	9
Achillea fragrantissima	37	49	8	55	17	5
Launaea spinosa	10	7	3	37	12	0
Matthiola arabica	32	34	10	35	13	0
Artemisia herba-alba	45	43	69	36	82	49
Anabasis articulata	0	0	0	3	11	58
Moricandia sinaica	0	0	0	1	0	53
Deverra tortuosa	7	3	0	17	2	49
Juniperus phoenicea	0	0	0	0	0	49
Gymnocarpos decandrus	3	6	2	29	17	47
Asparagus horridus	0	0	0	0	0	47
Reaumuria hirtella	0	0	0	0	2	45
Zygophyllum dumosum	0	0	0	0	0	40
Noaea mucronata	0	1	2	7	1	33

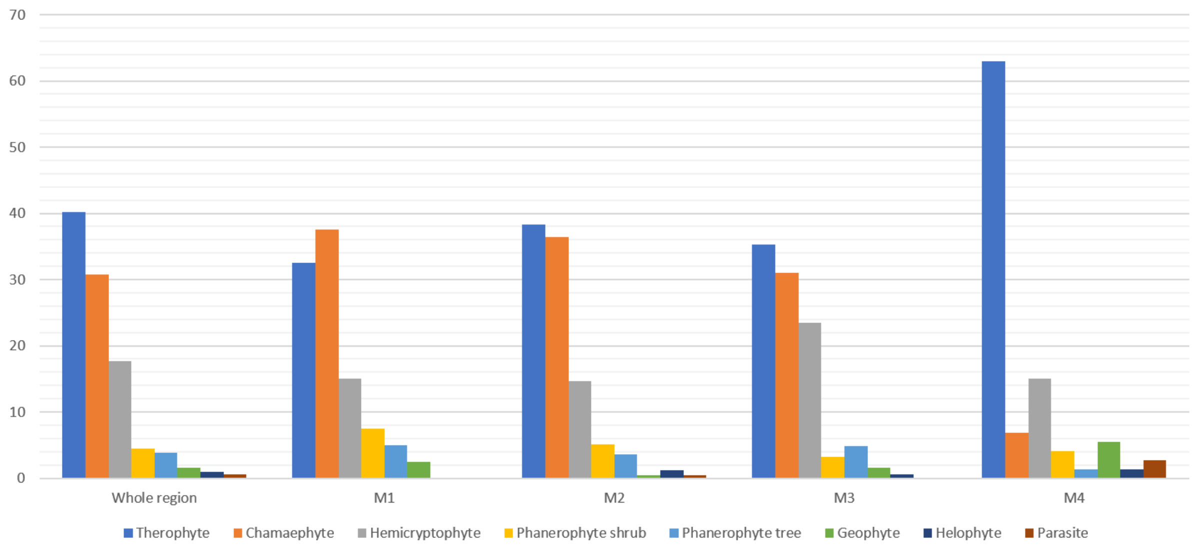

Figure 6. Proportions of plant life forms of the desert vegetation of Sinai, shown for the entire data set and separately for main groups M1 (40 species), M2 (253 species), M3 (187 species) and M4 (73 species).

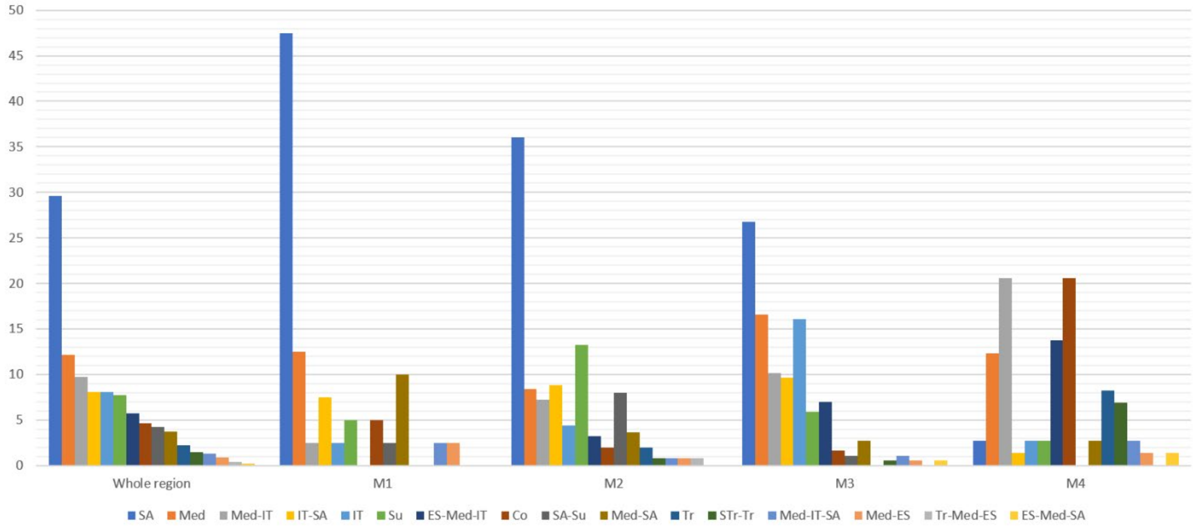

Figure 7. Proportions of chorotypes of the desert vegetation of Sinai, shown for the entire data set and separately for main groups M1, M2, M3 and M4. SA: Saharo-Arabian; Med: Mediterranean; Med-IT: Mediterranean-Irano-Turnian; IT-SA: Irano-Turanian-Saharo-Arabian; IT: Irano-Turanian; Su: Sudanian; ESMed-IT: Euro-Siberian-Mediterranean-Irano-Turanian; Co: Cosmopolitan; SA-Su: Saharo-Arabian-Sudanian; Med-SA: Mediterranean-Saharo-Arabian; Tr: Tropical; STr-Tr: Subtropical-Tropical; Med-IT-SA: Mediterranean-Irano-Turanian-Saharo-Arabian; Med-ES: Mediterranean-Euro-Siberian; Tr-Med-ES: Tropical-Mediterranean-Euro-Siberian; ES-Med-SA: Euro-Siberian-Mediterranean-Saharo-Arabian.

Main groups (M1 – M4) are differentiated from each other. With *Tetraena alba* as a dominant species, M1 is characterized by *Stipagrostis scoparia*, *Panicum turgidum*, *Nitraria retusa*, and *Cornulaca monacantha.* The communities of M1 mainly represent salt desert vegetation and belong to the classes *Salicornietea fruticosae* and *Retametea raetam*. They have the lowest species numbers (mean species number = 5) compared to other main groups. M1 was divided into three groups (M1G1 – G3). They predominantly occur in coastal and inland salt deserts. The vegetation largely consists of chamaephytes and therophytes but is dominated by the former type (Fig. 6). The chorotypes are mainly Saharo-Arabian, followed by Mediterranean and Mediterranean-Irano-Turanian subsequently (Fig. 7). The groups of M1 are primarily distributed in the Northern and Central regions of Sinai but rarely occur in Southern Sinai (Fig. 8).

M2 is characterized by *Zilla spinosa* (dominant species), *Fagonia mollis*, *Zygophyllum coccineum*, *Artemisia judaica*, *Haloxylon salicornicum*, *Retama raetam*, *Acacia tortilis*, *Fagonia arabica*, and *Iphiona scabra*. Although *Zilla spinosa* is present in all main groups, it occurs with the highest frequencies in M2. The groups of M2 predominantly represent the diverse lowland desert vegetation that can be found in ergs (sandy plains, dunes, and wadis) and regs (gravelly plains and wadis).

They belong to the classes *Retametea raetam*, *Haloxylonetea salicornici*, *Retamo-Tamaricetea fluviatilis*, and *Acacietea tortilis*. They are relatively species-poor (mean species number = 9) compared to groups of M3 and M4 but richer than those of M1. M2 was divided into fifteen groups (M2G1 – M2G15), which mainly occur in sandy plains and dunes, sandy wadis, gravelly wadis, and gravelly plains. The vegetation consists mainly of therophytes, chamaephytes, and hemicryptophytes (Fig. 6).

The prevailing chorotype is Saharo-Arabian, followed by the Mediterranean chorotype (Fig. 7). M2 groups predominantly occur in the Northern, Central, and Southern regions of Sinai (Fig. 8).

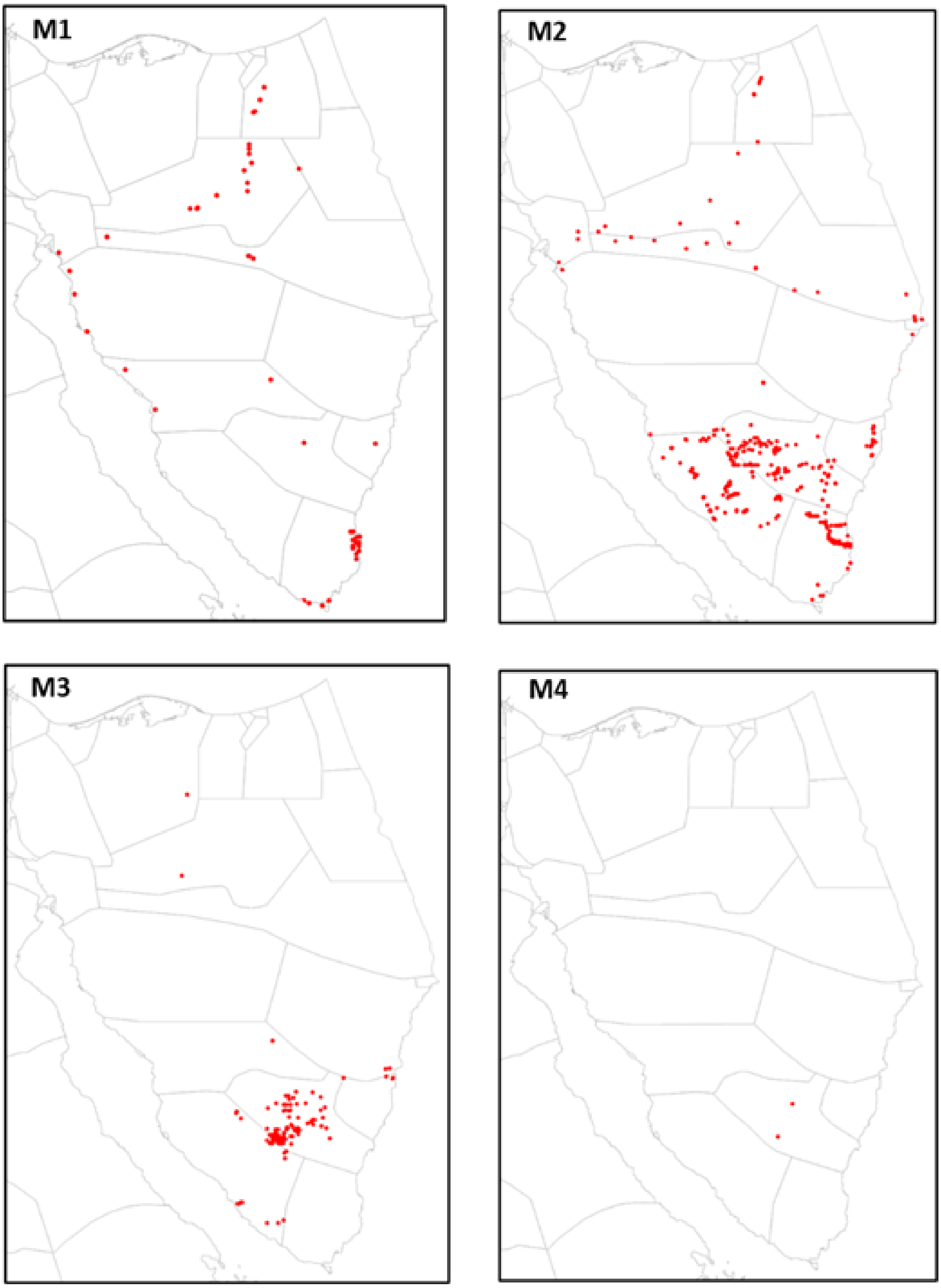

Figure 8. Geographic distribution of main clusters (M1–M4), showing the relevés as red dots.

M3 is dominated by differential species *Artemisia herba-alba.* Further differential species are *Alkanna orientalis*, *Teucrium polium*, *Stachys aegyptiaca*, *Phlomis aurea*, *Tanacetum sinaicum*, *Ballota undulata*, *Achillea fragrantissima*, *Chiliadenus montanus*, *Echinops* *spinosissimus*, *Origanum syriacum* subsp. *sinaicum*, and *Matthiola arabica*. The groups of M3 mainly represent the mountain desert vegetation and belong to the classes *Artemisietea herbae-albae*, *Anabasietea articulatae*, and *Chiliadenetea iphionoidis*. They have a higher mean species number (12) than M2 and M1 but lower than M4. M3 was divided into six groups (M3G1 – M3G6), which their main habitats are hamadas (rocky hillsides), rocky wadis, and outcrops. The majority of species life forms are therophytes, followed by chamaephytes (Fig. 6). The common chorotypes are Saharo-Arabian, Mediterranean, and Irano-Turanian (Fig. 7). The majority of groups of M3 can be found in the Southern Sinai, with very few occurrences in the Northern Sinai (Fig. 8).

Convolvulus arvensis dominates M4, while other characteristic species are *Euphorbia peplus*, *Chenopodium murale*, *Cynodon dactylon*, *Polypogon monspeliensis*, *Malva parviflora*, *Hordeum murinum*, *Oxalis corniculata*, and *Tetraena simplex*. M4 represents ruderal vegetation and provides the highest mean species number (17). M4 consists of only one group (M4G1) and belongs to the class *Stellarietea mediae*. The supporting habitats are bound to nutrient-rich soils and ruderal places (Danin, 1983; Hatim et al., 2016), commonly found in areas with human activities (e.g., farms). The main life forms are hemicryptophytes and geophytes (Fig. 6), while the chorotypes are mainly Mediterranean-Irano-Turanian and Cosmopolitan (Fig. 7). M4 community is restricted to the Southern Sinai region due to intensive farming (Fig. 8).

In line with the variation in climate and soil types (Danin, 1983), and partly defined by historical factors, the interaction of elements of four plant geographical regions (Saharo-Arabian, Irano-Turanian, Sudanian, Mediterranean) in the Sinai region adds to the high diversity of the vegetation. The chorotypes of the main four groups found in our study are similar to those described by Danin (1983) and Zahran & Willis (2009).

Moreover, the ruderal desert vegetation (M4) includes elements belonging to Cosmopolitan, Euro-Siberian, Tropical, and Subtropical chorotypes, not characteristic of the Sinai desert vegetation. The occasional appearances of these species in M4 and main groups M1 – M3 indicate the presence of farms in their distribution range. The farms in mountainous and some desert places have been part of the Sinai landscape for the last thousand years (Zalat & Gilbert, 2008), while the farms in Saint Catherine (Southern Sinai) represent a recent anthropogenic change within the last 50 years (Gilbert, 2011). Farms in the mountainous region in the Southern Sinai are suitable for cultivating many wild medicinal plants (Shaltout et al., 2019). Nevertheless, we think that farms may adversely impact natural vegetation due to land-use practices like grazing, cutting, and introducing cultivated plants patterns. Regulations for land management in Sinai may become necessary, assuming this impact increases continuously. Shaltout et al. (2004, 2021) stated that cessation of grazing and cutting in many enclosures in the South Sinai for six years improved their vegetation diversity, density, and cover.

2.4.2.3 Description of the individual communities

MAIN GROUP 1 Salt desert vegetation (three groups)

Tetraena alba group (M1G1) is characterized by *Tetraena alba* (the dominant species) and *Nitraria retusa*. It includes 79 relevés; its plant species mainly inhabit coastal and inland salt deserts. This vegetation occurs in the Northern, Central, and Southern regions of Sinai (electronic appendix). Similar vegetation types in Sinai were reported by Danin (1983), Migahid et al. (1959), Hussein (1988), Gibali (1988), El-Demerdash et al. (1996), Marie (2000), El-Ghani & Amer (2003), and Hatim et al. (2016). We assigned this group to the association *Zygophylletum albi* (Danin, 1983), which belongs to the class *Salicornietea fruticosae*. This class comprises vegetation communities on saline soils where low shrubs with succulent leaves dominate (Guinochet, 1951).

In *Salvadora persica* group (M1G2), *Salvadora persica* is the dominant species. Characteristic species are *Salvadora persica* and *Cyperus conglomeratus*. Community M1G2 consists of 14 relevés. Unlike the mother group M1, the predominant life forms are phanerophytes, mainly trees (electronic appendix). The species belong mainly to Sudanian and Saharo-Arabian chorotypes (electronic appendix), different from the M1 main chorotypes. The communities are found in the coastal desert of the Southern Sinai region (electronic appendix). This group is similar to vegetation communities found in Sinai by Helmy et al. (1996), El-Demerdash et al. (1996), and Hatim et al. (2016). M1G2 represents the association *Salvadoretum persicae*, which we – preliminarily – group in the class *Salicornietea fruticosae*.

Panicum turgidum dominates *Panicum turgidum* group (M1G3). Additional differential species are *Stipagrostis scoparia, Cornulaca monacantha, Convolvulus lanatus,* and *Artemisia monosperma*. This community includes 48 relevés. The plant species of this group can be found on sandy plains and dunes (ergs) in the Northern and Southern regions of Sinai (electronic appendix). This group is similar to communities reported in Sinai by Danin (1983), Danin and Orshan (1999), El-Demerdash et al. (1996), and Hatim et al. (2016). It reflects the association *Panicetum turgidi* (Danin, 1983). This association belongs to the class *Retametea raetam*, which includes desert plant communities on sandy soils (Zohary, 1973).

MAIN GROUP 2 Lowland desert vegetation (fifteen groups)

Zygophyllum coccineum group (M2G1) is characterized by *Zygophyllum coccineum* only. It contains 67 relevés. The predominant life forms are chamaephytes (electronic appendix), different from the main life forms in mother group M2. This community inhabits sandy wadis, plains, and dunes (ergs) in the Southern Sinai (electronic appendix). This group is similar to a community found in Sinai by El-Demerdash et al. (1996), Abd EL-Wahab et al. (2006), and Hatim et al. (2016). M2G1 represents the association *Zygophylletum coccinei*, which we assign to the class *Haloxylonetea salicornici*. Similar to the class *Retametea raetam*, this class occurs in sandy deserts. However, the class *Haloxylonetea salicornici* is confined to the most extreme, hyperarid deserts, which is reflected in the low species diversity, and absence of relatively high shrubs.

The only characteristic and dominant species of *Haloxylon salicornicum* group (M2G2) is *Haloxylon salicornicum*. This group includes 73 relevés with a relatively high mean species number (11) compared to the mean species number of the mother group M2 (9). It is dominated by chamaephytes (electronic appendix). It is found on sandy plains and dunes (ergs) in the Northern and Southern regions of Sinai (electronic appendix). This group is similar to vegetation communities described in Sinai by Migahid et al. (1959), Zohary (1973), El-Kady et al. (1998), Abd EL-Wahab et al. (2006), Morsy et al. (2010), and Hatim et al. (2016). M2G2 belongs to the association *Haloxylonetum salicornicae* (Zohary, 1973), which is part of the class *Haloxylonetea salicornici.*

Asphodelus fistulosus group (M2G3) is characterized by *Asphodelus fistulosus* (the dominant species) and *Ephedra alata*. It consists of 20 relevés. In contrast to the mother group M2, the primary life forms are hemicryptophytes (electronic appendix). The community inhabits sandy plains and dunes (ergs) in the Central and Southern regions of Sinai (electronic appendix). The group most likely fits in the association *Ephedretum alatae*, as described by Zohary (1973). We preliminary group M2G3 in the class *Haloxylonetea salicornici*.

Relevés of *Acacia tortilis* group (M2G4) are dominated by *Acacia tortilis*. It has 44 relevés and is dominated by phanerophytes, mainly trees (electronic appendix). This group occurs in sandy and gravelly wadis (ergs and regs) in the Central and Southern regions of Sinai (electronic appendix). This group is similar to those reported in Sinai by Danin (1983), El-Demerdash et al. (1996), Helmy et al. (1996), and Morsy et al. (2010). It reflects the association *Acacietum tortilis* of the class *Acacietea tortilis*. This class was described by Knapp (1968) for relatively dry lowlands in Sudan, Ethiopia, Eritrea, and Somalia. The *Acacia tortilis* communities in the Saharo-Arabian region represent outliers of this subtropical class, bound to desert sites with relatively good water availability.

Cleome droserifolia group (M2G5) is dominated by *Cleome droserifolia*. Other characteristic species are *Aerva javanica* and *Capparis aegyptia*, while *Acacia tortilis* is abundant in most sites. The community includes 64 relevés with a relatively high mean species number (12) in comparison to the mother group M2. Its vegetation mainly consists of chamaephytes (electronic appendix) and occurs in sandy and gravelly wadis. The communities are found primarily in the Central and Southern regions of Sinai (electronic appendix). Its species reflect Sudanian and Mediterranean chorotypes (electronic appendix). For M2G5, no corresponding association has been described in the literature. Still, based on the high cover of *Acacia tortilis* and its species composition, we provisionally assign this community to the *Acacietea tortilis*.

Tetraena simplex group M2G6 is characterized by *Tetraena simplex* (dominant), *Stipagrostis plumosa*, *Pulicaria undulata* subsp. *undulata* and *Citrullus colocynthis*. It includes 58 relevés with a relatively high mean number of species (11). The dominant life forms are hemicryptophytes (electronic appendix). This group occurs in sandy plains and sandy and gravelly wadis (ergs and regs) in the Central and Southern regions of Sinai (electronic appendix). This group is similar to communities reported in Sinai by El-Demerdash et al. (1996). While we are uncertain about the appropriate corresponding association for M2G6, we found that the species composition indicates the class *Retametea raetam*.

Forsskaolea tenacissima group (M2G7) has *Forsskaolea tenacissima* as a dominant species. Further differential species are *Indigofera arabica*, *Iphiona scabra*, *Fagonia indica* var. *indica*, and *Lotus polyphyllos*. The group includes 58 relevés and has a higher mean species number (16) than the main group M2. Its plant species are mainly chamaephytes (electronic appendix), while the supporting habitats are sandy plains and dunes (ergs) in the Southern Sinai (electronic appendix). We allocated M2G7 in the class *Retametea raetam* without finding a suitable corresponding association.

Hyoscyamus muticus group (M2G8) is characterized by *Hyoscyamus muticus,* followed by *Tephrosia purpurea* and *Lavandula pubescens*. It includes 24 relevés with a relatively high species number (15). Unlike M2, the dominant life forms of M2G8 are chamaephytes (electronic appendix). Relevés of M2G8 occur in sandy and gravelly plains and dunes (ergs and regs) in all regions of Sinai (electronic appendix). The prevailing chorotypes are the

Sudanian and Saharo-Arabian (electronic appendix). We suggested allocating this group to the class *Retametea raetam*. However, we refrained from further allocation on the level of association.

Fagonia scabra group (M2G9) differential species are *Fagonia scabra* (dominant), *Atriplex halimus*, *Caylusea hexagyna*, and *Ochradenus baccatus*. It includes 31 relevés with a relatively high species number compared to other groups (18). The primary life forms of the vegetation are chamaephytes (electronic appendix), while the supporting habitats are sandy plains and dunes and gravelly wadis (ergs and regs). This group occurs in the Central and Southern regions of Sinai (electronic appendix). M2G9 is similar to communities reported in Sinai by Zohary (1973), El-Demerdash et al. (1996), and Hatim et al. (2016). The species composition of M2G9 did not allow an allocation to any known association. Nevertheless, we can assign this group to the class *Retametea raetam*.

Artemisia judaica group (M2G10) is dominated by *Artemisia judaica*. It includes 77 relevés. In contrast to the main group M2, this group is dominated by chamaephytes (electronic appendix). It inhabits sandy and gravelly plains (ergs and regs) and is represented in the Central and Southern regions of Sinai (electronic appendix). M2G10 is similar to communities described in Sinai by Danin (1983), Abd EL-Wahab et al. (2006), and Hatim et al. (2016) and represents the association *Artemisietum judaicae* of the *Retametea raetam*.

Zilla spinosa group (M2G11) is characterized by *Zilla spinosa* (dominant), *Fagonia mollis*, and *Cleome amblyocarpa.* It includes 59 relevés. The dominant life forms are chamaephytes (electronic appendix). The supporting habitats are sandy and gravelly plains and wadis (ergs and regs) in the Central and, more frequently, the Southern regions of Sinai (electronic appendix). This group is similar to the ones reported in Sinai by Danin (1983), who described it as the association *Retamo raetam-Zilletum spinosae*, El-Demerdash et al. (1996), and Ayyad et al. (2000). It also resembles the *Zilletum spinosae*, as described by Kassas (1954). M2G11 fits in the class *Retametea raetam*.

Fagonia arabica, followed by *Reseda pruinosa*, dominates *Fagonia arabica* group (M2G12). This group includes 91 relevés with a relatively high mean species number (12) in comparison to that of the main group M2. This group is dominated by chamaephytes (electronic appendix), and its relevés occur in sandy and gravelly plains (ergs and regs) in all regions of Sinai (electronic appendix). The group has many species in common with M2G11; therefore, we consider it a variety of the *Retamo raetam-Zilletum spinosae* of the *Retametea raetam*.

Retama raetam group (M2G13) is dominated by *Retama raetam.* It includes 106 relevés. Unlike the main group M2, the dominant life forms are phanerophytes, mainly shrubs (electronic appendix), while the supporting habitats are gravelly plains and sandy and gravelly wadis (regs and ergs). This group is represented in all regions of Sinai (electronic appendix). A similar vegetation community was reported in Sinai by Migahid et al. (1959), Danin (1983), Helmy et al. (1996), Marie (2000), Abd EL-Wahab et al. (2006), Morsy et al. (2010), and Hatim et al. (2016). Nevertheless, Danin (1983) stated that this community is restricted to the Northern Sinai limestone hills, while Hatim et al. (2016) noted that it occurs on hummocks and wadi beds. It reflects the association *Retametum raetam* (Danin, 1983) of the class *Retametea raetam.*

Lycium shawii group (M2G14) is dominated by *Lycium shawii* and includes 19 relevés. The predominant life forms are phanerophytes, mainly shrubs (electronic appendix). Relevés of M2G14 occur in gravelly plains and wadis (regs). This group is widely distributed, with a focus on Southern Sinai (electronic appendix). No corresponding association for this group was found, but the species composition suggests assigning it to the class *Retametea raetam.*

Tamarix senegalensis is the dominant species in *Tamarix senegalensis* group (M2G15). Further characteristic species are *Launaea nudicaulis* and *Filago desertorum*. It includes 23 relevés with the highest mean species number (20) compared to the other groups of the main group M2. Relevés of M2G15 occur on ergs (sandy wadis, plains, and dunes), and inland salt deserts. This group is represented in the Northern, Central, and Southern regions of Sinai (electronic appendix). This group is similar to those reported in Sinai by Migahid et al. (1959), Danin (1983), El-Kady and El-Shourbagy (1994), Marie (2000), El-Ghani & Amer (2003), and Hatim et al. (2016). M2G15 represents the association *Tamaricetum niloticae* of the class *Retamo-Tamaricetea fluviatilis*, as Zohary (1973) described.

MAIN GROUP 3 Mountain desert vegetation (six groups)

Stachys aegyptiaca group (M3G1) is characterized by dominant *Stachys aegyptiaca*, *Ballota undulata*, and *Galium sinaicum*. It consists of 60 relevés. The vegetation mainly consists of chamaephytes (electronic appendix) and inhabits rocky hillsides (hamadas), wadis, and outcrops. It can be found at rocky wadi slopes and beds in the Sinai mountains. M3G1 occurs in the Southern Sinai (electronic appendix), and its species belong to the Mediterranean and Irano-Turanian chorotypes (electronic appendix), which are different from the main group M3 chorotypes. This group is similar to communities found in Sinai by Danin (1983), Ayyad et al. (2000), Abd EL-Wahab et al. (2006), and Hatim et al. (2016). However, Danin (1983) stated that this group is restricted to limestone outcrops in Northern Sinai. M3G1 represents the association *Stachydetum aegyptiacae* (Zohary 1973) of the class *Chiliadenetea iphionoidis* (= *Varthemietea iphionoidis* in Zohary 1973), representing rocky vegetation as described by Danin & Oshran (1999).

In *Phlomis aurea* group (M3G2), *Phlomis aurea* occurs as a dominant species. Further differential species are *Teucrium polium*, *Echinops spinosissimus*, and *Chiliadenus montanus.* M3G2 includes 107 relevés. Unlike the main group M3, the main life forms are hemicryptophytes (electronic appendix). Relevés of this group occur in rocky wadis and outcrops in the mountains of the Southern Sinai (electronic appendix). Its main chorotypes are the Irano-Turanian and the Saharo-Arabian (electronic appendix). It is similar to vegetation communities reported in Sinai by Danin (1983), Helmy et al. (1996), Ayyad et al. (2000), Abd EL-Wahab et al. (2006), Shaltout et al. (2015), and Hatim et al. (2016). We assigned M3G2 to the association *Tanaceto sinaici-Phlomitetum aureae* (Danin, 1983) of the class *Chiliadenetea iphionoidis*.

Characteristic species of *Tanacetum sinaicum* group (M3G3) are *Tanacetum sinaicum*, *Crataegus* x *sinaica*, and *Nepeta septemcrenata.* This group includes 62 relevés, while the primary life forms are chamaephytes (electronic appendix), inhabiting rocky outcrops. This group is represented in the Southern Sinai (electronic appendix). Its plant species mainly belong to the Mediterranean, followed by the Mediterranean-Irano-Turanian and Saharo-Arabian chorotypes (electronic appendix). It is similar to communities found in Sinai by Danin (1983), Moustafa and Zaghloul (1996), Ayyad et al. (2000), Abd EL-Wahab et al.

(2006), and Hatim et al. (2016). We allocated this group to the association *Artemisio herbae-albae-Tanacetetum sinaici* (Danin, 1983) of the class *Chiliadenetea iphionoidis*.

Alkanna orientalis group (M3G4) is dominated by *Alkanna orientalis* is dominant, while the other characteristic species are *Peganum harmala*, *Achillea fragrantissima*, *Launaea spinosa*, and *Matthiola arabica.* M3G4 includes 75 relevés with the highest mean species number of all groups (22) occurring in rocky wadis in the Southern Sinai (electronic appendix). The dominant life forms of this group are hemicryptophytes (electronic appendix). No corresponding association for this group was found, but the total species composition allocates this community to *Chiliadenetea iphionoidis*.

Artemisia herba-alba is the dominant species of *Artemisia herba-alba* group (M3G5). This group includes 89 relevés with a relatively low mean species number (7) compared to that of the main group M3. The life forms are mainly chamaephytes (electronic appendix). This group inhabits rocky wadis, predominantly represented in the Southern and, to a lesser extent, the Central regions of Sinai (electronic appendix). Most plant species belong to the Irano-Turanian and Saharo-Arabian chorotypes (electronic appendix). This group is similar to those reported in Sinai by Danin (1983), Ayyad et al. (2000), and Abd EL-Wahab et al. (2006). It reflects the association *Artemisietum herbae-albae* (Zohary, 1973). It is the only group that belongs to the class *Artemisietea sieberi*, which comprises steppe communities, in most cases dominated by low wormwood shrubs (Danin & Orshan, 1999). The class is concentrated in the cooler climate of the Irano-Turanian and Mediterranean region (Zohary, 1973), but in Sinai, similar communities are found in places where edaphic conditions are suitable.

Anabasis articulata group (M3G6) is dominated by *Anabasis articulata*. Further differential species are *Moricandia sinaica*, *Deverra tortuosa*, *Juniperus phoenicea*, *Gymnocarpos decandrus,* and *Asparagus horridus.* M3G6 includes 55 relevés. Unlike the main group M3, the main life forms are chamaephytes (electronic appendix). The supporting habitats are rocky and gravelly wadis. This group is represented in Northern and Southern Sinai (electronic appendix). This group is similar to a community reported in Sinai by Danin (1983) under the association *Anabasetum articulatae*, which is the only group of the class *Anabasietea articulatae*, being described for extreme arid and hot, stony and gravelly deserts in Zohary (1973) and Danin & Oshran (1999). It is an hyperthermic vicariant of the class *Artemisietea sieberi*.

MAIN GROUP 4 Ruderal desert vegetation (one group)

Characteristic species of *Convolvulus arvensis* group (M4G1) are *Convolvulus arvensis* (dominant)*, Euphorbia peplus, Chenopodium murale,* and *Cynodon dactylon*. This group includes 47 relevés with relatively high mean species numbers (17). The vegetation is dominated by therophytes (electronic appendix). This group represents the ruderal deserts and occurs mainly close to arable fields. This group is similar to communities reported in Sinai by Ahmed (1983), Gibali (1988), Marie (2000), and Hatim et al. (2016). M4G1 is similar to the association *Chenopodio albi-Solanetum villosi* (Zohary, 1973), and we placed it in the broadly defined class of weed communities, *Stellarietea mediae*.

Although the first three main groups are well separated, there is a floristic link between M1 and M2, indicating the transitional state of main group M1 from salt desert to lowland desert vegetation. This interference is apparent between M1G1 and M1G3 and groups M2G3, M2G5, and M2G6 as the characteristic species (*Tetraena alba* and *Panicum turgidum*) of the former groups appear in the latter groups with relatively high abundance values.

Many groups have a similar distribution within each main group (M) and occur in similar habitats. Thus, we think it is likely that small ecological differences cause pronounced differences in species composition. Additional to the plant diversity found on the regional level, these findings reflect the diversity of desert vegetation on a more local scale, with its mosaic of rather diffuse but delimited vegetation communities (Danin, 1983). On the other hand, M4 is inarguably segregated from M1 – M3 indicating its character of ruderal vegetation. Its species composition is predominantly driven by farming activities.

In Sinai, habitat type and altitude, which affect soil moisture, are the most critical factors controlling the distribution of vegetation groups and their related plant life forms (Kassas & Girgis, 1965; Zohary, 1973; Ayyad, 1973; Danin, 1983; Kassas & Batanouny, 1984; Moustafa, 1990; Moustafa & Zaghloul, 1993; Helmy et al., 1996; Hatim et al., 2016). The observed vegetation groups of salt and lowland deserts (M1 and M2 main groups) occur at lower altitudes and have the lowest mean species numbers. This may be related to a weak water storing capacity and the scarcity of rainfall, resulting in very open and scarce vegetation (Hatim et al., 2016). On the other hand, vegetation groups at higher altitudes (mountain deserts, M3) have higher mean species numbers. Such habitats have an increased water availability related to wadi-filling materials, sediments, and high proportions of gravels and fine grains in the soil pockets, giving them the ability to retain water efficiently (Ayyad et al., 2000). M4 has the highest mean species number as it occurs on nutrient-rich soils with high water availability in ruderal desert places. However, many of its species (e.g.*, Convolvulus arvensis*, *Chenopodium murale*, *Cynodon dactylon*, *Malva parviflora*, *Hordeum murinum*, *Sonchus oleraceus*, and *Solanum nigrum*) are widespread, and their occurrences are the results of human disturbances. This finding, again, indicates the negative impact of farms by introducing such species to the area and the need for adapting regulations for land management.

Our findings show that the study area is inhabited by many plant life forms strongly adapted to prevailing conditions in the Sinai desert region. Among them, therophytes are the most common ones (40%), followed by chamaephytes (30.7%) and hemicryptophytes (17.7%). Hemicryptophytes grow in arid places when they experience large amounts of rainfall or flooding. On the other hand, therophytes and geophytes flourish in areas with nutrient-rich soils and high water availability (represented in M4 and M3 main groups).

Of the described 25 vegetation communities, many are similar to communities mentioned by Migahid et al. (1959), Danin (1983), Hussein (1988), Gibali (1988), El-Demerdash et al. (1996), Helmy et al. (1996), Marie (2000), and Hatim et al. (2016). Most of the groups could be assigned to associations described in the literature. However, seven of them do not correspond to any of the previously described associations. The distinction of these groups in our study can be related to the higher comprehensiveness of our data compared to those used in previous studies. It might be possible that also changes in species composition have occurred. However, this is not easy to test on the available data.

We set up a preliminary scheme, shown below, based on the 25 found vegetation groups, including four syntaxonomical levels (class, order, alliance, association). However, many questions can only be answered by analyzing data sets of desert relevés for much larger regions, including the Middle East and the Sahara. For instance, it is unclear whether the *Acacia*-dominated desert savannahs should be split into different classes or not. The exact floristic differences between the sandy desert classes *Retametea raetam* and *Haloxylonetea salicornici*, and between the gravelly desert classes *Anabasietea articulatae* and *Artemisietea sieberi* are also not clear. Such uncertainties also remain on some lower levels of the current syntaxonomical scheme. The names of the syntaxa were adapted according to the latest taxonomy of the species, in line with the International Code of Phytosociological Nomenclature (Theurillat et al., 2021).

- ***Salicornietea fruticosae* Br.-Bl. et Tx. ex A. Bolòs y Vayreda et O. de Bolòs in A. Bolòs y Vayreda 1950**
  - *Limoniastretalia guyoniani* Guinochet 1951
    - *Zygophyllion albae* Géhu, Costa & Uslu 1990
      - *Zygophylletum albi* Zohary 1973
        - *Tetraena alba* community (M1G1)
      - *? Salvadoretum persicae* Kassas et Zahran 1965
        - *Salvadora persica* community (M1G2)

- ***Retametea raetam* Eig 1939**
  - *Stipagrosto-Retametalia raetam* Zohary 1973
    - Alliance ?
      - *Panicetum turgidi* Zohary 1973
        - *Panicum turgidum* community (M1G3)
  - *Haloxylo-Retametalia raetam* Zohary 1973
    - Alliance ?
      - *Tetraena simplex* community (M2G6)
      - *Forsskaolea tenacissima* community (M2G7)
      - *Hyoscyamus muticus* community (M2G8)
      - *Fagonia scabra* community (M2G9)
      - *Artemisietum judaicae* Zohary 1973 (M2G10)
      - *Retamo raetam-Zilletum spinosae* Danin 1983 (M2G11 and M2G12)
      - *Retametum raetam* Zohary 1973 (M2G13)
      - *Lycium shawii* community (M2G14)

- ***Haloxylonetea salicornici* Zohary 1955**
  - Order ?
    - ? *Zygophyllion coccinei* El Sharkawy et Fayed 1982
      - *Zygophylletum coccinei* Zohary 1973
        - *Zygophyllum coccineum* community (M2G1)
      - *Haloxylonetum salicornicae* Zohary 1973
        - *Haloxylon salicornicum* community (M2G2)
      - *Ephedretum alatae* Zohary 1973
        - *Asphodelus fistulosus* community (M2G3)

- ***? Retamo-Tamaricetea fluviatilis* Zohary 1973**
  - ? *Tamaricetalia africanae* Braun-Blanquet et Bolòs 1957
    - ? *Tamaricion africanae* Braun-Blanquet et Bolòs 1957
      - *Tamaricetum niloticae* Zohary 1973
        - *Tamarix senegalensis* community (M2G15)

- ***Acacietea tortilis* Knapp 1968**
  - ? *Acacietalia tortillis* Knapp 1968

? *Acacion tortilis* Eig 1946
Acacietum tortilis Eig 1946
Acacia tortilis community (M2G4)
Cleome droserifolia community (M2G5)

***Artemisietea herbae-albae* Zohary 1952**
Artemisietalia herbae-albae Zohary 1973
Artemision herbae-albae Eig 1946
Artemisietum herbae-albae Zohary 1973
Artemisia herba-alba community (M3G5)

***Anabasietea articulatae* Zohary 1952 ex Danin et Solomeshch 1999**
Anabasietalia articulatae Zohary 1955 ex Danin et Solomeshch 1999
Agathophoro-Anabasion articulatae Danin, Orshan et Zohary 1975 ex Danin & Solomeshch 1999
Anabasietum articulatae Zohary 1973
Anabasis articulata community (M3G6)

***Chiliadenetea iphionoidis* Zohary 1955 ex Danin et Solomeshch 1999**
Artemisio sieberi-Chiliadenetalia iphionoidis Danin, Orshan et Zohary 1975 ex Danin et Solomeshch 1999
Tanaceto-Artemision herbae-albae Zohary 1973
Stachydetum aegyptiacae Zohary 1973
Stachys aegyptiaca community (M3G1)
Tanaceto sinaici-Phlomitetum aureae Danin 1983
Phlomis aurea community (M3G2)
Artemisio herbae-albae-Tanacetetum sinaici Danin 1983
Tanacetum sinaicum community (M3G3)
Alkanna orientalis community (M3G4)

***Stellarietea mediae* Tüxen et al. ex Von Rochow 1951**
Order ?
Alliance ?
Chenopodio albi-Solanetum villosi Zohary 1973

Convolvulus arvensis community (M4G1)

Based on our expert knowledge, the resulting classification satisfactorily represents vegetation communities of the Sinai desert region. It is worth mentioning that two main factors may have impacted the outcomes of this study. First, the strongly restricted access to the Northern Sinai due to security issues resulted in a lower representation of its vegetation in the database than other Sinai regions. And second, the high representation of the vegetation from the Southern Sinai due to its importance as a center of medicinal and endemic plants. However, we think that the data of the vegetation of the Northern Sinai collected from literature could have decreased that impact.

2.5 Conclusions

The high diversity of vegetation, plant life forms, chorotypes, the relatively low species numbers, and the strongly overlapping regions and habitats are challenging for the numerical classification of Sinai desert vegetation. Nevertheless, our study presents a sound and ecologically convincing classification of the Sinai desert vegetation. Yet, there is still a need for more detailed studies revealing the ecological and historical factors that determine the different vegetation communities and studies on the broader context of the Sinai desert vegetation and its position in the Saharo-Arabian region.

Besides using a more comprehensive dataset (1,421 relevés), our study differs significantly from previous studies in applying different, up-to-date analyses of vegetation science, as well as providing enhanced, updated descriptions, distribution maps, and assignments into a syntaxonomical scheme of many vegetation communities, including seven new plant communities.

3

The vegetation around the foothills of the Hijaz Mountains, Saudi Arabia

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3.1 Introduction

The Arabian Peninsula is an interesting area from a floristic perspective as it lies in the transition zone of several phytogeographical regions (Al-Nafie 2008). The Mediterranean, Irano-Turanian, Saharo-Arabian and Sudano-Zambezian regions all meet on the Arabian Peninsula (Takhtajan et al. 1986; Zohary 1973). However, the common impression of this desert region as a barren wasteland has led to little interest in studying this region's floristic and phytosociological diversity. Fortunately, the last decades have marked an increase in our knowledge of the flora and vegetation of the Arabian Peninsula in general and that of Saudi Arabia in particular, resulting in several publications. See, for example, Kürschner & Neef (2011), Al-Sodany et al. (2011), Al-Khamis et al. (2012), El-Demerash et al. (1994), Alyemeni (2000) and Al-Fredan (2008).

Despite this, there are still vast areas that are uncharted in this regard. Even though the vegetation of the Asir mountain range has received some attention from botanists, demonstrated by the studies of Fayed & Zayed (1989), El-Demerash et al. (1994), El-Karemy & Zayed (1996), Al Wadie (2002) and El-Deen (2005), the vegetation of the more northerly located Hijaz Mountains and the adjacent coastal plains have received only little attention. In 1957, Vesey Fitzgerald (1957) presented a rough description of the vegetation along the coast up to the inland side of the mountains, whereas Mahmoud *et al.* (1982) paid attention to the coastal area near Rabigh, and Abd El-Ghani (1996) studied the vegetation in the southernmost part of the mountain range along the road connecting the two holy cities Makkah and Medina.

Extensive knowledge of the floristic composition and phytosociology is vital not only for phytogeographical and ecological studies but also for adequate protection and management of ecosystems and their biodiversity in a world with rapidly changing climate and land use. Therefore, the current study aims to improve the ecological knowledge of the foothills of the Hijaz Mountains by giving an account of its flora and vegetation concerning the environmental conditions.

3.2 Materials & Methods

3.2.1 Study Area

The Hijaz Mountains, located at the western edge of the Arabian shield, comprise a mountain range in the northwestern part of Saudi Arabia stretching out along the Red Sea coast. To the west, the mountain range is bordered by the Tihamah (the Red Sea coastal region), which consists mostly of gently sloping, sandy and gravelly plains with varying soil depths and salt concentrations (Mahmoud et al. 1982; Alsherif et al. 2013; Guba & Glennie 1998). The Hijaz Mountains start from the Red Sea coastal area, where the terrain rises gradually from flat sandy plains to the foothills of mountains and further into slopes; these slopes rise to the top of the mountains at approximately 2000 m high. Eastwards, the Hijaz Mountains flow out into the Central Plateau, harboring the vast Arabian desert. The Hijaz mountains largely consist of a variety of precambrian, hard bedrock, mainly granite, metamorphic (gneiss) and volcanic rocks, with sedimentary rocks (schists) at the base (Guba & Glennie 1998). The areas where these precambrian rocks are overlain by young volcanic (basaltic) rocks are known as *harrah*.

The area, unlike the Asir Mountains which extend from the Hijaz Mountains southwards, is located within the Nubo-Sindian local center of endemism of the Saharo-Sindian regional zone (Kürschner 1998; Alfarhan 1999), but also contains elements of neighboring floristic regions, including the Mediterranean and Somali-Masai regional centers of endemism (Woldewahid et al. 2007). The area consists of many different habitats, such as wadis, runnels, sand sheets, gravels, rock deserts, and hillocks. These habitats all have their specific floristic elements and different plant formations. The diversity is further enhanced by the relatively high amount of rainfall in the higher parts of the mountains. Because of these gradients and diversity, the Hijaz Mountains are considered one of the floristically richest regions of Saudi Arabia (Collenette 1998).

In general, the climate of the study area is influenced by maritime and tropical continental air masses (Fisher & Membery 1998). The upper sectors of the mountains represent a transitional zone between the monsoon and Mediterranean climates, which is influenced by the proximity to the Red Sea and the relatively high altitude (Abd El-Ghani 1996). In the lowlands, the climate is relatively dry with rainfall not exceeding 100 mm each year, leading to the development of scarcer vegetation (Abd El-Ghani 1996), except for the wadis (Kassas & Imam 1954).

3.2.2 Vegetation survey

Field sampling was performed during the spring of 2015, when most species were expected to grow after increased rainfall. Two transects were set up: one between the Hijaz Mountains and the coast and one at the eastern side of the Hijaz Mountains (Fig. 1). The coastal transect was positioned along Saudi Arabian highway 5 between Jeddah and Haql. The inland transect followed highways 15 and 328, starting at Jeddah and ending at Sulailah. Sample locations were selected subjectively to cover most of the observed variation in vegetation and habitats. Plant cover was visually quantitatively estimated as a cover score for each species in each stand. Plants were identified using Collenette (1985; 1999), Miller *et al.* (1996) and Chaudhary (1999; 2000a; 2000b; 2000c; 2001). Herbarium specimens were deposited in the Herbarium of Botany and Microbiology Department at the King Saud University. In addition, the GPS coordinates of every sample location were recorded. Using these coordinates, the elevation of each sample location was determined using Google Earth Pro 7.3.3.7786.

3.2.3 Soil sample analysis

In addition to the vegetation surveys, a sample of surface soil (0-15 cm) was taken from most of the stands. Samples were air dried and sieved with a 2 mm sieve to remove gravel and other coarse materials. In these soil samples, the following parameters were measured: texture, pH, electrical conductivity, organic matter, calcium carbonate and the concentration of the elements N, Na, K, Ca, Mg, Fe and Mn. Soil structure was determined using the Bouyoucos (1962) hydrometer method. Soil-water extracts (1:5) were prepared to determine pH and electrical conductivity (EC) using pH and conductivity meters, respectively. Calcium carbonate content was determined by rapid titration after Sparks (1996). Organic matter content was determined by loss-on-ignition (Krishna 2002). Soil samples were prepared for measurements of nutrient content using a TMC digestion after Sparks (1996). The total inorganic nitrogen content was determined by applying a spectrophotometric approach (Lindner 1944). The concentration of Na and K in the samples was measured by flame spectrophotometry, the concentration of Ca, Mg, Fe and Mn by atomic absorption spectrophotometry.

3.2.4 Data analysis

Plant species were allocated to life-forms according to Raunkiaer (1934) and to chorological units based on Zohary (1973) and Wickens (1978). The vegetation data were stored and organized using Turboveg 2.99 (Hennekens & Schaminée 2001). To determine if there are meaningful clusters (groups) in the data, the Hopkins' test (Python, version 3.7.6, electronic appendix) was used. This is a statistical hypothesis test which calculates the Hopkins' statistic (H) (Hopkins & Skellam 1954). The null hypothesis (H_0) states that the data follow a uniform distribution (implying no meaningful clusters), whereas the alternate hypothesis (H_1) states that the data are not uniformly distributed (presence of clusters). If the Hopkins' statistic outcome is larger than 0.5, the alternate hypothesis can be accepted and the data can be organized into meaningful clusters (Hopkins & Skellam 1954).

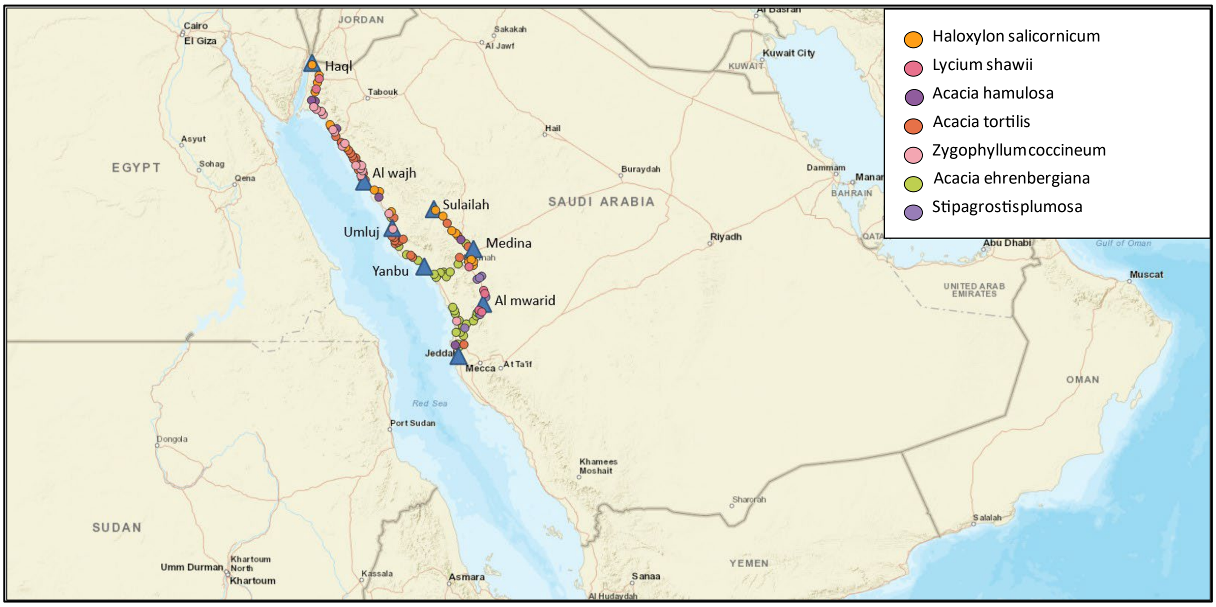

Figure 1. Map of the study area showing the approximate locations of the vegetation plots. The color of each dot indicates the community the plot belongs to.

To calculate the approximate optimal number of clusters, the Elbow method (Ketchen & Shook 1996); Python, version 3.7.6 (electronic appendix) was used. In the Elbow method, a cluster analysis for the data is performed and the sum of within-cluster variance (WCSS) for different clusters numbers is calculated. The number of clusters values are plotted against their opposite WCSS values to find the optimal number of clusters, which is the last breaking point (elbow) of the plotted curve.

Using JUICE 7.1 (Tichý 2002), the vegetation plots were classified using a hierarchical modified TWINSPAN algorithm (Roleček et al. 2009) with pseudo-species cut levels 0, 5, 25, 50. Hierarchical subdivision was stopped when it did not result in vegetation types with ecologically meaningful characteristic species. To improve the classification, nine vegetation plots were reallocated among the resulting groups. Reallocations only took place if (i) the segregation of the cluster by differential species constancy values was improved and (ii) the silhouette values (JUICE, Silhouette function) of the clusters remained unchanged or were increased. Ordination of the vegetation plots with the environmental data was done using a Detrended Correspondence Analysis (DCA), using R 4.0.2 (R Core Team, 2015) and the package vegan 2.5-6 (Oksanen et al. 2019).

The differences between the environmental variables of the different clusters were tested using Kruskal Wallis tests. Pairwise Wilcoxon rank sum tests with p-values adjusted using a Bonferroni correction were used as post hoc test to determine differences between individual groups in case the Kruskal Wallis tests showed the presence of significant differences. All of these tests were done using R 4.0.2 (R Core Team 2015).

3.3 Results

3.3.1 Floristic diversity

In total, 110 plots were sampled, containing a total of 214 plant species belonging to 42 families. The families Asteraceae and Fabaceae had the highest numbers of species, each of them accounting for 11.2 % of the observed species. The Poaceae and Amaranthaceae each represented 7.9 % of the recorded species, and the Brassicaceae and Zygophyllaceae 6.0 %. Furthermore, 19 families were monotypic, whereas four families were represented by two species each.

The life-form spectrum was dominated mainly by therophytes, which accounted for 41.8 % of the recorded species (Fig.2). Chamaephytes, phanerophytes and hemicryptophytes constituted 28.8, 15.9 and 12.0 % of the total number of species, respectively. Geophytes were by far the least represented life-form containing only 1.4 % of the total species (Fig. 2).

The recorded plant species belonged to 16 different chorotypes, of which seven were uniregional, six were biregional and three were pluriregional (Fig. 3). The three most common chorotypes were the Saharo-Arabian, Sahel-Sudano-Zambezian and Tropical African chorotypes with 72 (33.6%), 42 (22.4%), and 21 (9.8%) species belonging to these types, respectively. The Mediterranean chorotype was represented by only five species (2.3%) and species with a bi- and pluriregional chorotypes with a Mediterranean origin, such as Mediterranean-Saharo-Arabian, were just as rare or even more so. The influence of non-native species (mainly from the American Continents) is small in the study area, with only three species (1.4%).

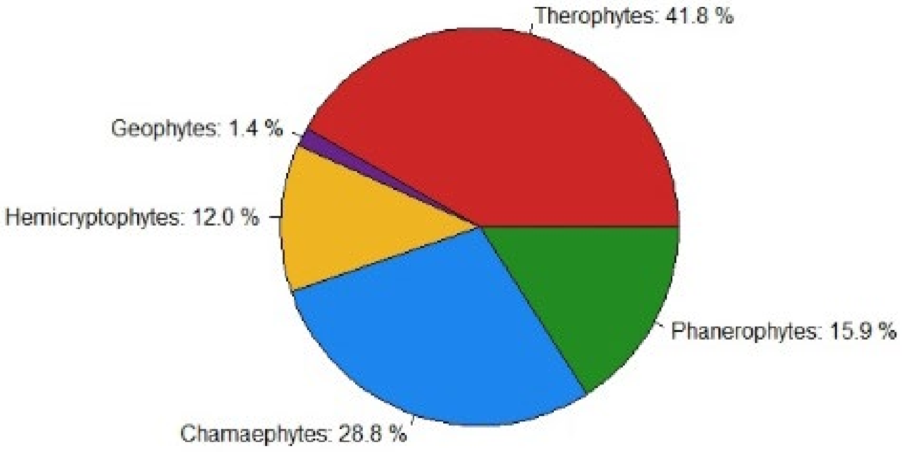

Figure 2. The life-form spectrum of the transects vegetation

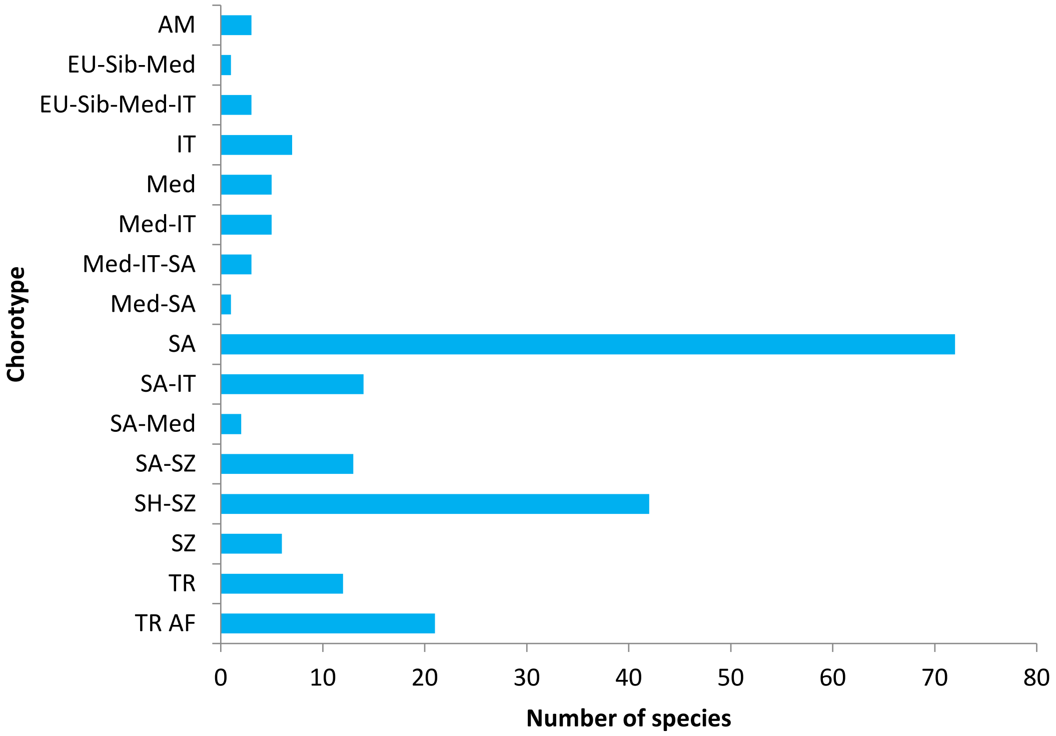

Figure 3. The chorotype spectrum of the transects vegetation. AM-American, Eu-Sib-Med-Euro-Siberian-Mediterranean, EU-Sib-Med-IT-Euro Siberian-Mediterranean-Irano Turanian, IT-Irano Turanian, Med-Mediterranean, Med-IT-Mediterranean-Irano Turanian, Med-IT-SA-Mediterranean-Irano Turanian-Saharo Arabian, Med-SA-Mediterranean-Saharo Arabian, SA-Saharo Arabian, SA-IT-Saharo Arabian-Irano Turanian, SA-Med, Saharo Arabian-Mediterranean, SA-SZ-Saharo Arabian- Sudano-Zambezian, SH-SZ-Sahel- Sudano-Zambezian, SZ- Sudano-Zambezian, TR-Tropical, TR AF-Tropical African

3.3.2 Vegetation classification

The outcome of the Hopkins' statistical analysis of the vegetation data was 0.9; thus, the alternate hypothesis, implying that the database contains clusters, was accepted. The expected optimal number of clusters based on the Elbow method was seven (Fig. 4). The hierarchical modified TWINSPAN analysis of the 110 vegetation plots resulted in the formation of seven vegetation communities grouped into three clusters (C1 - C3) (Fig. 5, Table 1). C1 consisted of three communities which were mainly associated with wadis and runnels and mainly occurred in the inland transect. C2 also contained three communities, but these vegetation types were mainly associated with the coastal plains. C3 contained only one community, the Stipagrostis plumosa community, which had a low number of associated species and occurred on coarse sandy plains. Cluster C1 occurred at higher altitudes than cluster C2 (p=3.1e-8). In addition, the soils of the stands of C1 contained more Ca than those of C2 (p=0.0087). Furthermore, the stands of C1 contained more species than C3 (p=0.022).

All reported communities grew on sandy substrates with relatively low amounts of silt and clay (Table 2). The differences in soil pH were small, with all of the communities having high pH values, ranging between 8 and 9.2. The differences in electrical conductivity were much bigger. When plotted on the first two DCA axes, the communities cluster to some extent, although there is still considerable overlap (Fig. 6). The vegetation plots from the *Acacia hamulosa* community are the most strongly clustered together on the positive side of the first

DCA axis and the negative side of the second. Most of the different nutrients seem to be positively correlated to each other as well as the silt and clay content and elevation. The exceptions to this are the nitrogen and iron concentration, which are negatively correlated to the other variables but positively correlated to each other and the sand content as well as to latitude.

Table 1. Shortened synoptic table with the percentage frequency of occurrence and the number of plant species within each of the seven vegetation communities. Only differential species (with frequencies ≥ 30%) are included, and their cells are shaded. The dominant species of each community is shaded.

Group No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
No. of vegetation plots	19	7	6	28	16	28	6
No. of species	79	99	34	85	48	88	23
Haloxylon salicornicum	100	43	17	14	44	4	0
Calotropis procera	37	14	0	7	6	25	33
Citrullus colocynthis	37	14	0	25	13	18	17
Lycium shawii	5	86	17	39	25	14	0
Centaurea pseudosinaica	5	71	17	0	0	0	0
Aizoon canariense	21	71	17	11	0	11	0
Sisymbrium erysimoides	0	71	0	0	0	0	0
Asphodelus tenuifolius	26	71	33	7	0	0	0
Ochradenus baccatus	16	57	0	25	0	14	17
Malva parviflora	0	57	17	0	0	0	0
Trichodesma africanum	0	43	17	7	0	0	0
Zilla spinosa	11	43	0	0	0	0	0
Cuscuta planiflora	0	43	0	0	0	0	0
Rumex vesicarius	5	43	17	0	0	0	0
Echium horridum	0	43	0	0	0	0	0
Solanum glabratum	0	43	0	0	0	0	0
Otostegia fruticosa	0	43	0	0	0	0	0
Acacia hamulosa	0	0	83	0	0	7	0
Aristida adscensionis	16	0	50	21	6	7	0
Indigofera spinosa	0	43	50	4	0	4	0
Sclerocephalus arabicus	0	43	50	0	0	0	0
Maerua crassifolia	26	14	33	25	0	7	0
Acacia tortilis	21	29	33	96	75	36	17
Panicum turgidum	11	0	0	46	19	25	17
Blepharis ciliaris	11	14	17	43	13	4	0
Fagonia indica	11	14	17	32	6	11	17
Zygophyllum coccineum	5	0	0	18	94	29	17
Zygophyllum simplex	42	14	33	54	69	54	33
Hyphaene thebaica	11	0	0	0	31	0	0
Acacia ehrenbergiana	11	43	17	4	19	86	0
Leptadenia pyrotechnica	5	14	0	4	0	36	0
Senna italica	32	14	0	18	6	36	17
Dipterygium glaucum	0	0	0	4	0	32	0
Stipagrostis plumosa	26	0	0	25	0	14	83
Capparis decidua	0	14	0	7	6	7	50

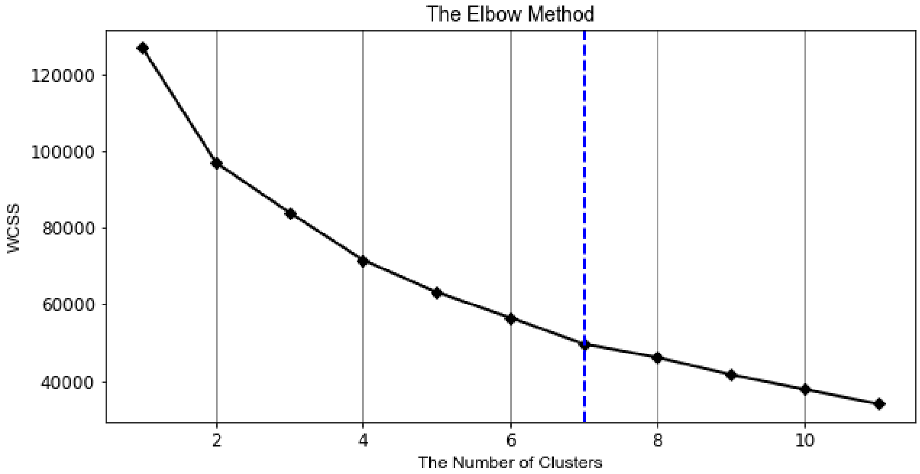

Figure 4. The plot of the Elbow method showing the expected optimal number of clusters. The WCSS values (Within Cluster Sum of Squared distances) represent the mean distances between the plots of a group and its centroid. The lowest the value of WCSS, the more meaningful the clusters are, and the better to correspond to an optimal number of clusters. In our case, the Elbow corresponds to the number of clusters, 7.

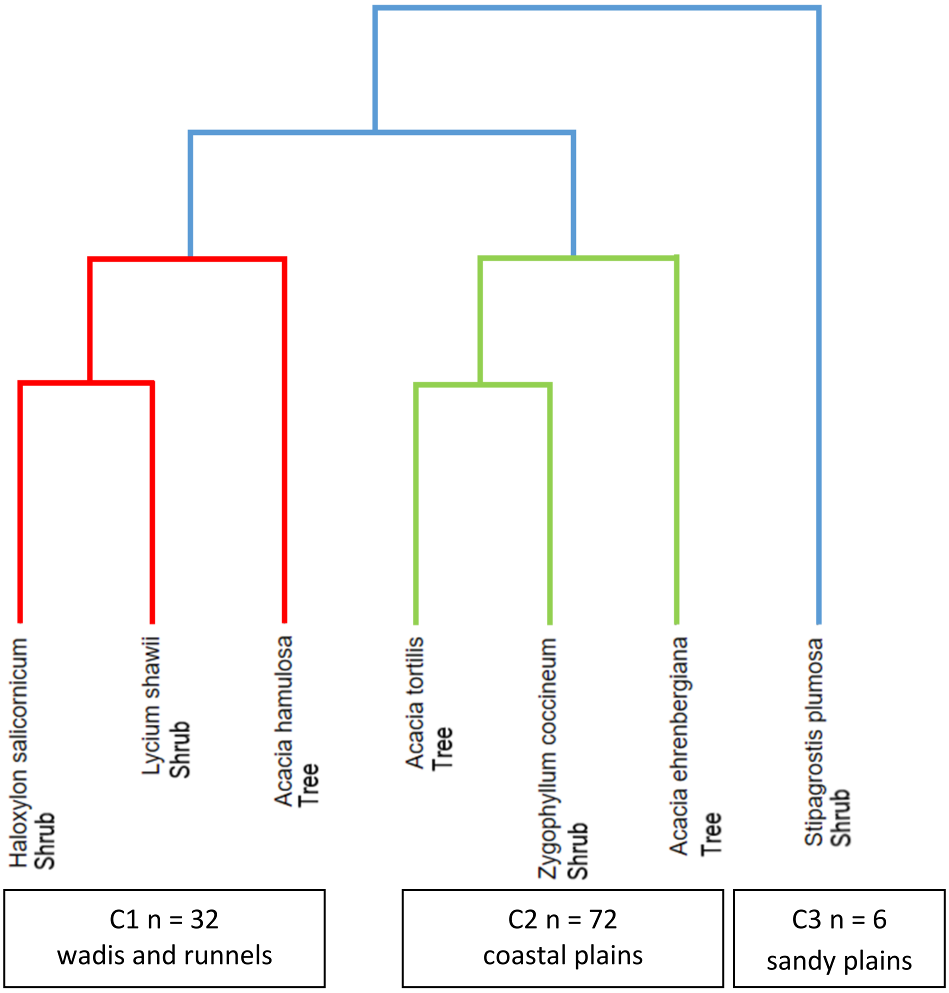

Figure 5. The dendrogram resulting from the hierarchical modified TWINSPAN analysis, containing seven vegetation communities organized into three clusters (C1-C3) with their ecological types indicated. n: the total number of vegetation plots in each cluster.

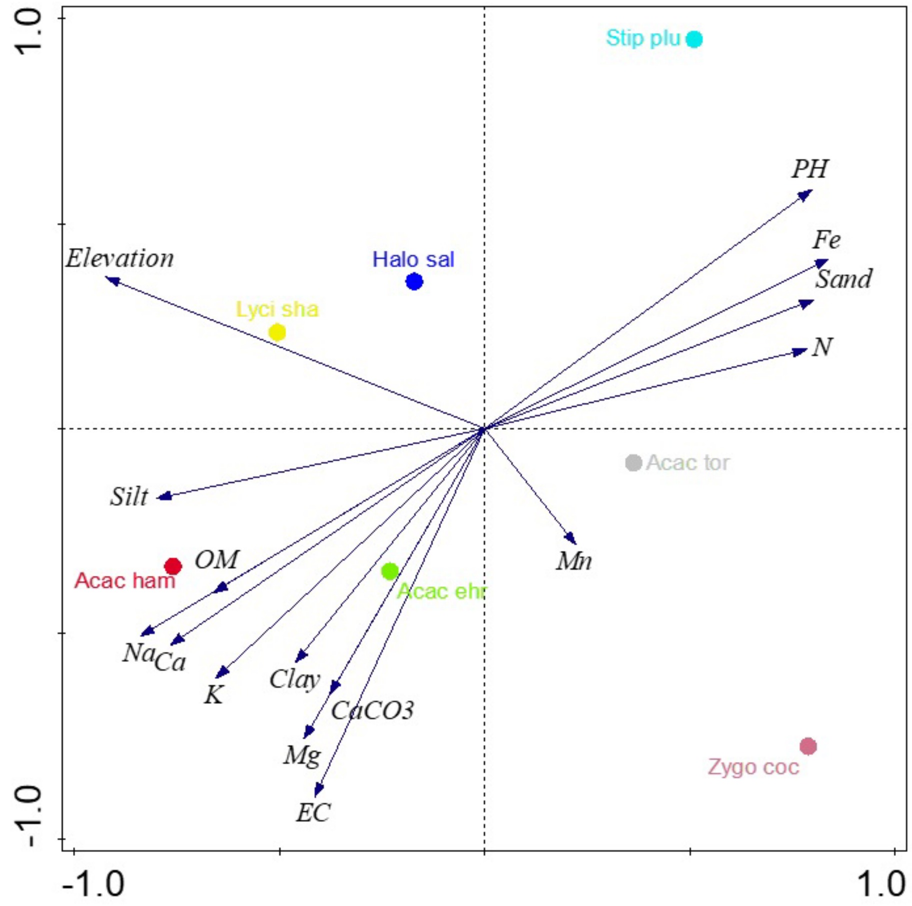

Figure 6. DCA of environmental factors and vegetation communities with arrow indicating the effects of the environmental variables and the communities are indicated by their abbreviations.

3.3.2.1 Haloxylon salicornicum community

The first shrubland community is dominated by the dwarf shrub *Haloxylon salicornicum*. *Haloxylon salicornicum* is a xeromorphic chamaephyte which is widely distributed within the Irano-Turanian and Saharo-Arabian bioprovinces. With 19 stands, this vegetation type is the most abundant shrubland community in the study area. This type of shrubland occurs in the northernmost part of both the coastal and inland transects. It occurs more northerly than the *Acacia hamulosa* (p=0.0067) and *Acacia ehrenbergiana* (p=2.1e-7) communities. In the inland transect, it appears just south of Medina and stays prevalent, sometimes even dominating the vegetation, all the way up to the northern end of the transect. In the coastal transect, it is found north of the town of Umluj, persisting up to the Jordanian border. At the northern part of the coastal transect in the mountains along the Gulf of Aqaba, this vegetation type becomes dominant once again. Due to its occurrence in both the inland and coastal transects this community occurs on a lower average elevation than the *Lycium shawii* and *Acacia hamulosa* communities. The only community of lower elevations is the *Zygophyllum coccineum* (p=0.0024) community. This community was characterized by shallow runnels and plains where the soil has a coarse texture. Its most common associates are the dwarf shrub *Zygophylum simplex*, the shrub *Calotropis procera* and the perennial herb *Citrullus colosynthis*.

3.3.2.2 *Lycium shawii* community

The second vegetation community is dominated by the perennial shrub *Lycium shawii*. This community is very species rich. Though it is only represented by seven stands in the current study, it still comprises the largest species list out of all communities described in this study. The average number of species per stand is higher than that of the *Haloxylon salicornicum* (p=0.0156), Acacia tortilis (p=0.0109), *Zygophyllum coccineum* (p=0.0081) and Acacia ehrenbergiana (p=0,0057) communities. This community is mainly recorded on mountain slopes and in wadis with sandy soils. Of all communities, it is found at the highest average altitude, mainly occurring between 700 and 1,000 meters above sea level. This causes it to occurs at higher elevations than all communities from the C2 and C3 clusters, namely: the *Acacia ehrenbergiana* (p=0.0024), *Acacia tortilis* (p=0.0040), *Zygophyllum coccineum* (p=0.0044) and *Stipagrostis plumosa* (p=0.0490) communities. Like the *Acacia hamulosa* community it occurs in the southern part of the inland transect, between Jeddah and Medina. However, unlike the *Acacia hamulosa* community, it recurs in the most northern part of the transect, in the mountains along the Gulf of Aqaba. Its soil has the highest average silt and organic matter (OM) contents, indicating a relatively good water availability. It is a well-structured community consisting of different layers of vegetation. The shrub layer is dominated by *Lycium shawii*, sometimes accompanied by the shrub *Ochradenus baccatus* or by different species of Acacia trees (*A. ehrenbergiana*, *A. origena*, *A. johnwoodii* and *A. gerrardii*). The herb layer frequently contains the dwarf shrub *Haloxylon salicornicum* as well as various herbs, the most common of which are the annuals *Asphodelus tenuifolius*, *Centaurea pseudosinaica*, *Malva parviflora*, *Sisymbrium erysimoides*. Patches of the creeping annual herb *Aizoon canariense* are a characteristic feature of this community.

3.3.2.3 *Acacia hamulosa* community

This vegetation type is dominated by *Acacia hamulosa*. With only 6 stands, this vegetation type is the rarest of the three Acacia communities in the study area. *Acacia hamulosa* is a phanerophyte taking the form of a small tree or shrub. It is distributed within the Sudano-Zambezian and Saharo-Arabian floristic regions. This community has been found on slopes and wadis on loamy soils in the southern part of the inland transect, between Jeddah and Medina. Along with the *Lycium shawii* community, it is one of the most southerly occurring communities, distributed at lower latitudes than the *Haloxylon salicornicum* (p=0.0067, as mentioned previously), Acacia tortilis (p=0.0097) and *Zygophyllum coccineum* (p=0.0359) communities. Just like the *Lycium shawii* community, it occurs at high elevations mainly between 600 and 1,000 meters above sea level. It occurs higher than all the communities of cluster C2, namely: the *Acacia ehrenbergiana* (p=0.01114), *Acacia tortilis* (p=0.0135) and *Zygophyllum coccineum* (p=0.0095) communities. Of all plant communities in this study, this community's soil is the finest, on average containing the most clay and the least sand. It also has the lowest average pH and highest average electrical conductivity (EC) values. It contains the highest average concentrations of $CaCO_3$, Na, K, Ca, Mg, and the lowest average values of N and Fe. When compared to the other communities within C1, its soil is characterized by a low average N and Fe. In addition, this community's soil varies most markedly from that of the *Acacia tortilis* community, containing more Ca (p=0.04337) and less N (p=0.012) and Fe (p=0.0035). The dominant *Acacia hamulosa* is sometimes accompanied by *Mearua crassifolia* trees. Other species common in this vegetation type include the dwarf shrub Indigofera spinosa, the annual herb *Sclerocephalus arabicus* and the annual grass *Aristida adscensionis*.

3.3.2.4 *Acacia tortilis* community

With 28 stands, this community is the most widely represented vegetation type in the study area together with the Acacia ehrenbergiana community. Its main distribution within the study area comprises the area north of the towns of Yanbu up to the Gulf of Aqaba, dominating the vegetation just north of Yanbu as well as between the towns Al Wajh and Duba. The most striking feature of this community is the shrub layer, consisting mainly of Acacia tortilis. It often takes the form of a small tree with an umbrella-shaped crown. This community requires a relatively well-drained substrate and is therefore found on the coarsest soils, consisting of the highest average sand content and the lowest average silt content. The most commonly co-occurring species are the annual herb *Zygophyllum simplex* and the perennial tussock grass Panicum turgidum which both occurred in about half of the stands of this type. Other relatively common co-occurring are the perennial herbs *Blepharis ciliaris* and *Fagonia indica*.

3.3.2.5 *Zygophyllum coccineum* community

The fifth community is a vegetation dominated by *Zygophyllum coccineum*. This community was represented by 16 stands. *Zygophyllum coccineum* is a perennial dwarf shrub that is distributed mainly around the Red Sea within the Saharo-Arabian floristic region. This vegetation type is confined to the coastal plains of the Tihamah area in the northern parts of the coastal transect, occurring from the area around the town of Umluj up to the area around the town of Gayal. Bound to the coastal plains, it occurs on the lowest average altitude of all communities. The soils of this community had the highest average concentrations of N and Mn. The species most commonly associated with this community is the annual herb of the same genus *Z. simplex*. The shrub layer of this vegetation community is often populated by the trees *Acacia tortilis*, Acacia raddiana and Hyphaene thebaica. The dwarf shrub *Haloxylon salicornicum* also occurs in almost half of the stands of this type.

3.3.2.6 *Acacia ehrenbergiana* community

The third *Acacia* dominated community is represented by 28 stands and one of the most common plant communities in the study area. *Acacia ehrenbergiana* is a phanerophyte taking the form of a small tree or shrub. It is widely distributed within the Saharo-Arabian floristic region, with the center of the species distribution in the southern parts of the Sahara. This community dominates the coastal plains in the southern part of the coastal transect, between the towns of Yanbu and Jeddah, and is also found in the southern part of the inland transect, up to the town of Almwared. It occurs at lower latitudes than the *Haloxylon salicornicum* ($p=2.1e-7$, as mentioned previously), *Acacia tortilis* ($p=5.9e-9$) and *Zygophyllum coccineum* ($p=1.4e-5$) communities. Its soil is characterized by a low average N and Fe compared to the other communities within cluster C2. Its soil has a lower N than the Acacia tortilis ($p=0.00034$) and *Zygophyllum coccineum* ($p=0.00509$) as well as a lower Fe compared to the Acacia tortilis ($p=2.6e-5$) and *Zygophyllum coccineum* ($p=4.1e-5$) communities. In addition, its soil has a lower pH than the *Haloxylon salicornicum* ($p=0.0205$) and Acacia tortilis ($p=0.0076$) communities. The shrub layer of this vegetation community is dominated by *Acacia ehrenbergiana*, occasionally accompanied by the shrub *Leptadenia pyrotechnica*. Dwarf shrubs are a conspicuous element of this vegetation type with *Zygophyllum simplex*, Senna italica and *Dipterygium glaucum* all represented in some of the stands. *Astragalus vogelii var. fatmensis* is the most common herb in this community, though still only occurring in 21 % of the stands of this type.

3.3.2.7 *Stipagrostis plumosa* community

This pseudo-steppe community is dominated by *Stipagrostis plumosa*. *Stipagrostis plumosa* is a hemicryptophyte taking the form of tussock grass. This community occurred sporadically in the northernmost parts of both the coastal and the inland transect. With only six stands, this community is one of the least represented vegetation types. This community was most abundant on sandy plains without any gravel or stones. Its soil was coarse and poor in nutrients with the lowest clay and organic matter content. It had the highest pH and the lowest EC. Finally, it had the lowest concentrations of CaCO3, Na, K, Ca, Mg, Mn and the highest concentration of Fe. The most common co-occurring plant species were the shrub Capparis decidua and the dwarf shrub *Zygophyllum simplex*.

3.4 Discussion

3.4.1 Classification challenges

The vegetation units are not very strongly defined, with many species frequently occurring in different communities. The plant cover, therefore, consists of a large number of indifferent species. The occurrence of several pluriregional elements in the study area indicates a large influence of adjacent phytogeographical regions, further complicating the formation of consistent vegetation units. However, this relatively large number of indifferent species is a typical characteristic of desert vegetation, which complicates vegetation classification in the region. This is in accordance with the findings of Kassas (1953), who theorized that the open character of desert communities does not allow the dominant species to exert a controlling influence on the rest of the community. Other authors also experienced problems in describing the vegetation in desert systems adequately using the Braun-Blanquet method (Zohary 1973). Zohary (1973) theorized that the methodology of Braun-Blanquet, which was developed with mesic-temperate vegetation in mind, is not completely suitable to analyze the vegetation of arid zones.

In our opinion, the methodology can be applied to desert vegetation, although the resulting communities are relatively poorly defined. This has been shown with the use of clustering analysis. To present a verified clustering analysis, the clustering tendency was calculated using Hopkins' statistical hypothesis method. The low species numbers of some stands and significant differences among percentage frequencies of species occurrences make the process of classification challenging. These limitations were overcome by applying a modified TWINSPAN followed by the reallocations of nine vegetation plots among the resulted groups based on mathematically verified Silhouette analyses to improve the final result. Nevertheless, the communities, as defined in this study, as well as their zonation, are in accordance with communities described by other authors. The construction of a hierarchical classification system, with associations, alliances, orders and classes remains a huge challenge for desert vegetation of the Sahara and the Arabian Peninsula, and requires an extensive data set from a wide range of geographical areas and habitats. The current study contributes to such an overview.

3.4.2 Community zonation

The northern parts of both the inland and coastal transects were dominated by *Haloxylon salicornicum* communities. These communities have been reported abundantly in the inland sand and gravel (harrah) deserts of northern and central Arabia (Zohary 1973; Danin &

Orshan 1999; Kürschner 1998) as well as in similar habitats in the adjacent Sinai Peninsula in Egypt (Hatim et al. 2016; 2021). On the Arabian Peninsula they cover more land than any other type (Mandaville 1990; Al-Khamis et al. 2012), especially on coarse textured soils (Kürschner & Neef 2011). Its dominance in the northern regions of the coastal transect might be a consequence of the sampling procedure, as the stands along the Gulf of Aqaba were taken more inland due to the inaccessibility of the coastal area. Therefore, this part of the transect might be more akin to the inland transect.

In the coastal transect, directly south of the *Haloxylon salicornicum* zone, the *Acacia tortilis* community dominates the vegetation. This community is an example of the drought-resistant, deciduous *Acacia*-*Commiphora*-woodlands that are widespread on the Arabian Peninsula in wadis, foothills and lower mountain slopes (Deil & Al Gifri 1998; Kürschner 1998). Such communities in a broad sense have been described from subtropical Northern Africa under the class name Acacietea tortilis (Knapp 1968). They have been recorded quite commonly along the Red Sea coast of Saudi Arabia, although the species assemblages and associates differ (Vesey-Fitzgerald 1957; Kassas 1957; Zohary 1973). In addition, vegetation types dominated by *Acacia tortilis* have been found in the opposing Red Sea coastal region of Egypt (Zahran & Willis 1992) and in the deserts of Israel (Danin & Orshan 1999). In most studies, these communities have been recorded in depressions, wadis and slopes, often covered with rocks, pebbles or gravel (Al Wadie 2002; Danin & Orshan 1999; Fayed & Zayed 1989). *Stipagrostis plumosa* is widely distributed over the Arabian Peninsula, and communities with S*tipagrostis plumosa* are described from stabilized, deep sand habitats in Arabia by Mandaville (1998). In addition, they are recorded as a dominating species in many vegetation types on the Israeli sand sheets (Danin & Orshan 1999). However, the incidents of *Stipagrostis plumosa* communities reported from the Hijaz mountain range are reported either from the southern parts of our study area (Fayed & Zayed 1989) or even further to the south in the Asir mountains. It must be noted, however, that the southern portion of the Hijaz mountains (as well as the Asir mountains) are far more extensively studied than the northern reaches of the mountain range. This, in conjunction with the cryptic nature of this vegetation, might mean that it can easily be missed, especially whilst sampling in the dry season. The apparent absence of this community in the northern portions of the Hijaz mountains might therefore be the result of a low total sampling effort. Communities dominated by *Zygophyllum coccineum* are typical coastal communities on coarse soil in the Arabian desert (Deil 1998). They have been recorded on the coastal plains of the study area (Vesey-Fitzgerald 1957; Mahmoud et al. 1982) as well as on the opposing Sinai Peninsula (Abd El-Wahab et al. 2006; Hatim et al. 2016; 2021). In addition, they have been recorded as a dominant species in communities in the south of the Hijaz Mountains (Abd El-Ghani 1996) as well as in the Asir Mountains (El Karemy & Zayed 1992; El-Deen 2005). In these studies, these vegetation types were recorded in deep alluvial plains, wadis and runnels (El Karemy & Zayed 1992; Abd El-Ghani 1996).

The southernmost part of both transects was dominated by the *Acacia ehrenbergiana* community, which is in accordance with the more southerly distribution of the species. The *Acacia ehrenbergiana*-community fits the description of the wadi communities with Sudanian and Xero-tropical taxa by Kürschner (1998). According to this author, these communities are typical for the western plains (Tihamah) with extensive areas of fluvial deposits and aeolian sands. He mentions *Leptadenia pyrotechnica* as an important associate in places where the wind plays a role in the deposition of sediments. In addition, it has been recorded as a dominant species in communities in the south of the Hijaz Mountains (Abd El-Ghani 1996) as well as in the Asir Mountains (El Karemy & Zayed 1992; El-Deen 2005). In these studies, these vegetation types were also recorded in deep alluvial plains, wadis and runnels (El Karemy & Zayed 1992; Abd El-Ghani 1996) at low elevations (Danin & Orshan 1999). *Acacia hamulosa* dominated communities have also previously been recorded in the more southern ranges of the western mountains of Saudi Arabia. They were recorded in both the south of the Hijaz mountains (Abd El-Ghani 1996; Batanouny & Baeshin 1982) as well as in the Asir mountain ranges (El-Deen 2005; Fayed & Zayed 1989), where they were mostly found on slopes and runnels covered with rocks (Batanouny & Baeshin 1982; El-Deen 2005; Fayed & Zayed 1989). In addition, the combination of *Acacia hamulosa*, *A. tortilis* and *Maerua crassifolia* fits the description of a Sudanian thorn woodland type by Kürschner (1998), which he considers typical for the Tihamah coastal plain and the southern coast of the Arabian Peninsula. Plant communities dominated by *Lycium shawii* are common around the Arabian Peninsula (Ghazanfar & Osborn 2010). In addition, Kürschner (1998) mentions *Lycium shawii* as an associate in wadi communities of *Acacia raddiana*, *A. tortilis* and *A. gerrardii*, which he considers typical for the central part of Arabia. These communities have also been recorded within the southern reaches of the study area by Abd El-Ghani (1996) and Mahmoud et al. (1982) and stretching southward along the Asir Mountains by Fayed and Zayed (1989). In these studies, this community is reported on gravel or pebble covered, coarse textured soils in shallows, runnels and slopes (Abd El-Ghani 1996). To the north, these communities have also been reported in wadi systems (Danin & Orshan 1999).

3.4.3 Underlying environmental factors

Of the environmental factors measured in this study, latitude and altitude seem to exert the most significant influences on this vegetation pattern. Due to the general circulation of air, the distance from other water sources and local factors like mountain barriers, the rainfall on the Arabian Peninsula mainly comes from the Arabian Sea located to the south of the peninsula (Alyamani & Sen 1993). Therefore, the annual average rainfall increases from north to south with the southwestern highlands receiving the most rainfall. In addition to the latitudinal gradient, the physiographic features of the landscape exert a heavy influence on local weather conditions going so far as having a bigger influence on the microclimate than the macroclimatic conditions do (Alyamani & Sen 1993; Abd El-Ghani 1996). The coastal plains are generally hot and dry, with hot summers and dry periods all throughout the year (Vesey-Fitzgerald 1957). As the elevation rises, precipitation increases and becomes more equally distributed throughout the year (Fayed & Zayed 1989). Along the same line, the mean air temperature decreases with an increasing elevation (Fayed & Zayed 1989) which lowers the potential evapotranspiration in these areas (Alyamani & Sen 1993). Both of these factors contribute to a higher and more consistent level of soil moisture, which has often been described as being the primary distinguishing factor affecting desert vegetation communities (Zohary 1973; Hatim et al. 2016; 2021). An effect that can also be seen, on a larger scale, in the difference in vegetation and species diversity between the Hijaz and the more southerly located Asir mountain ranges.

3.4.4 Conclusion

In two transects, one coastal and one inland, along the foothills of the Hijaz mountains, 110 vegetation plots were made, the classification of which resulted in a division into seven distinct communities, dominated by: *Acacia hamulosa*, *Lycium shawii*, *Haloxylon salicornicum*, *Stipagrostis plumosa*, *Acacia ehrenbergiana*, *Zygophyllum coccineum* and

Acacia tortilis. These communities were divided into three clusters based on their floristic composition; a cluster of three communities (*Acacia hamulosa*, *Lycium shawii* and *Haloxylon salicornicum*) is mainly found in wadis and runnels, another cluster of three communities (*Acacia ehrenbergiana*, *Zygophyllum coccineum* and *Acacia tortilis*) found on the coastal plains, and a cluster consisting of only the *Stipagrostis plumosa* community found on the inland plains. The communities displayed clear differences in their distribution patterns, with (1) the *Haloxylon salicornicum* community dominating the inland transect as well as the most northern part of the coastal transect, (2) the *Acacia tortilis* community dominating the vegetation directly south of the *Haloxylon salicornicum* zone, (3) the *Acacia ehrenbergiana* community dominating the southernmost part of both transects, (4) the *Stipagrostis plumosa* and *Zygophyllum coccineum* co-occurring with the *Haloxylon salicornicum* and *Acacia tortilis* communities on the plains in the northern parts of the coastal transect and (5) the *Acacia hamulosa* and *Lycium shawii* communities co-occurring in the wadis and runnels in the southern part of the transect dominated by the *Acacia ehrenbergiana* community. These patterns in the distribution of the communities were mainly caused by differences in latitude and altitude affecting local rainfall and through that soil moisture.

4

Vegetation diversity in the Saharo-Arabian desert region

4.1 Introduction

Deserts, characterized by hyperaridity with annual precipitation typically below 100 mm (Nicholson, 2005), present unique challenges for vegetation studies. These ecosystems exhibit a mosaic of sparse plant life, predominantly confined to topographic features such as depressions, wadis, runnels, and rocky pavements that accumulate water from extensive catchment areas (Ward, 2016). The communities in these regions are generally treeless and often composed of few species, with low vegetation cover complicating traditional phytosociological assessments (Danin, 1983). Despite these challenges, understanding desert vegetation is crucial for biodiversity conservation and ecosystem management in arid regions (Durant et al., 2012).

This chapter aims to provide a comprehensive overview of the vegetation across the Saharo-Arabian region, spanning from the western coasts of Morocco and Mauritania to the eastern shores of the Arabian Peninsula. We employ the Braun-Blanquet approach (Westhoff & Van der Maarel, 1973) to construct a schema of plant communities, offering a framework for integrating local studies and contextualizing regional diversity patterns. This method, while developed for more mesic environments, has been adapted for desert ecosystems and remains a valuable tool for vegetation classification in arid regions (Peet & Roberts, 2013).

Three seminal geobotanical studies have significantly influenced our understanding of Saharo-Arabian vegetation. Quézel's (1965) inductive survey of Western and Central Saharan vegetation provides detailed associations and attempts to place these within higher syntaxa. Knapp's (1968) deductive classification of Eastern African vegetation, while primarily focused on tropical areas, offers insights into neighbouring North African and Arabian plant communities. Zohary's (1973) widely accepted system for the Near and Middle East, particularly Israel, Sinai, and adjacent regions, also employs a deductive approach, describing vegetation from higher to lower syntaxonomic units. However, these studies share limitations: they pay little attention to intermediate syntaxa (orders and alliances), lack cross-regional comparisons, and, in the cases of Knapp (1968) and Zohary (1973), are not based on extensive published relevé data. Furthermore, the absence of cross-referencing between these works has resulted in inconsistencies in vegetation classification across the region.

The classification schemes proposed by Quézel (1965) and Zohary (1973), while groundbreaking, require updating to align with the current International Code of Phytosociological Nomenclature (Theurillat et al., 2021). For instance, Zohary's (1973) work lacks essential scientific reference material (i.e., vegetation relevés), rendering many of his syntaxa as nomina nuda under the current Code. This highlights the need for a modern, comprehensive syntaxonomical framework for the region.

Quézel's (1965) work references numerous local studies on Saharan vegetation, primarily focusing on high mountain areas, their valleys, and isolated wet zones. Notable contributions include studies of the Tibesti (Maire & Monod, 1950), L'Air (Bruneau de Miré & Gillet, 1956), L'Enedi (Gillet, 1968), and Western Sahara (Guinochet & Quézel, 1954; Quézel & Simoneau, 1960, 1963). However, phytosociological research in extensive sandy areas (ergs, regs, oueds) remains scarce, representing a significant knowledge gap. Knapp's (1968) overview, while valuable, is limited to the southern fringes of our study area and lacks clear methodological documentation. The Arabian Peninsula, forming the eastern extent of the Saharo-Arabian region, remains the least studied area. While recent overviews of main vegetation types exist (e.g. Ghazanfar & Osborn, 2015), syntaxonomical studies based on field data classification are mostly restricted to localized investigations (e.g. El-Ghanim et al., 2010; Alatar et al., 2012).

The urgency of our study is underscored by the current global biodiversity crisis, exacerbated by excessive land use, exploitation, and climate change (IPBES, 2019). Desert ecosystems, often overlooked in conservation efforts, are particularly vulnerable to these pressures (Davies et al., 2012). Our research leverages an extensive vegetation plot database of 4,689 relevés, employing state-of-the-art methods in vegetation science to address critical questions: (i) What desert vegetation communities can be identified in the Saharo-Arabian region at various hierarchical scales? (ii) What is their geographical distribution? (iii) Which abiotic and biotic factors explain their diversity and distribution patterns? By synthesizing a comprehensive syntaxonomical framework that incorporates both historical and recent data, we aim to provide an improved foundation for evidence-based decision-making in Saharo-Arabian nature conservation and environmental policy. This work will not only contribute to our understanding of these unique ecosystems but also facilitate further in-depth studies on desert vegetation dynamics and responses to global change.

4.1.1 Study Area

The Saharo-Arabian region (Fig. 1), a floristic domain within the Holarctic Kingdom as proposed by Takhtajan (1986), encompasses the world's largest contiguous area of hot deserts and semi-deserts. This vast expanse stretches from the Atlantic coast of North Africa to the eastern shores of the Arabian Peninsula, covering approximately 11.5 million square kilometres. The region includes the temperate parts of the Sahara desert, the Sinai Peninsula, the Arabian Peninsula, Southern Palestine, and Lower Mesopotamia, with the latter extending from the Hamrin Mountains to the Faw Peninsula near the Persian Gulf (Masry, 2014).

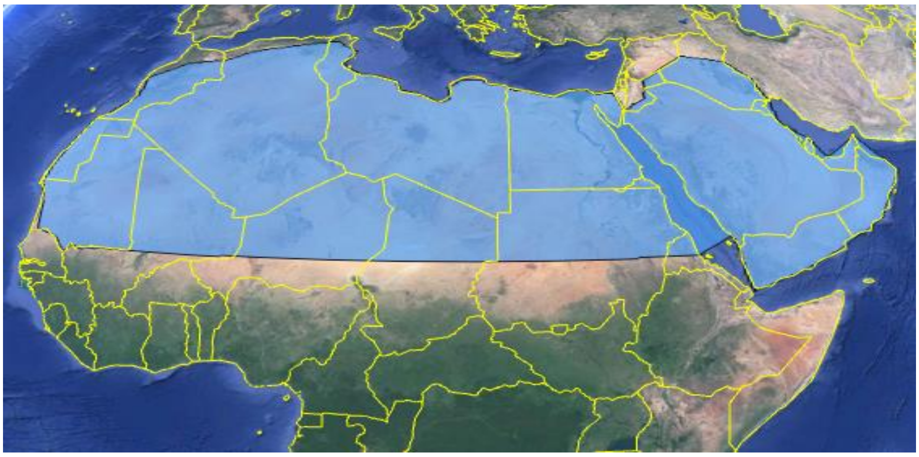

Figure 1. A map showing the extent of the Saharo-Arabian region shaded in light blue.

The Saharo-Arabian region is characterized by diverse landforms, dominated by extensive stone plateaus (hamadas) and sandy plains (ergs). Sand dunes in these areas can reach impressive heights of over 180 meters (Strahler & Strahler, 1987). The landscape is sculpted by aeolian processes and infrequent rainfall, resulting in distinctive features such as gravel plains (regs), dry valleys (wadis), ephemeral lakes (oueds), and salt flats (sebkhas or chotts). Unusual formations, like the Richat structure in Mauritania, add to the region's geological diversity. Richat is an eroded geological dome 40 kilometres in diameter, exposing sedimentary rock in layers that appear as concentric rings, The area also encompasses several mountain ranges, including the Hoggar, Tibesti, Aïr, Saharan Atlas, Adrar des Iforas, and the Red Sea Hills. Emi Koussi, a shield volcano in the Tibesti range of northern Chad, stands as the highest peak in the Sahara at 3,415 meters.

The climate of the Saharo-Arabian region is characterized by extreme aridity, high temperatures, and significant diurnal temperature fluctuations. Annual precipitation is generally less than 100 mm, with some areas receiving virtually no rainfall for years (Houérou, 1992). The region experiences a gradient of aridity, with slightly higher rainfall (100-250 mm) in the northern and southern fringes. For instance, Biskra in Algeria and Ouarzazate in Morocco in the north, and Timbuktu in Mali and Agadez in Niger in the south, fall within this range. The central hyper-arid core, covering about 31% of the Sahara's total area, receives less than 10 mm annually, with some areas receiving as little as 0.5 mm per year. Rainfall is notably unreliable and erratic, varying considerably from year to year.

Temperatures across the Saharo-Arabian region remain high year-round, particularly in low-lying areas where average summer highs generally exceed 40°C. In extremely low-lying areas, especially along the Persian Gulf, summer temperatures can reach 48°C. The Arabian Desert's temperatures can be particularly extreme, with some places recording temperatures as high as 55°C. Winter temperatures are more variable, with cooler conditions prevailing at higher elevations and in the northern parts of the region. The Arabian Desert experiences invigoratingly cool winters, especially at high elevations and in the far north.

The Saharo-Arabian region exhibits a complex biogeographical pattern, reflecting its climatic and topographic diversity. Quézel (1978) and Le Houérou (1990) delineated numerous phytogeographic subdivisions within the region (Fig. 2), each characterized by distinct floristic assemblages and ecological conditions. These range from Mediterranean-influenced zones in the north to tropical elements in the south, with various transitional areas in between. The Mediterranean Region in the northern Sahara, for instance, is characterized by winter rains and flora dominated by Holarctic Mediterranean families such as Asteraceae, Chenopodiaceae, Brassicaceae, and Geraniaceae.

Vegetation in the Saharo-Arabian region is sparse and highly adapted to extreme aridity. Plant life is primarily confined to areas with access to water, such as wadis, depressions, and oases (Evenari et al., 1985). The southern limit of the Sahara is botanically indicated by the southern limit of *Cornulaca monacantha*, a drought-tolerant member of the Chenopodiaceae, or the northern limit of *Cenchrus biflorus*, a grass typical of the Sahel (Walton, 2017). The flora shows a mixture of Saharo-Arabian, Irano-Turanian, and Sudano-Zambezian elements, with varying degrees of endemism (Zohary, 1973).

The Sahara and Arabian deserts, while part of the broader Saharo-Arabian region, exhibit some distinct characteristics. The Sahara, covering 9.2 million square kilometers, is significantly larger than the Arabian Desert, which occupies 2.33 million square kilometers (Cook & Vizy, 2015; Explorer, 2022). The Arabian Desert is considered an extension of the Sahara over the Arabian Peninsula. While both deserts experience extreme aridity, the Sahara has more extensive hyperarid areas, with its hyperarid core receiving less than 5 mm annually (Houérou, 1992). The Arabian Desert generally receives around 100 mm of rain per year, with only a few areas receiving as little as 30-40 mm annually (Edgell, 2006).

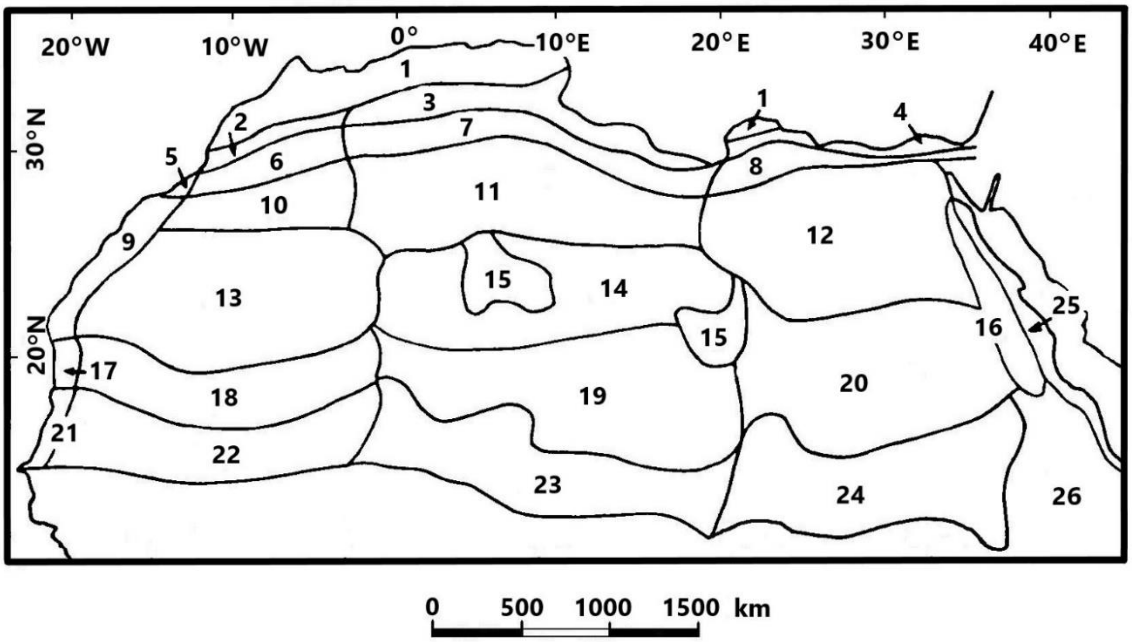

Figure 2. Diagram of the phytogeographic subdivisions of the Sahara and neighboring territories (after Quéezel, 1978; Le Houerou, 1990). The regions include: 1. Mediterranean region (semi-arid to hyper-humid zones), 2. Western arid steppic zone, 3. Central arid steppic zone, 4. Eastern arid steppic zone, 5. Oceanic Northern Sahara transition zone, 6. Western Northern Sahara transition zone, 7. Central Northern Sahara transition zone, 8. Eastern Northern Sahara transition zone, 9. Oceanic Central Sahara, 10. North-Western Central Sahara, 11. Northern Central Sahara, 12. North-Eastern Central Sahara, 13. Western Central Sahara, 14. Central Central Sahara, 15. Central Sahara Highlands, 16. Eastern Sahara Highlands, 17. Oceanic Southern Sahara, 18. Western Southern Sahara, 19. Central Southern Sahara, 20. Eastern Southern Sahara, 21. Oceanic Sahel, 22. Western Sahel, 23. Central Sahel, 24. Eastern Sahel, 25. Saharo-Arabian region, Eastern Sahara Zone, Red Sea shores, and 26. Sudano-Angolan region, East African & Erythreo-Sabean domain, East African Montane Zone.

The Arabian Desert's sunshine duration is remarkably high, ranging between 2,900 to 3,600 hours annually, with clear-sky conditions prevailing throughout the year (Edgell, 2006). Despite the brightness of the sun and moon, visibility at ground level is often reduced due to dust and humidity. The Arabian Desert experiences high summer humidity in coastal regions and some highlands, with dew and fog occurring at night or early morning (Ghazanfar & Fisher, 1998). Rainfall in the Arabian Desert can range from 0 to 500 mm, with torrential rains occasionally flooding the main drainage basins (Edgell, 2006). The Sahara shows a stronger gradient from Mediterranean influences in the north to tropical in the south, while the Arabian Desert has more uniform Saharo-Arabian elements with some Irano-Turanian influences (Zohary, 1973; Ghazanfar & Fisher, 1998).

4.2 Methods

4.2.1 Data Compilation

We compiled a comprehensive dataset of plot-based vegetation records from the Saharo-Arabian region, in total 6,748 relevés encompassing 2,160 taxa (species and subspecies). This dataset integrates multiple sources:

1. sPlot database (Bruelheide et al., 2019): 3,848 relevés
2. Sinai database (our own): 1,421 relevés
3. Digitized literature: 958 relevés

4. International collaborators: 521 relevés

The compilation process involved standardizing taxonomic nomenclature following the WorldFloraOnline (2022) and harmonizing structural data to ensure consistency across sources. We used the TurboVeg 3 software package (Hennekens & Schaminée, 2001) to construct and manage the Saharo-Arabian vegetation plot database.

4.2.2 Data Analysis

Our analytical approach comprised three main steps: (a) assessing clustering tendency, (b) determining the optimal number of clusters, and (c) performing the final cluster analysis.

4.2.2.1 Clustering Tendency

To evaluate the presence of meaningful clusters in our dataset, we employed the Hopkins' test (Hopkins & Skellam, 1954) using Python (version 3.7.6). This statistical hypothesis test measures the probability (H) that a given dataset is generated by a uniform or continuous data distribution. The null hypothesis (H_0) assumes a continuous distribution (implying no meaningful clusters), while the alternative hypothesis (H_1) suggests a non-uniform distribution (indicating the presence of clusters). We reject the null hypothesis if $H > 0.5$ (Hopkins & Skellam, 1954; Banerjee & Dave, 2004).

4.2.2.2 Optimal Number of Clusters

To estimate the optimal number of clusters, we applied the Elbow method (Ketchen & Shook, 1996) using Python (version 3.7.6). This involved:

1. Performing multiple cluster analyses with varying, predefined cluster numbers (k)
2. Calculating the sum of within-cluster variance (W) for each analysis
3. Plotting k values against their corresponding W values
4. Identifying the 'elbow' (breakpoint) of the plotted curve

The breakpoint represents the k value corresponding to the lowest W value before the curve plateaus, indicating the optimal number of clusters (Thorndike, 1953).

4.2.2.3 Classification and Related Analyses

We classified the data using a hierarchical modified TWINSPAN algorithm (Roleček et al., 2009) implemented in JUICE 7.1 (Tichý, 2002). Based on the data structure, we set pseudo-species cut levels at 0, 5, 25, and 50. We ceased further hierarchical subdivision when modified TWINSPAN failed to produce groups with ecologically meaningful differential species (Tsiripidis et al., 2009).

To enhance the validity of the groups, we reallocated 194 relevés based on two criteria:

1. Improved constancy values of the differential species post-reallocation
2. Consistent or enhanced average silhouette values (calculated using JUICE's Silhouette function) of relevant groups

For syntaxonomical classification, we adopted names of syntaxa from literature, updating them in accordance with the latest International Code of Phytosociological Nomenclature (Theurillat et al., 2021). We assigned each group to a syntaxonomical class based on vegetation structure, differential, dominant, and accompanying species. Where possible, we further classified down to the level of orders, alliances, and associations. In cases of insufficient data about the broader context of the Saharo-Arabian desert vegetation, we refrained from allocating certain syntaxa (indicated by question marks in the syntaxonomy scheme) to lower or upper syntaxonomical levels.

4.3 Results and Discussion

4.3.1 Clustering tendency and the optimal number of clusters

Clustering methods produce clusters by default, even if the data hardly show any variation. In this case, calculated clusters (groups) would be meaningless (Cross & Jain, 1982). For this reason and to present a mathematically approved approach, we calculated the clustering tendency using Hopkins' statistical hypothesis method. As the result was H = 0.95, we rejected the null hypothesis, meaning the database very likely contains clusters.

The approximated optimal number of clusters based on the Elbow method was 56 (Fig. 3). Since this value (56) is heuristic, we can accept the actual number of clusters (55). The deviation of the actual number of clusters (55) from the expected one (56) resulted from the reallocation of the relevés among the groups.

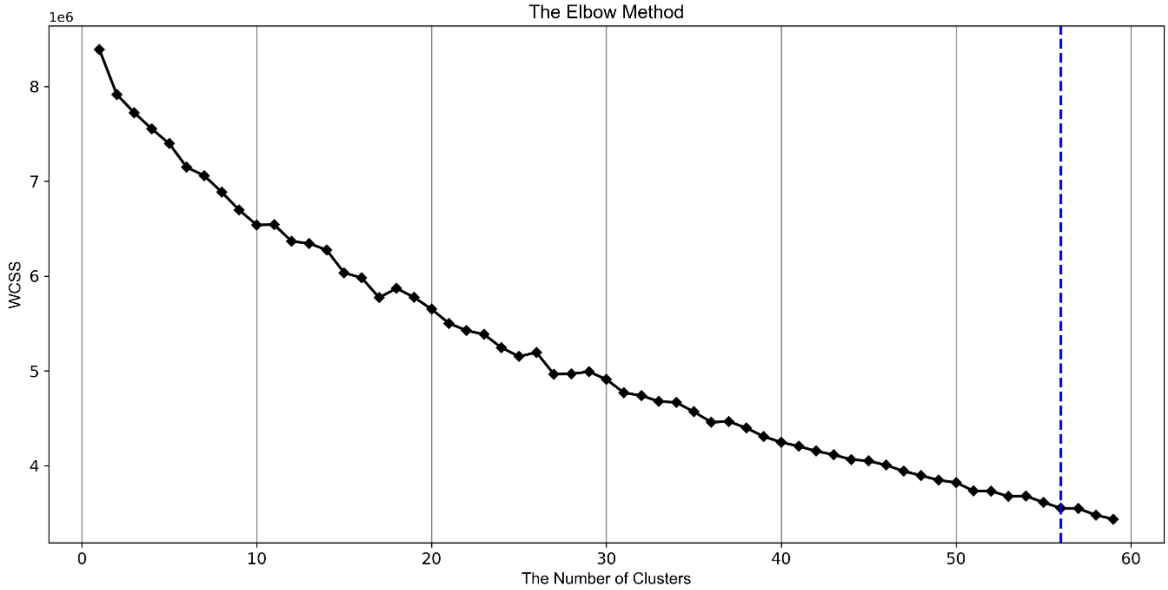

Figure 3. Diagram of the Elbow method showing the expected optimal number of clusters. Within Cluster Sum of Squares (WCSS), values represent the sum of squared Euclidean distances between the plots and the centroid. The lower the value of W, the more meaningful the clusters, and the better the correspondence to an optimal number of clusters. The Elbow is the last breaking point, seen before the flattening of the curve and corresponding to a low WCSS value. In our case, the Elbow corresponds to the number of clusters, 56.

4.3.2 Classification

After trying different approaches to classify the desert vegetation of Saharo-Arabian region, we found that modified TWINSPAN generated the best results. However, the low species numbers of some plots and substantial differences among species-abundance values made our data set challenging to classify. We overcame these limitations by manually reallocating several relevés based on mathematical Silhouette values analysis and our expert knowledge. The classification resulted in 15 groups (M1 – M14) including 55 types (Fig. 4).

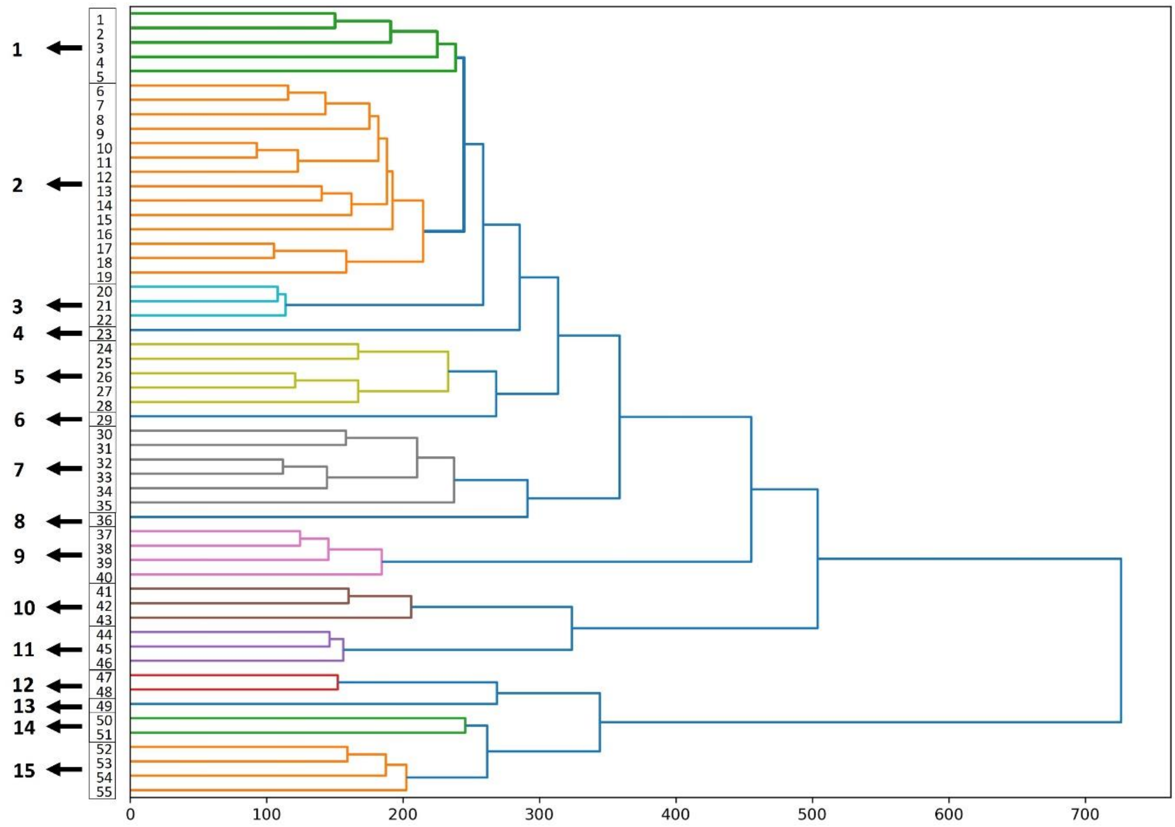

Figure 4. Dendrogram of the final classification based on the agglomerative clustering using Bray–Curtis analysis among the 55 types. The numbers from 1 to 15 represent the 15 groups (indicated by separate colours) at the threshold of similarity degree of 250.

Frequency values for the characteristic species of the 15 groups (1–15) are given in Table 1, while those of the 55 types are available in an electronic appendix. The most characteristic species (frequency 20% or more and highest of all groups) of the 15 groups and the 55 types are shaded in grey.

Table 1. Shortened synoptic table of the classified vegetation relevés of the 15 main groups (1-15). The table shows the number of relevés, the list of plant species and their percent frequencies for each main group. Only species with frequencies >= 20% are included, and their value cells are shaded. The dominant species of each main group is also shaded.

Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Number of Relevés	363	1222	289	109	278	13	553	38	345	235	245	195	40	190	305
Vachellia gerrardii	33	1	0	0	1	0	1	0	0	0	0	0	0	0	0
Sesuvium portulacastrum	22	3	0	1	3	0	6	0	0	4	11	0	0	0	1
Emex spinosa	22	1	0	6	3	0	1	0	0	0	0	0	0	1	0
Lycium shawii	21	4	7	0	1	0	14	0	2	0	0	0	0	0	0
Haloxylon salicornicum	11	24	20	0	1	0	13	0	0	0	0	0	0	0	0
Zygophyllum molle	1	4	63	1	3	0	9	0	31	0	0	0	0	0	0
Artemisia judaica	1	1	60	0	2	0	9	0	15	0	0	0	0	0	0
Zilla spinosa	23	11	57	0	4	0	37	0	41	10	3	0	0	1	5
Retama raetam	1	7	36	5	2	0	5	0	1	0	9	0	0	0	1
Zygophyllum arabicum	0	5	25	0	1	0	8	24	14	0	0	0	0	0	0
Erodium crassifolium	1	1	0	47	0	0	0	0	1	0	0	0	0	0	0
Noaea mucronata	0	3	0	39	0	0	1	0	2	0	0	0	0	1	0
Scorzonera psychrophila	0	0	0	38	0	0	0	0	0	0	0	0	0	0	0
Anthemis pseudocotula	6	0	0	37	0	0	0	0	0	0	0	0	0	0	0
Seriphidium sieberi	3	1	0	35	0	0	0	0	0	0	0	0	0	0	0
Salvia lanigera	0	1	0	32	0	0	1	0	1	0	0	0	0	0	0
Helianthemum ledifolium	1	1	0	32	0	0	0	0	0	3	0	8	18	0	1
Filago desertorum	1	1	1	30	0	0	1	0	4	0	0	0	0	0	0
Centaurea aegyptiaca	0	1	2	29	0	0	1	0	4	0	0	0	0	0	0

Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Gymnocarpos decander	9	1	0	28	0	0	1	0	0	8	8	0	0	0	0
Helianthemum vesicarium	0	0	0	28	0	0	0	0	0	0	0	0	0	0	0
Trigonella stellata	7	2	4	28	1	0	2	0	9	1	0	0	0	1	0
Anabasis articulata	0	8	18	28	1	0	8	0	1	0	0	0	0	1	1
Matthiola longipetala	6	2	1	28	0	0	1	0	3	2	0	0	0	0	0
Erucaria rostrata	1	1	0	27	1	0	0	0	0	0	0	0	0	0	0
Rostraria smyrnacea	1	1	0	27	1	0	0	0	0	0	0	0	0	0	0
Schismus arabicus	1	1	1	25	1	0	1	0	3	0	3	0	0	0	0
Gagea reticulata	1	0	0	25	0	0	0	0	0	0	0	0	0	0	0
Diplotaxis harra	4	1	6	25	1	0	8	0	14	2	0	5	3	5	5
Prospero hanburii	0	1	0	25	0	0	0	0	0	0	0	0	0	0	0
Carex pachystylis	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0
Poa sinaica	0	0	0	24	1	0	0	0	0	0	0	0	0	0	0
Plantago coronopus	4	1	0	23	0	0	0	0	0	0	0	0	0	0	0
Helianthemum kahiricum	1	1	1	23	0	0	1	0	1	1	0	0	0	0	0
Ranunculus asiaticus	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0
Zygophyllum dumosum	1	2	0	22	0	0	1	0	0	0	0	0	0	0	0
Calendula arvensis	16	1	1	22	2	0	1	0	0	5	0	0	0	0	0
Plantago ovata	9	1	0	22	1	0	1	0	1	18	1	1	0	0	0
Scorzonera papposa	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0
Hippocrepis unisiliquosa	0	1	0	22	0	0	0	0	0	0	0	0	0	0	0
Moraea sisyrinchium	2	1	0	21	0	0	0	0	0	0	0	0	0	0	0
Reaumuria negevensis	0	0	0	21	0	0	0	0	0	0	0	0	0	0	0
Salsola tetrandra	1	5	0	20	0	0	0	0	0	0	0	0	0	0	0
Helianthemum ventosum	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0
Erucaria microcarpa	1	1	0	20	0	0	0	0	0	0	0	0	0	0	0
Malva parviflora	15	3	1	6	26	0	1	0	2	0	0	0	0	0	0
Chenopodium murale	2	1	1	0	20	0	1	0	1	0	0	0	0	0	1
Pulicaria inuloides	0	1	0	0	1	92	1	0	0	0	0	0	0	0	0
Scirpoides holoschoenus	0	1	0	0	12	92	1	0	1	1	0	0	0	0	0
Blumea bovei	0	1	0	0	3	85	0	0	0	0	0	0	0	0	0
Cynodon dactylon	10	5	1	3	43	69	5	0	6	3	0	0	0	0	0
Veronica anagallis-aquatica	0	1	0	0	1	62	1	0	1	0	0	0	0	0	0
Cyperus laevigatus	0	0	0	0	7	62	0	0	1	0	0	0	0	0	0
Helichrysum luteoalbum	0	1	0	0	4	54	0	0	0	2	0	0	0	0	0
Centaurium pulchellum	0	1	0	0	3	46	1	0	0	0	0	0	0	0	0
Polypogon monspeliensis	1	2	0	0	19	31	0	0	1	0	0	0	0	0	0
Juncus articulatus	0	0	0	0	0	23	0	0	0	0	0	0	0	0	0
Equisetum ramosissimum	0	0	0	0	2	23	0	0	1	0	0	0	0	0	0
Agrostis gigantea	0	0	0	0	1	23	0	0	0	0	0	0	0	0	0
Mentha longifolia	0	1	1	0	6	23	0	0	12	0	0	0	0	0	0
Vachellia tortilis	3	9	4	0	3	0	50	42	0	0	16	0	0	0	0
Forsskaolea tenacissima	1	3	1	0	3	0	35	0	1	10	23	0	0	0	0
Trichodesma africanum	1	2	1	0	1	0	24	0	2	0	0	0	0	0	0
Citrullus colocynthis	10	5	9	0	9	0	22	13	1	1	0	0	0	0	0
Zygophyllum simplex	0	7	1	0	4	0	21	0	0	0	0	0	0	0	0
Iphiona scabra	0	3	4	0	0	0	20	0	3	0	0	0	0	0	0
Aristida mutabilis	1	1	0	0	0	0	5	79	0	0	0	0	0	0	0
Aristida funiculata	0	0	0	0	0	0	1	71	0	0	0	0	0	0	0
Panicum turgidum	5	7	1	0	7	0	36	61	4	0	2	0	0	0	0
Indigofera exigua	0	0	0	0	0	0	0	47	0	0	0	0	0	0	0
Euphorbia granulata	5	1	0	0	1	0	6	47	0	1	0	0	0	0	0
Schoenefeldia gracilis	0	0	0	0	0	0	0	47	0	0	0	0	0	0	0
Eragrostis pilosa	6	1	0	0	3	0	1	45	0	0	0	0	0	0	0
Vachellia seyal	0	1	0	0	0	0	9	42	0	0	0	0	0	0	0
Limeum obovatum	0	0	0	0	0	0	0	39	0	0	0	0	0	0	0
Aerva javanica	1	3	5	0	3	0	33	37	0	0	0	0	0	0	0
Blepharis edulis	0	1	1	0	0	0	5	34	0	0	0	0	0	0	0
Capparis decidua	0	1	0	0	0	0	5	34	0	0	0	0	0	0	0
Heliotropium bacciferum	15	4	0	0	3	0	17	29	0	0	0	0	0	0	0
Chrozophora brocchiana	0	1	0	0	0	0	1	29	0	0	0	0	0	0	0
Vachellia flava	7	2	0	0	0	0	7	29	0	0	0	0	0	0	0
Sporobolus cordofanus	0	0	0	0	0	0	0	29	0	0	0	0	0	0	0
Enteropogon prieurii	1	0	0	0	0	0	0	29	1	0	0	0	0	0	0
Indigofera sessiliflora	0	0	0	0	0	0	0	29	0	0	0	0	0	0	0
Aristida adscensionis	2	2	0	0	0	0	4	29	0	3	7	0	0	0	0
Stipagrostis plumosa	10	14	9	0	1	0	19	26	2	2	0	0	0	1	0
Dactyloctenium aegyptium	1	0	0	0	5	0	1	26	0	0	0	0	0	0	0

Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Zygophyllum olivieri	0	1	0	0	0	0	1	26	0	0	0	0	0	0	0
Gisekia pharnaceoides	3	1	0	0	0	0	1	26	0	0	0	0	0	0	0
Eragrostis cilianensis	0	0	0	0	1	0	0	26	0	0	0	0	0	0	0
Cleome arabica	2	2	2	0	1	0	7	24	2	3	0	0	0	0	0
Stipagrostis uniplumis	0	1	0	0	0	0	0	24	0	0	0	0	0	0	0
Monsonia nivea	1	2	0	0	0	0	1	24	0	0	0	0	0	0	0
Tragus racemosus	1	0	0	0	0	0	1	24	0	0	0	0	0	0	0
Crotalaria arenaria	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0
Tephrosia apollinea	0	0	0	0	0	0	1	24	0	0	0	0	0	0	0
Tribulus mollis	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0
Aristida hordeacea	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0
Aristida sieberiana	0	0	0	1	0	0	1	21	0	0	0	0	0	0	0
Trianthema sedifolia	0	0	0	0	0	0	0	21	0	0	0	0	0	0	0
Teucrium polium	4	2	3	0	0	0	5	0	63	0	0	1	8	1	0
Alkanna orientalis	0	1	3	0	0	0	1	0	61	0	0	0	0	0	0
Phlomis aurea	0	0	1	0	0	0	0	0	54	0	0	0	0	0	0
Tanacetum sinaicum	0	0	1	0	0	0	1	0	54	0	0	0	0	2	0
Stachys aegyptiaca	0	2	5	5	0	0	1	0	50	0	0	0	0	0	0
Chiliadenus montanus	0	1	4	0	0	0	0	0	36	0	0	0	0	0	0
Achillea fragrantissima	16	1	10	0	1	0	3	0	36	0	0	0	0	0	0
Ballota undulata	0	2	3	2	0	0	1	0	34	0	0	0	0	1	0
Echinops spinosissimus	3	1	2	0	0	0	4	0	33	15	2	5	30	0	2
Origanum syriacum	0	0	1	0	0	0	1	0	30	0	0	0	0	0	0
Matthiola arabica	0	1	3	0	0	0	0	0	28	0	0	0	0	1	0
Nepeta septemcrenata	0	1	1	0	0	0	1	0	23	0	0	0	0	1	0
Haloxylon scoparium	1	5	0	5	0	0	1	0	0	72	42	0	0	0	4
Stipa capensis	22	1	0	28	0	0	1	0	0	62	5	4	0	2	17
Medicago laciniata	5	1	0	17	5	0	1	0	0	49	23	2	23	0	3
Pallenis hierochuntica	1	1	1	14	0	0	0	0	0	46	6	0	0	0	9
Launaea nudicaulis	7	3	1	1	0	0	3	0	8	36	2	9	23	1	5
Notoceras bicorne	1	0	0	0	0	0	1	0	0	31	1	0	0	0	1
Leisera leiseroides	0	0	0	0	0	0	1	0	0	29	2	4	15	0	5
Picris asplenioides	1	1	0	0	0	0	1	0	0	29	2	16	15	1	26
Stipagrostis obtusa	0	3	0	0	0	0	1	0	2	28	4	1	5	0	1
Launaea arborescens	0	4	0	0	0	0	4	0	0	28	13	3	3	2	25
Farsetia occidentalis	0	2	0	0	0	0	3	0	0	27	12	0	0	0	1
Acanthorrhinum ramosissimum	0	3	0	0	0	0	1	0	0	23	12	0	0	0	1
Salvia aegyptiaca	7	3	1	0	0	0	4	0	1	20	14	1	0	0	0
Ifloga spicata	9	8	1	3	1	0	1	0	0	20	2	0	0	0	1
Helianthemum ellipticum	0	3	0	0	0	0	1	0	0	20	4	5	0	1	1
Fagonia longispina	0	2	0	0	0	0	1	0	0	9	77	0	0	0	0
Anvillea radiata	0	1	0	0	0	0	1	0	0	14	68	1	0	0	1
Asphodelus fistulosus	0	1	0	0	0	0	3	0	0	37	52	1	0	0	1
Morettia canescens	2	6	2	0	0	0	8	0	1	35	51	0	0	0	6
Convolvulus trabutianus	0	2	0	0	0	0	1	0	0	42	47	0	0	0	3
Gymnocarpos sclerocephalus	4	1	0	0	1	0	1	3	0	3	42	0	0	0	0
Plocama reboudiana	0	2	0	0	0	0	1	0	0	0	38	0	0	0	0
Lotus glinoides	2	1	0	0	0	0	1	0	1	1	33	0	0	0	0
Reseda villosa	1	1	0	0	0	0	4	0	0	7	26	0	0	0	4
Drimia noctiflora	1	1	0	0	0	0	0	0	0	20	26	0	0	0	0
Ephedra alata	1	4	1	0	0	0	1	0	1	0	26	0	0	0	0
Diplotaxis pitardiana	0	1	0	0	0	0	0	0	0	2	21	0	8	0	1
Seriphidium herba-alba	0	4	15	0	0	0	5	0	50	25	5	94	55	25	73
Carlina brachylepis	0	0	0	0	0	0	0	0	0	32	3	88	80	29	70
Schismus barbatus	9	5	10	0	0	0	2	0	6	34	1	86	80	28	72
Stipa parviflora	0	1	0	14	0	0	1	0	2	10	0	64	63	10	43
Picris hispanica	0	0	0	0	0	0	0	0	0	3	0	63	30	23	8
Filago congesta	0	0	0	0	0	0	0	0	0	19	1	59	18	7	4
Artemisia mesatlantica	0	0	0	0	0	0	0	0	0	0	0	54	43	15	16
Minuartia montana	0	0	0	0	0	0	0	0	0	0	0	51	0	20	17
Astragalus tribuloides	1	1	0	35	1	0	1	0	1	23	1	48	35	8	7
Echium humile	1	1	0	0	0	0	2	0	0	14	1	46	13	1	19
Teucrium mideltense	0	0	0	0	0	0	0	0	0	1	0	45	0	1	15
Herniaria hirsuta	2	1	0	14	0	0	1	0	0	9	0	37	10	13	32
Reseda phyteuma	0	0	0	0	0	0	0	0	0	0	0	30	13	4	5
Adenocarpus bacquei	0	0	0	0	0	0	0	0	0	0	0	28	3	1	16
Hordeum murinum	2	1	0	6	4	0	1	0	0	1	0	28	5	18	18
Paronychia chlorothyrsa	1	1	0	0	0	0	1	0	0	12	0	27	23	6	19

Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Launaea fragilis	0	1	0	0	0	0	0	0	0	2	0	27	0	4	3
Androsace maxima	0	0	0	0	0	0	0	0	0	0	0	25	18	8	9
Achillea falcata	0	0	0	0	0	0	0	0	0	1	0	21	15	3	8
Erodium cicutarium	3	1	1	0	0	0	0	0	0	4	0	21	13	14	15
Bromus rubens	0	0	0	0	0	0	0	0	0	9	0	62	80	25	54
Lactuca viminea	0	0	0	0	0	0	0	0	0	0	0	43	80	14	13
Bufonia tenuifolia	0	0	0	0	0	0	0	0	0	0	0	78	80	15	26
Salvia verbenaca	0	1	0	0	0	0	0	0	0	2	0	29	70	8	12
Taeniatherum caput-medusae	0	0	0	0	0	0	0	0	0	0	0	2	63	2	1
Centaurea debdouensis	0	0	0	0	0	0	0	0	0	0	0	1	60	6	0
Bromus tectorum	0	1	0	1	0	0	0	0	0	2	0	50	55	28	5
Stipa barbata	0	0	0	8	0	0	0	0	0	0	0	16	55	8	2
Filago micropodioides	0	0	0	0	0	0	0	0	0	1	0	0	53	2	1
Medicago polyceratia	0	0	0	0	0	0	0	0	0	1	0	27	50	24	9
Scorzonera pygmaea	0	0	0	0	0	0	0	0	1	0	0	1	48	7	1
Cladanthus scariosus	0	0	0	0	0	0	0	0	0	0	0	1	48	16	10
Dactylis glomerata	0	0	0	1	0	0	0	0	0	0	0	8	48	17	6
Alyssum simplex	0	0	0	0	0	0	0	0	0	0	0	17	45	8	7
Lasiopogon muscoides	0	0	0	0	0	0	0	0	0	6	0	25	40	3	9
Linaria simplex	0	0	0	0	0	0	0	0	0	1	0	3	38	2	1
Paronychia arabica	6	2	0	0	0	0	3	0	0	23	19	28	38	6	26
Minuartia funkii	0	0	0	0	0	0	0	0	0	0	0	8	35	12	2
Echinaria capitata	0	0	0	0	0	0	0	0	0	0	0	22	35	14	11
Catananche caerulea	0	0	0	0	0	0	0	0	0	0	0	1	35	5	1
Filago prolifera	0	0	0	0	0	0	0	0	0	1	0	12	33	4	2
Erodium laciniatum	8	3	1	2	0	0	1	0	3	9	0	13	33	4	4
Helianthemum croceum	0	0	0	0	0	0	0	0	0	1	0	28	30	8	1
Erysimum incanum	0	0	0	0	0	0	0	0	0	0	0	25	30	18	9
Erodium oxyrhinchum	1	1	0	6	0	0	4	0	0	6	0	10	28	2	1
Aegilops geniculata	0	0	0	0	0	0	0	0	0	0	0	6	25	3	0
Polycarpon polycarpoides	0	0	0	0	0	0	0	0	0	0	0	15	25	24	12
Sideritis montana	0	0	0	0	0	0	0	0	0	1	0	13	25	2	7
Paronychia argentea	0	0	0	4	0	0	0	0	0	1	0	5	23	1	1
Lygeum spartum	0	1	0	0	0	0	1	0	0	1	0	5	23	0	2
Neatostema apulum	0	0	0	0	0	0	0	0	0	0	0	0	23	1	0
Taraxacum atlanticum	0	0	0	0	0	0	0	0	0	0	0	2	23	8	0
Koeleria vallesiana	0	1	0	0	0	0	0	0	0	0	0	0	20	10	0
Helianthemum salicifolium	0	1	0	14	0	0	0	0	0	1	0	14	20	3	9
Ononis spinosa	0	0	0	0	0	0	0	0	0	0	0	0	20	0	0
Plantago ciliata	15	5	0	0	0	0	1	0	1	11	2	2	20	0	1
Hormathophylla spinosa	0	0	0	0	0	0	0	0	0	0	0	1	0	56	2
Vella mairei	0	0	0	0	0	0	0	0	0	0	0	0	0	35	1
Euphorbia megalatlantica	0	0	0	0	0	0	0	0	0	0	0	2	0	35	5
Artemisia negrei	0	0	0	0	0	0	0	0	0	0	0	2	0	32	4
Bupleurum spinosum	0	0	0	0	0	0	0	0	0	0	0	2	20	31	3
Cytisus balansae	0	0	0	0	0	0	0	0	0	0	0	0	0	29	0
Erinacea anthyllis	0	0	0	0	0	0	0	0	0	0	0	0	0	29	1
Lactuca reviersii	0	0	0	0	0	0	0	0	0	0	0	21	3	27	17
Astragalus ibrahimianus	0	0	0	0	0	0	0	0	0	0	0	1	18	25	1
Centaurea josiae	0	0	0	0	0	0	0	0	0	0	0	3	8	22	1
Filago pyramidata	2	1	0	1	1	0	0	0	0	4	0	3	18	2	43
Hertia maroccana	0	0	0	0	0	0	0	0	0	1	0	22	0	4	32
Reseda nainii	0	0	0	0	0	0	0	0	0	6	0	12	5	1	28
Thymus saturejoides	0	0	0	0	0	0	0	0	0	0	0	6	23	5	28
Genista scorpius	0	0	0	0	0	0	0	0	0	4	1	7	20	11	25
Crucianella hirta	0	0	0	0	0	0	0	0	0	18	1	12	3	0	22

4.3.2.1 Vegetation groups description and classification

The classification of the large data set resulted in 55 types, which will be described here by clustering them into groups. We used the Dendrogram tree of Figure 4 to group the 55 types into 15 groups, using a degree of similarity of about 250 (the horizontal axis in Figure 4) as a threshold for the groups. These 15 groups are described by their species composition, the diversity within the group, their ecology, and their distribution. We also provide a reference plant community from the literature. In that way, this classification forms a basis for an overview of plant communities at the level of alliances or lower for the whole Saharo-Arabian desert.

Vegetation group 1, *Vachellia gerrardii*-group (types 1 – 5)

This group comprises five distinct vegetation types, encompassing 363 relevés. It is characterized by the predominance of tall shrubs, notably *Vachellia gerrardii*, *Lycium shawii*, and *Zilla spinosa*, in association with a diverse group of annual species including *Calendula arvensis*, *Plantago ciliata*, *Sesuvium portulacastrum*, *Emex spinosa*, and multiple *Astragalus* species. These plant communities are predominantly found in sandy and rocky habitats (ergs and hamadas). The spatial distribution of this group is primarily confined to Saudi Arabia, with four of the five types occurring within its borders. Type 4, however, represents an outlier, based on data from Chad, Tunisia and Algeria. (Figure 5).

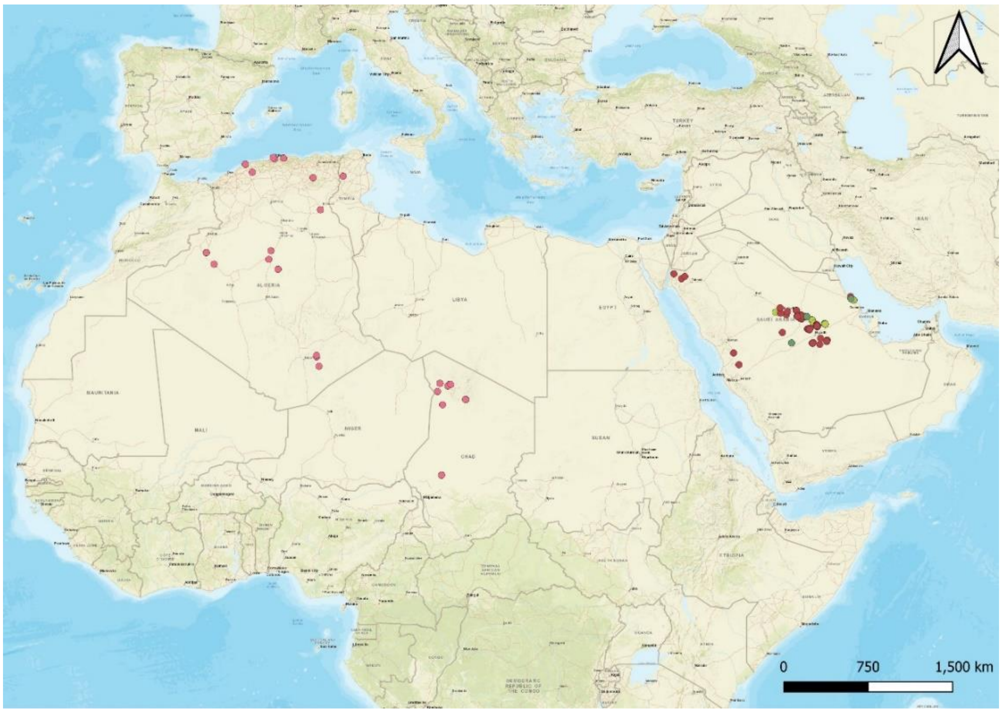

Figure 5. Distribution of relevés of vegetation group 1. The dots with different colours represent the relevés of the 5 vegetation types.

The environmental parameters governing these habitats are marked by significant diurnal and seasonal temperature fluctuations, with mean annual temperatures frequently surpassing 20°C. Precipitation is notably scarce, typically not exceeding 150 mm annually, and is characterized by brief, intense episodes. Hydrological resources are limited, primarily derived from sporadic rainfall events and occasional groundwater accumulations in wadis and topographic depressions (White, 1983).

Type 1 and 2 are dominated by annual species, like *Calendula arvensis, Tripleurospermum auriculatum, Plantago ciliata, Astragalus eremophilus*, *Althaea ludwigii, Astragalus bombycinus, Astragalus sparsus, Anthemis zoharyana* and *Atractylis carduus*. The first type lacks a shrub-cover of *Vachellia*, while in type 2 *Vachellia gerrardii* is a dominant shrub. Both types are found in Saudi Arabia. *Astragalus* is one of the most diverse genera in Saudi-Arabia, with many species with restricted ranges (Thomas et al., 2013) and the center of its diversity in the Irano-Turanian phytogeographical region, especially in Central Asia (Podlech, 1986).

Type 3, also occurring in Saudi Arabia, is characterised by the shrubs *Lycium shawii* and *Vachellia gerrardii*, with an understory of annuals and small shrubs like *Anvillea garcinii, Ochradenus baccatus, Gymnocarpos decander, Rhanterium epapposum, Hyparrhenia hirta, Blepharis ciliaris, Ephedra foliata,* and *Astragalus spinosus*. The combination of *Anvillea garcinii* and *Blepharis ciliaris*, together with small grasses, has been described for rock pavements on cuesta's in Central Saudi-Arabia (Kürschner, 1998).

Type 4 is an outlier within this *Vachellia gerrardii*-group. This vegetation is found in Algeria, Tunisia and Chad. This type is dominated by species from temporary wet sites, like *Glinus lotoides* (= *Mollugo glinus*), *Eragrostis pilosa, Anticharis glandulos*, *Anticharis senegalensis* and *Cyperus michelianus*, in combination with ruderal species, like *Portulaca oleracea*, *Chloris virgata* and *Eragrostis pilosa*. This type has some of the herbs (like *Plantago ciliata*, *Astragalus eremophilus*, *Rumex vesicarius* and *Sesuvium portulacastrum*) in common with the other types of this group, which is obvious the reason for its classification within this group.

Type 5, which is found in Saudi Arabia and Kuwait, is dominated by *Emex spinosa* and *Ifloga spicata.* It shares some annuals with the other types of this group, like *Plantago boissieri* and *Calendula arvensis,* but it has also many differentiating small herbs, like *Lotus halophilus, Erodium laciniatum, Carthamus oxyacantha, Cutandia dichotoma, Senecio glaucus, Launaea capitata, Astragalus arpilobus, Plantago coronopus,* and *Erodium cicutarium.* It also has some saline species of group 2, like *Zygophyllum qatarense* and *Seidlitzia rosmarinus*, which indicates that the type is transitional between group 1 and 2.

Vachellia gerrardii is one of the most widespread *Vachellia*-species on the Arabian Peninsula. It is found in a wide range of habitats, mostly sites with relatively good availability of water, like rocky or gravelly wadi beds and on mountain slopes (Alatar et al., 2015; Al-Aklabi et al., 2016). In the relatively wetter, more subtropical part of the peninsula such thorny shrubland is found on the dry, rain-shadow sites of the mountains (Kürschner, 1998). Also the *Astragalus* species are found in spots with relatively good water supply, some in more sandy conditions, others on silt (Thomas et al., 2013). Most of the *Astragalus*-species and many other characteristic species (a.o. *Rumex vesicarius*, *Bassia muricata*, *Emex spinosa*, *Reseda pruinosa*) of this group are annuals, which temporary appear in relatively wet, often rocky, sites.

Types 1 to 3 contain the species *Zilla spinosa*, *Astragalus spinosus*, *Rhazya stricta*, *Astragalus spinosus* and *Anvillea garcinii* and a scattered tree layer of *Vachellia*-species, a combination that is described for the wadis of Central Saudi Arabia (Deil, 1998). The combination of *Anvillea garcinii*, *Anastatica hieronchuntica* and *Blepharis ciliaris* (all represented in type 3), together with small grasses, has been described for rock pavements on cuesta's in Central Saudi-Arabia (Kürschner, 1998). Types 2 and 3 belong to the class *Acacietea tortilis* Knapp 1968, order *Acacietalia tortilis* Knapp 1968, and are tentatively assigned to the alliance *Acacion tortilis* Eig 1946. They represent (pseudo)savanna vegetation characteristic of the Arabian Peninsula. Type 1 and 5 miss the *Vachellia*-shrub species, but have many annual species in common with type 2 and 3. Type 5 consists mainly of psammophytic annual species (*Emex spinosa*, *Ifloga spicata*, *Plantago boissieri*), which are opportunistic species appearing after favourable winter or spring rains (Mandaville in Ghazanfar & Fisher 1998, chapter 8). These psammophytic annual communities of the Saudi Peninsula most likely fit in the class *Anabasietea articulatae* Zohary 1952 ex Danin et Solomeshch 1999, for which the class *Haloxylonetea salicornici* Zohary 1955 is a synonym. The same ecological conditions apply to type 1, for which we provisionally propose a new alliance, the *Astragalion eremophili-annulari*, because of the high presence of *Astragalus* species.

Type 4 is an outlier in the whole table, representing plant communities in wadis with humid sands on the border of rocks and sand, where water is available for a short period (some weeks to some months) after rains. Quézel (1965) describes it only from the Central and Southern Sahara, where it occurs mainly in mountains. According to him, it fits in the class *Isoëto-Nanojuncetea*, described in Europe for vegetation of annual wetland herbs. But, because of the many local species, it is considered a separate, subtropical and Saharan order by Quézel: *Mollugineto-Anticharidetalia*.

Vegetation group 2 *Haloxylon salicornicum* group (types 6 – 19)

Group 2 is a very broad and diverse group, constructed of 14 types. A general characteristic is that most of the types contain relatively species-poor relevés. The overall species composition indicates a combination of saline and psammophytic, sandy conditions, with some outliers in mountains. Types 6 to 9 and 16 are plant communities of saline environments. Type 9 and 15 represent mountain vegetation. All the other types are typical communities of deep sandy deserts, some occurring in hyperarid (extreme) deserts. This group is geographically broadly distributed in eastern, middle, and western Saudi Arabia, the Sinai Peninsula in Egypt, Chad, Niger, Tunisia, Algeria, Mauritania, and Morocco (Fig. 6).

Type 6 is predominantly found in the Sahara, from Mauritania to Egypt, with a few relevés from Saudi Arabia and Kuwait. This vegetation type is characterized by *Suaeda vermiculata*, *Halocnemum strobilaceum*, *Mesembryanthemum nodiflorum*, while the western relevés also contain *Frankenia pulverulenta*, *Limoniastrum guyonianum*, *Traganum nudatum*, *Zygophyllum album*, *Aeluropus littoralis*, *Salicornia arabica* and *Salsola tetrandra*. The eastern relevés differ from the western amongst others by *Suaeda aegyptiaca* and *Malva parviflora*. This type reflects the class *Halopeplido-Suaedetea* Knapp 1968 (= *Suaedetea fruticosae* Zohary 1973) a vicariant class of the European *Salicornietea fruticosae*. This is a class of saline desert vegetation. The western relevés contain *Limoniastrum guyonianum*, which indicates the order *Limoniastretalia guyoniani* Guinochet 1951. Several alliances have been described under this order, of which the differences are not clear (see Géhu et al. 1990, 1992). This type may fit best in the alliance *Limoniastrion guyoniani* Quézel 1965. The eastern relevés belong probably to a different alliance, possibly to the alliance *Zygophyllion simplicis* (Deil & Müller-Hohenstein 1996), which we fit in the same class.

Type 7 is found mainly in Saudi Arabia and Kuwait, with some outliers from the Sinai in Egypt. The main species that dominate this vegetation type are *Phragmites australis, Tamarix aucheriana, Aeluropus lagopoides* and *Juncus rigidus*. The combination of *Tamarix aucheriana* and *Phragmites australis* indicates the class *Nerio-Tamaricetea* Br.-Bl. and O. de Bolos 1958, which is a woodland class of fresh, brackish and saline waters. Here, the type contains several salt-tolerant plants, indicating saline conditions. The type fits probably in the alliance *Tamaricion africanae* Braun-Blanquet et Bolòs 1957.

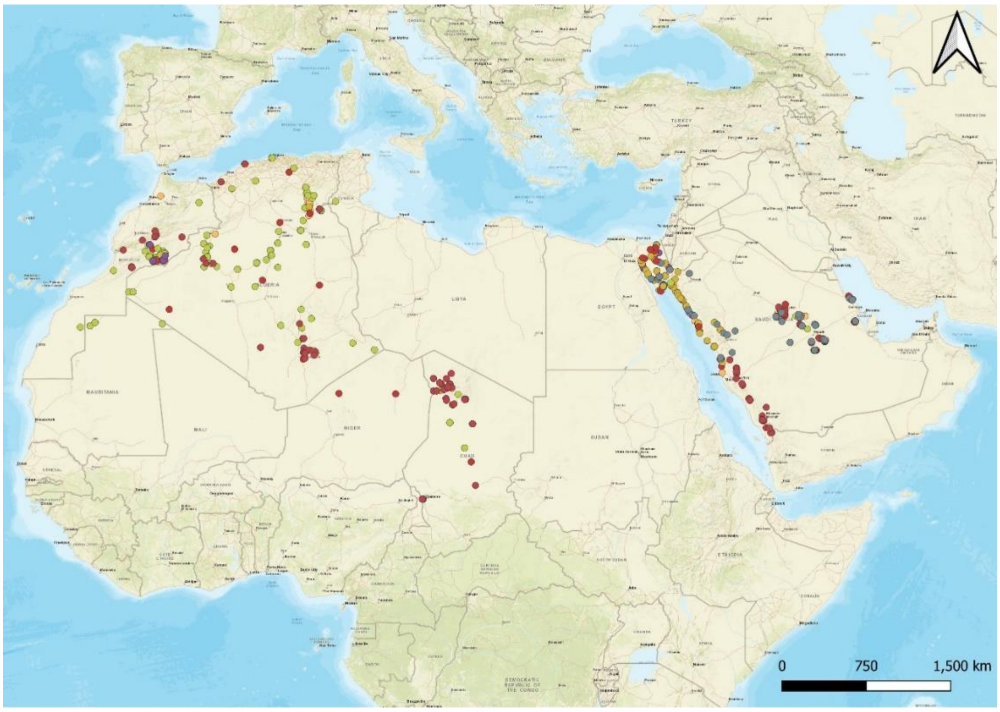

Figure 6. Distribution of relevés of vegetation group 2. The dots with different colors represent the relevés of the 19 vegetation types.

Type 8 is found on the Arabian Peninsula (Saudi Arabia, Kuwait, United Arabs Emirates) and is characterised by *Zygophyllum qatarense* (= *Tetraena qatarense*), *Limonium stocksii, Seidlitzia rosmarinus, Suaeda aegyptiaca, Atriplex leucoclada,* and *Sphaerocoma aucheri*. Both the associations *Zygophylletum qatarensis* and *Halopeplidetum perfoliatae* apply to this type, which fits in the broader halophytic class *Halopeplido-Suaedetea* Knapp 1968. We propose a provisional alliance *Zygophyllion qatarensis* for these associations.

Type 9 is a strange outlier within this group, for which it is unclear why it is placed by the algorithm in this group; an explanation can be that it is rather species poor, like many other types within this group. However, a few species in this type are also found, in much lower numbers, in the types of group 15, with which this type has the most similarities. The 21 relevés in this type are from the High Atlas mountains in Morocco and are characterized by the presence of *Platycapnos saxicola, Linaria tristis* (= *L. lurida*), *Viola dyris, Silene ayachica, Vicia glauca,* and *Senecio chalureaui*. Type 9 represents the endemic association *Violo dyris-Linarietum luridae* Quézel 1957, within the alliance *Platycapnion saxicolae* Quézel 1952, and order *Erinacetalia anthyllidis* Quezel 1952 (see Taleb & Fennane 2019). These endemic low shrub communities are placed in the broader Mediterranean garrigue class *Ononido-Rosmarinetea*.

Type 10, present in Saudi Arabia and Sinai in Egypt, is mainly dominated by *Zygophyllum album* and *Diplotaxis acris*. This type resembles a community described in Hatim et al. (2021) and assigned to the association *Zygophylletum albi* (Danin, 1983), which was assigned to the class *Salicornietea fruticosae* (see chapter 2). However, we use the class-name *Halopeplido-Suaedetea* Knapp 1968 here, as a desert vicariant of this mainly Mediterranean class. The differences between the two classes have to be sorted out. The most fitting alliance for type 10 seems the *Zygophyllion albae* Géhu et al. 1990.

The vegetation of Type 11, which is found in Saudi Arabia and the Sinai in Egypt, is predominantly composed of *Zygophyllum coccineum*. This type is similar to communities described by El-Demerdash et al. (1996), Abd El-Wahab et al. (2006), and Hatim et al. (2021). Several relevés have a high cover of *Vachellia tortilis*, certainly those from Saudi-Arabia, and represent the alliance *Acacion tortilis*. Relevés from the Sinai that lack the shrub species represent the alliance *Zygophyllion coccinei*. This alliance belongs to the hyperarid sand desert vegetation, the class *Anabasietea articulatae*.

Type 12 is a combination of relevés from Saudi Arabia and Egypt, marked by the dominance of *Nitraria retusa* or *Salsola imbricata*. Also this type represents associations of the alliance *Zygophyllion coccinei*.

Type 13 is very heterogeneous, with relevés spanning across Saudi Arabia, Egypt, Chad, Niger, Algeria, Morocco and Mauritania. Type 13 is dominated by *Neurada procumbens, Moltkiopsis ciliata, Cornulaca monacantha, Aristida pungens,* and *Polycarpaea repens*. These are all psammophytic species, which fit in the class *Anabasietea articulatae*. The eastern occurrences fit the description of the association *Calligono comosi-Artemisietum monospermae* by Mandaville (1990, see also Mandaville in Ghazanfar & Fisher 1998, chapter 8). These communities also fit in the class *Anabasietea articulatae*, order *Aristidetalia pungentis* Guinochet 1951.

Type 14 represents vegetation of hamadas and rocky wadis, mainly occurring in Chad, Algeria, Morocco, and Mauritania, features *Traganum nudatum, Zygophyllum glutinosum, Kickxia aegyptiaca,* and *Asteriscus graveolens* as its characteristic species. It probably can be assigned to the class *Asterisco graveolentis-Forsskaoletea tenacissimae* Quézel 1965.

Type 15 vegetation is characterised by some species with a broad ecology, like *Cenchrus ciliaris, Dichanthium annulatum,* and *Conyza stricta*, but it combines two rather different subtypes. About half of the relevés are from Saudi Arabia and contain *Juniperus procera* as one of the dominant species. Also, *Lavandula dentata* and *Kleinia cliffordiana* are also characteristic. This subtype represents northern occurrences of the subtropical mountain class *Juniperetea procerae*. The second subtype represents stony wadi communities of the Hoggar and Tibesti mountains in Algeria and Chad (with a few more species-poor relevés from Morocco). These have *Helianthemum lippi*, *Lavandula pubescens* (subsp. *antinea*), *Deverra scoparia*, *Morettia canescens* and *Cymbopogon schoenanthus* and represent the endemic mountain class *Lavanduletea antineae*, alliance *Lavandulion antineae*.

The vegetation type 16, found in Morocco, is characterized by the presence of *Zygophyllum gaetulum, Salsola imbricata, Limonium alleizettei,* and *Festuca arundinacea*. It represents the association *Tetraenetum gaetulum* of the alliance *Limoniastreto-Zygophyllion* Quézel 1965, which is part of the class *Halopeplido-Suaedetea*.

Type 17, located in Sinai, is mainly dominated by *Haloxylon salicornicum*, *Salsola tetrandra* and *Suaeda pruinosa*. It belongs to the class *Anabasietea articulatae*.

In Saudi Arabia and Sinai in Egypt, Type 18 is characterized by the dominance of *Haloxylon salicornicum* and *Rhazya stricta*. This type is also part of the class *Anabasietea articulatae*, alliance *Haloxylonion salicornici* Quézel 1964 and association *Haloxylonetum salicornicae* Zohary 1973.

Finally, Type 19, which thrives in Sinai in Egypt, is dominated by a diverse group of species including *Deverra tortuosa, Anabasis articulata, Thymelaea hirsuta, Gymnocarpos decandrus, Asphodelus ramosus, Moricandia sinaica, Asparagus stipularis, Reaumuria hirtella, Juniperus phoenicea,* and *Zygophyllum dumosum*. It is similar to a community reported in Sinai by Danin (1983) and Hatim et al. (2021) under the association *Anabasietum articulatae* Zohary 1973, which is part of the class *Anabasietea articulatae*.

Vegetation group 3 *Zygophyllum molle-Artemisia judaica*-group (types 20 – 22)

This is a group of three types (in total 289 relevés), which are characterised by *Zygophyllum molle*, *Artemisia judiaca*, *Zilla spinosa* and *Retama raetam*. In this group many differential species of group 2 are present, but with relatively low frequency. *Haloxylon salicornicum* is a common species of groups 2 and 3. The three types are all relatively species-poor, with *Retama raetam* dominant in type 20, *Zygophyllum molle* dominant in type 21, and *Artemisia judaica* in type 22.

Figure 7. Distribution of relevés of vegetation group 3. The dots with different colours represent the relevés of the 3 vegetation types.

This group represents different psammophytic communities, all from the dry sandy and rocky areas (hamada) (Danin, 1996) in the Sinai desert (Fig. 7). Such vegetation has been described under the class *Retametea raetam* Eig 1939. In the table, it is represented by three types, which correspond to the associations *Retamo raetam-Zilletum spinosae* Danin 1983 (type 20), *Retametum raetam* Zohary 1973 (type 21) and *Artemisietum judaicae* Zohary 1973 (type 22). These latter two associations have been combined in the order *Haloxylo-Retametalia raetam* Zohary 1973, but no alliance has been described so far. We propose a provisional alliance *Artemision judaicae-Retamion raetam*. Some discussion exists about the separation of the classes *Retametea raetam* Eig 1939, *Anabasietea articulatae* Zohary 1952 ex Danin et Solomeshch 1999 and *Haloxylonetea salicornici* Zohary 1955. They all have been described for psammophytic vegetation, but the latter two, which we consider synonyms, are restricted to the most extreme, hyperarid deserts. The exact differences between these classes require further study.

Vegetation group 4 *Erodium crassifolium*-group (type 23)

This group has one vegetation type comprising 104 relevés. It is a stepping vegetation group mainly found in high-altitude areas with cooler temperatures (Ozenda, 2004) in the Negev area in Israel (Fig. 8). This region has an annual rainfall of 200 mm and is under a strong pressure of grazing using the lignified plants for burning fuel (Danin & Orshan, 1999).

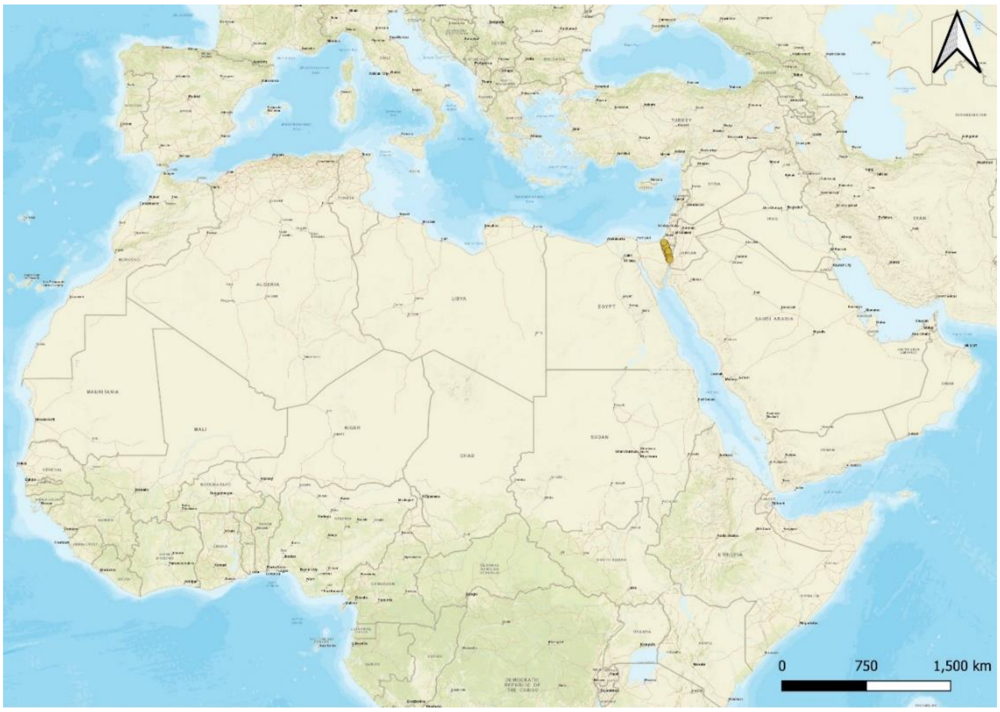

Figure 8. Distribution of relevés of vegetation group 4.

This group exhibits high homogeneity with few dominant species such as *Erodium crassifolium, Noaea mucronata, Scorzonera psychrophila, Anthemis pseudocotula, Seriphidium sieberi, Salvia lanigera, Helianthemum ledifolium, Filago desertorum, Centaurea aegyptiaca, Gymnocarpos decander, Helianthemum vesicarium, Trigonella stellata and Anabasis articulata*. The predominant life forms are hemicryptophytes and chamaephytes. Chorotypes include Mediterranean and Saharo-Arabian regions.

This group represents the association *Noaeetum mucronatae* Eig 1946, which is described as part of the class *Artemisietea sieberi* Zohary 1952 ex Danin et Solomeshch with order *Artemisietalia sieberi* Danin et Solomeshch ord. nov. (Danin & Orshan, 1999). This is a class of steppic communities. Originally, such communities have been described as a class *Artemisietea herbae-albae*, but as the characteristic *Artemisia* species in the near-east is not Artemisia herba-alba s.s., the names of the syntaxa have been adapted.

Vegetation group 5 *Malva parviflora-Chenopodium murale*-group (types 24 – 28)

This group has five types (24 to 28), of which the first two contain many wetland species (a.o. *Juncus maritimus*, *Typha domingensis*) and the last three have the species *Malva parviflora, Lolium rigidum*, *Convolvulus arvensis* and *Chenopodium murale* in common. The latter are all ruderal species with a worldwide distribution in both tropical and temperate regions. *Juncus maritimus*, a halophytic species, dominates type 24 while *Malva parviflora* and *Convolvulus arvensis* dominate types 26 and 27 respectively. Specifically in types 24 and 28, *Tamarix senegalensis* is one of the dominant species. The five types have the ruderal species *Polypogon monspeliensis* and *Euphorbis peplus* in common. Geographically, this group can be found in Saudi Arabia, Sinai in Egypt, Chad, Niger, Algeria, Morocco and Mauritania (Fig. 9).

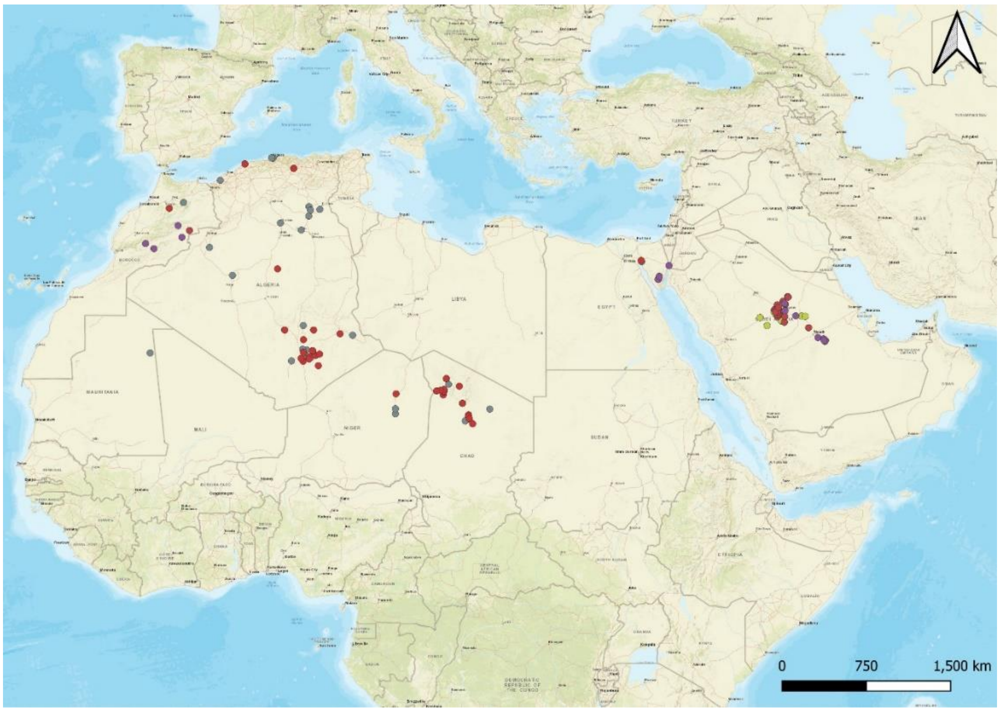

Figure 9. Distribution of relevés of vegetation group 5. The dots with different colours represent the relevés of the 5 vegetation types.

The first type represents the worldwide class *Phragmito-Magnocaricetea* Klika in Klika et Novák 1941, which combines vegetation of tall helophytes. These are communities of oases and other water bodies that are not specifically part of the scope of this study. The second type also has many wetland species, but it also represents partly a shrub community of fresh and brackish water bodies, which belongs to the class *Nerio-Tamaricetea*. The last three types of this group belong to the worldwide class *Chenopodietea* Br.-Bl. in Br.-Bl. et al. 1952, a worldwide class of annual weed communities of arable crops, gardens and waste places. It is unknown to which syntaxa on a lower level (order, alliances, associations) these ruderal communities in the deserts belong, but also these types are outside the scope of the study of desert communities. The Tamarix dominated relevés of type 28 fit in the class *Nerio-Tamaricetea*.

Vegetation group 6 *Pulicaria inuloides- Scirpoides holoschoenus*-group (type 29)

This group, comprising one type and 19 relevés, is homogeneous and dominated by wetland species. It thrives in freshwater wetlands and marshes (Cowardin et al., 1979), inhabiting permanent and semi-permanent wetlands. The life forms are primarily hygrophytes and hydrophytes, with chorotypes including Mediterranean and tropical elements. The relevés are mostly from water bodies occurring in the high mountains of the Central Sahara.

This group belongs to the worldwide class *Phragmito-Magnocaricetea* Klika in Klika et Novák 1941. This class combines reed and tall sedge communities of marshlands. The relevés of the group range from the coast of Morocco and Algeria to inland oases in Chad (Fig. 10).

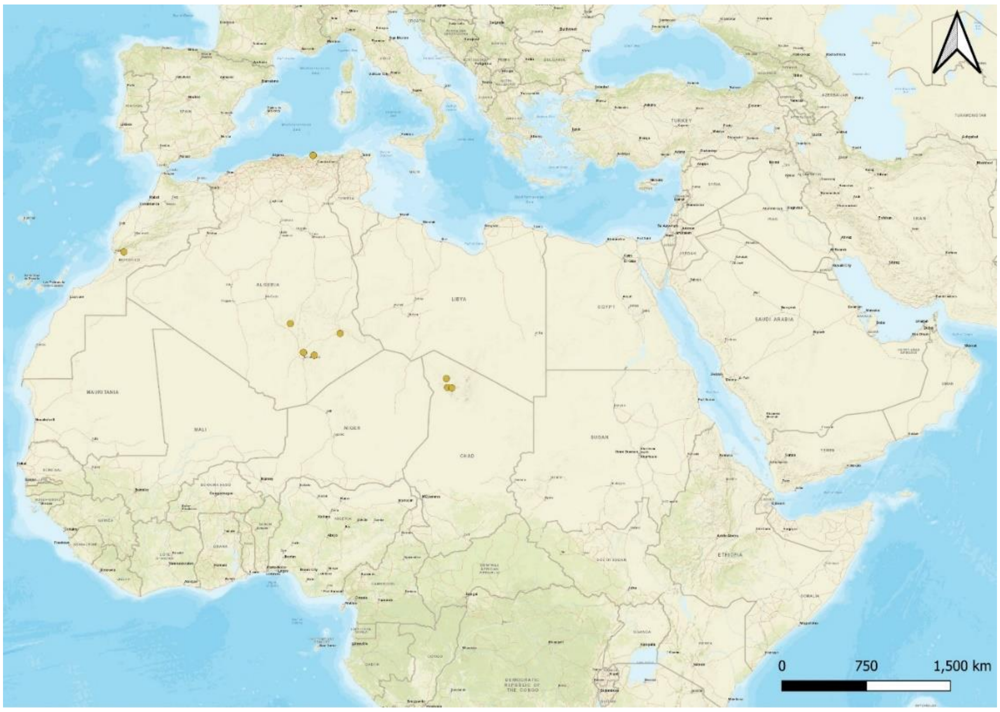

Figure 10. Distribution of relevés of vegetation group 6.

Vegetation group 7 *Vachellia tortilis-Forsskaolea tenacissima*-group (types 30 – 35)

This is a group of six types altogether built up of 553 relevés. Common species of the types are *Vachellia tortilis, Forsskaolea tenacissima, Trichodesma africanum, Citrullus colocynthis, Zygophyllum simplex*, and *Iphiona scabra*. *Vachellia tortilis* has the highest frequency but occurs in 50% of the relevés, which indicates the level of homogeneity of the group. *Vachellia tortilis* is also a common species between this group and group 8. The group shows moderate homogeneity with a mix of grasses and shrubs. It is adapted to dry, sandy environments, dominating ergs and sandy regs (Le Houérou, 1996). The life forms include therophytes and chamaephytes, with chorotypes spanning Saharo-Arabian and tropical regions in Saudi Arabia, Sinai in Egypt, Chad, Niger, Algeria, Morocco and Mauritania (Fig. 11).

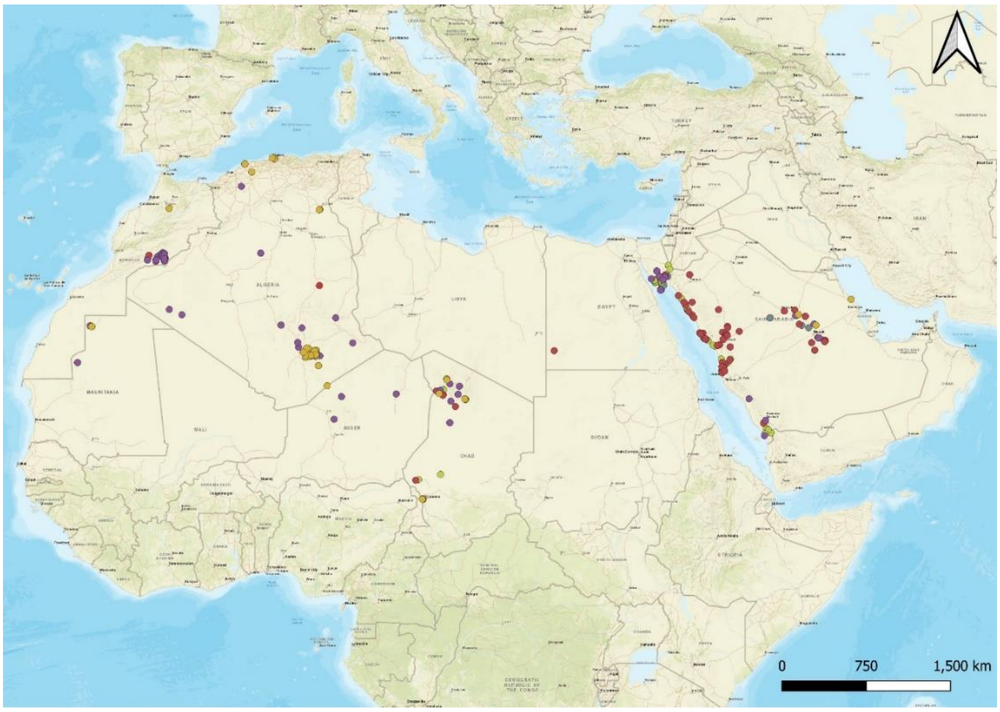

Figure 11. Distribution of relevés of vegetation group 7. The dots with different colours represent the relevés of the 6 vegetation types.

The six types all have a moderate frequency of *Vachellia tortilis* and *Forsskaolea tenacissima*, while some have *Vachellia flava* or *Vachellia seyal* as dominant tree or shrub. However, not in all relevés these woody species are present. This means that not all relevés represent "savanna", a vegetation characterised by patches of "Acacia"-trees. However, the *Vachellia*-dominated vegetation in the deserts is often found in the form of very open communities. Therefore it is likely that the relevés of group 7 represent both the *Vachellia*-dominated patches as well as some open patches in-between the shrubs and trees. Type 30 is relatively species rich with, amongst others, *Zygophyllum simplex, Stipagrostis plumosa, Zygophyllum scabrum, Iphiona scabra, Pulicaria undulata, Zygophyllum indicum, Lotus polyphyllos, Indigofera arabica, Aerva lanata*. Type 31 is differentiated by *Zilla spinosa*, *Caylusea hexagyna*, and *Capparis cartilaginea* and contains relevés from Morocco and Algeria.

The largest part of this group represents a variety of savanna communities from the desert region, which have been described by the class *Acacietea tortilis* Knapp 1968. The more recently described class *Panico turgidi-Acacietea raddianae* Costa et al. 2016 is a synonym name for this savanna class. Quézel (1965) described a *class Pergulario tomentosae-Pulicarietea crispae*, a savanna-class of the (subtropical) desert regions (both Sahara and Arabian Peninsula), which we also consider as a synonym of the *Acacietea tortilis*. The *Acacia tortilis*-communities of the Sahara are associated with habitats that have a relatively good water supply, like gravelly wadi-beds, alluvial plains and terraces (El-Karemy & Zayed 1992, Benghanem et al. 2016, Abbas et al. 2021). Quézel (1954, 1965) described the alliance *Panico turgidi-Acacion raddianae*, an alliance of tree and thorn shrubs on rocky wadis next to mountains on relatively nutrient rich sediments, occurring through the subtropical Sahara. Most of the here-described savanna relevés of type 30 to 34 fit in this alliance. The parts of type 32 to 34 with *Vachellia seyal* or *Vachellia flava*, found in the Arabian Peninsula, likely fit in the subtropical order *Acacietalia seyalis* of the savanna class *Acacietea tortilis*, which was described by Knapp (1968) for lowlands of Ethiopia and Sudan. The combination of *Zilla spinosa*, *Astragalus spinosus*, and *Rhazya stricta* with a scattered tree layer of *Vachellia*-species is described for the wadis of Central Saudi Arabia (Deil, 1998). We have no information on lower syntaxonomical units than the order.

Type 35, however, misses the typical *Vachellia* trees and is considered part of the *Asterisco graveolensis-Forsskaoletea tenacissimae* Quézel 1965, a class of desert vegetation of rocky plains and slopes (ergs, hamadas). It meets the description of the alliance *Aerveto-Fagonion* Quézel 1954, which is placed in the order *Aerveto-Fagonietalia flamandi* Tomaselli ex Braun-Blanquet 1967.

Vegetation group 8 *Aristida mutabilis-Aristida funiculata*-group (type 36)

This group consists of only one type, comprising 38 relevés. It has high homogeneity and is dominated by annuals, especially grasses, combined with some high *Vachellia*-shrubs. It is a characteristic type of arid regions with seasonal rainfall, typically found in the southern, more subtropical part of the Sahara. The data are from Sudan and Chad (Fig. 12). The characteristic species are *Aristida mutabilis, Aristida funiculata, Schoenefeldia gracilis, Indigofera exigua, Euphorbia granulate, Vachellia seyal, Limeum obovatum, Blepharis edulis, Capparis decidua, Vachellia flava, Indigofera sessiliflora* and *Aristida adscensionis*.

This type belongs to the subtropical order *Acacietalia seyalis* of the savanna class *Acacietea tortilis*, which was described by Knapp (1968) for the lowlands of Ethiopia and Sudan.

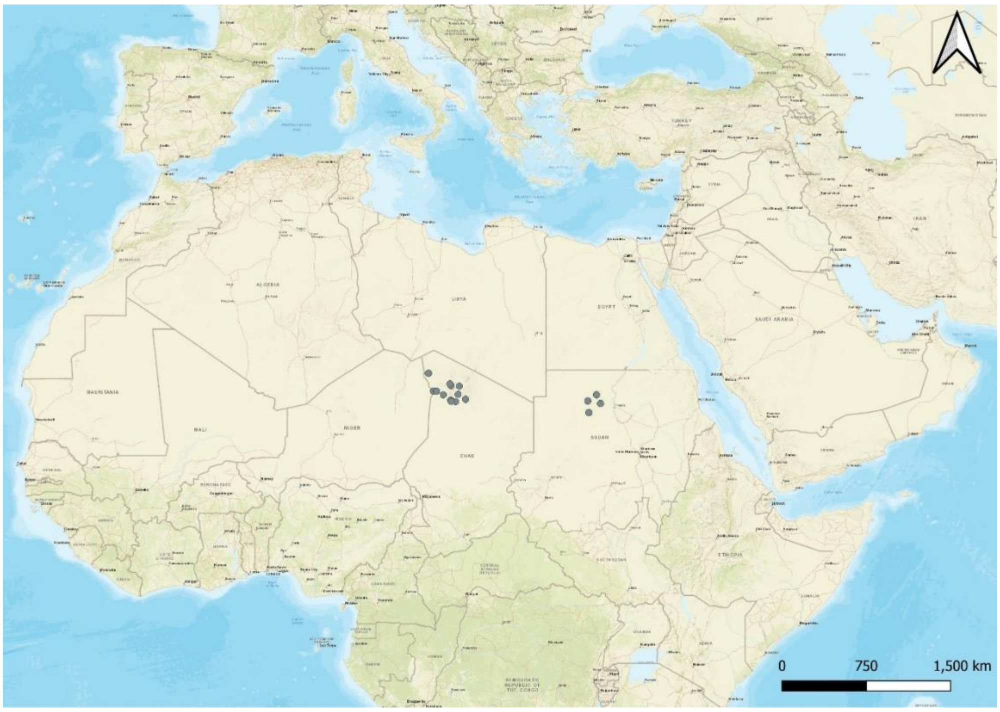

Figure 12. Distribution of relevés of vegetation group 8.

Vegetation group 9 *Teucrium polium*-group (types 37 – 40)

This group consists of four vegetation types summing up to 345 relevés in total. It is a highly homogeneous desert mountain group with few dominant perennial herbs. The characteristic species are *Teucrium polium, Alkanna orientalis, Tanacetum sinaicum, Stachys aegyptiaca, Chiliadenus montanus, Achillea fragrantissima, Ballota undulata, Echinops spinosissimus, Origanum syriacum, Matthiola arabica*, and *Nepeta septemcrenata*. These species are adapted to rocky and stony habitats, commonly found on rocky outcrops and hamadas (Batanouny, 2001). The life forms are hemicryptophytes and chamaephytes, with chorotypes including Irano-Turanian, Mediterranean and Saharo-Arabian elements. The data are from mountains in Sinai and in Algeria (Fig. 13).

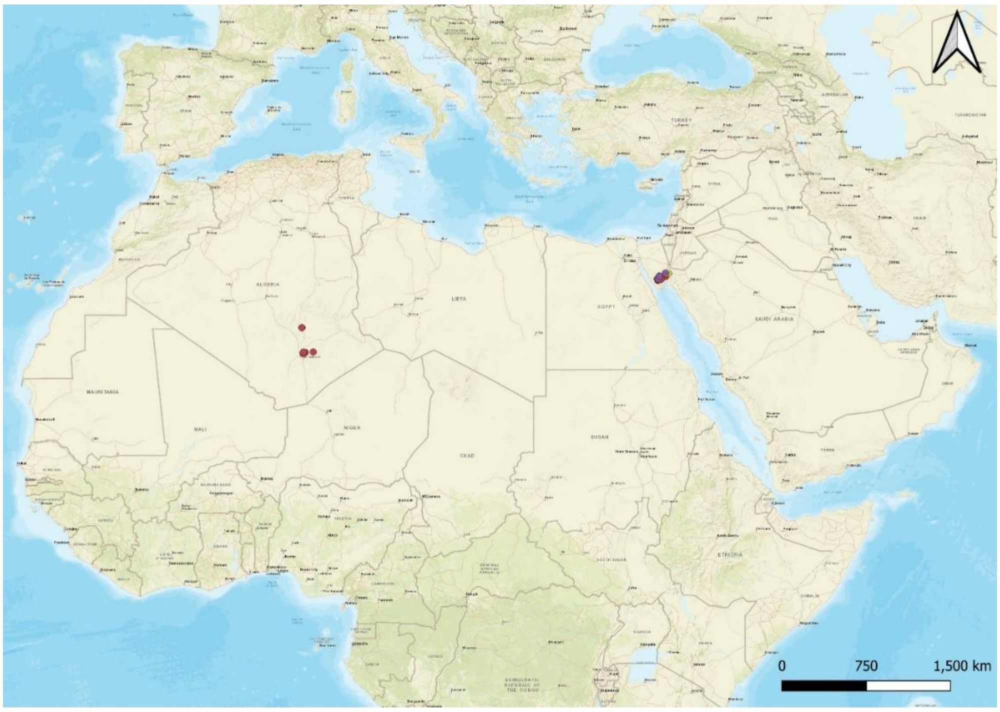

Figure 13. Distribution of relevés of vegetation group 9. The dots with different colours represent the relevés of the 4 vegetation types.

Type 37 is dominated by *Tanacetum sinaicum*, *Crataegus sinaica*, and *Teucrium polium*. This group can be found in southern Sinai in Egypt. It is similar to communities described by Danin (1983), Moustafa & Zaghloul (1996) and Hatim et al. (2021). This type reflects the association *Artemisio herbae-albae-Tanacetetum sinaici* (Danin, 1983) of the class *Chiliadenetea iphionoidis*.

The characteristic species of type 38 are *Phlomis aurea*, *Chiliadenus montanus*, *Origanum syriacum*, *Matthiola arabica*, *Nepeta septemcrenata*, and *Plantago sinaica*. This vegetation type is found in Sinai in Egypt in rocky wadis and outcrops. It reflects vegetation communities reported in Sinai by Danin (1983), Helmy et al. (1996), Ayyad et al. (2000), and Hatim et al. (2021). This type can be assigned to the association *Tanaceto sinaici-Phlomitetum aureae* (Danin, 1983) of the class *Chiliadenetea iphionoidis*.

Type 39 is dominated by *Ballota undulata*, *Galium sinaicum*, *Lavandula pubescens*, *Deverra scoparia*, and *Stachys aegyptiaca*. The vegetation mainly consists of chamaephytes and is found in rocky hillsides (hamadas), wadis, and outcrops in the Sinai mountains. The Sinai part of the type is similar to communities found in Sinai by Danin (1983), Ayyad et al. (2000), Abd EL-Wahab et al. (2006), and Hatim et al. (2021). It reflects the association *Stachydetum aegyptiacae* (Zohary, 1973) of the class *Chiliadenetea iphionoidis*. A few relevés are however from rocky slopes and outcrops in Algeria and characterised by *Crambe kralikii*, *Olea europaea* subsp. *lapperrini*. *Lavandula pubescens* subsp. *antinea*, These represent communities of a different endemic mountain class, *Lavanduletea antineae*, which is also represented by a part of type 15.

The characteristic species of type 40 are *Alkanna orientalis*, *Achillea fragrantissima*, *Peganum harmala*, *Launaea spinosa*, *Zygophyllum arabicum*, and *Gomphocarpus sinaicus*. This type can be found in rocky wadis in southern Sinai in Egypt. The dominant life forms of this type are hemicryptophytes. No corresponding association for this group was found, but the species composition assigns this community to the class *Chiliadenetea iphionoidis* as well (Hatim et al., 2021).

Vegetation group 10 *Haloxylon scoparium*-group (types 41 – 43)

This group has three vegetation types comprising 235 relevés. The characteristic species of this group are *Haloxylon scoparium*, *Stipa capensis*, *Medicago laciniata*, *Pallenis hierochuntica*, *Launaea nudicaulis*, and *Notoceras bicorne*. The group has many species in common with group 11, like *Convolvulus tributianus*, *Asphodelus fistulosus*, *Haloxylon scoparium*, *Morettia canescens*, *Drimia noctiflora*. Type 10 is differentiated from type 11 by amongst others *Notoceras bicorne*, *Stipa capensis*, *Pallenis hierochuntica* and *Launaea nudicaulis*. This group is rather homogeneous and is primarily found in rocky plains (regs, hamadas) and rocky wadis in Mauritania, Algeria and Chad (Fig. 14). The predominant life forms are therophytes and chamaephytes.

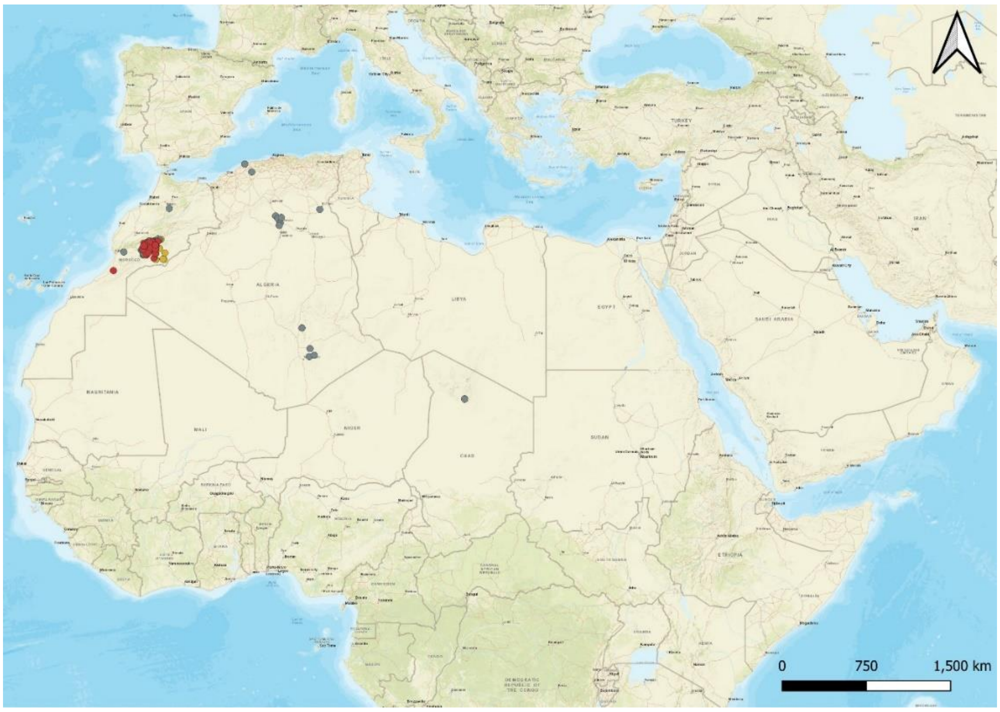

Figure 14. Distribution of relevés of vegetation group 10. The dots with different colours represent the relevés of the 3 vegetation types.

These three types represent plant communities of the class *Pergulario tomentosae-Puliocaretea crispae* Quézel 1965 and the alliance *Antirrhineto-Zillion macropterae* Quézel 1965, which was described for vegetation of (mostly) stony wadis. Quézel (1965) included also savanna-communities under this class, but these are better considered as part of the *Acacietea tortilis*. Type 42 contains a few relevés that may be classified as high mountain steppic communities of the class *Helianthemeto-Paronychietea* Quézel 1965. This class and the allioance *Moricandieto-Senecion hoggariensis* were described for perennial grasslands on rocky soils of the summits of the Hoggar & Tibesti mountains (Quézel 1965). *Stipagrostis obtusa* is one of the dominant perennials in this type. Type 43 includes some relevés of the alliance *Senecion flavi* Quézel 1965, class *Asterisco graveolentis-Forsskaoletea tenacissimae* Quézel 1965, which indicates a transition towards the next group.

Vegetation group 11 *Fagonia longispina*-group (types 44 – 46)

This group has three vegetation types comprising 245 relevés. The characteristic species are *Fagonia longispina*, *Anvillea radiata*, *Asphodelus fistulosus*, *Morettia canescens*, *Convolvulus trabutianus*, *Gymnocarpos sclerocephalus*, *Plocama reboudiana*, *Forsskaolea tenacissima* (also in type 43), and *Lotus glinoides*. This group is highly homogeneous and can be found in wadi beds and dry river channels (wadis) in Morocco and Algeria (Fig. 15). The life forms are phanerophytes and chamaephytes, with chorotypes including Saharo-Arabian and tropical elements.

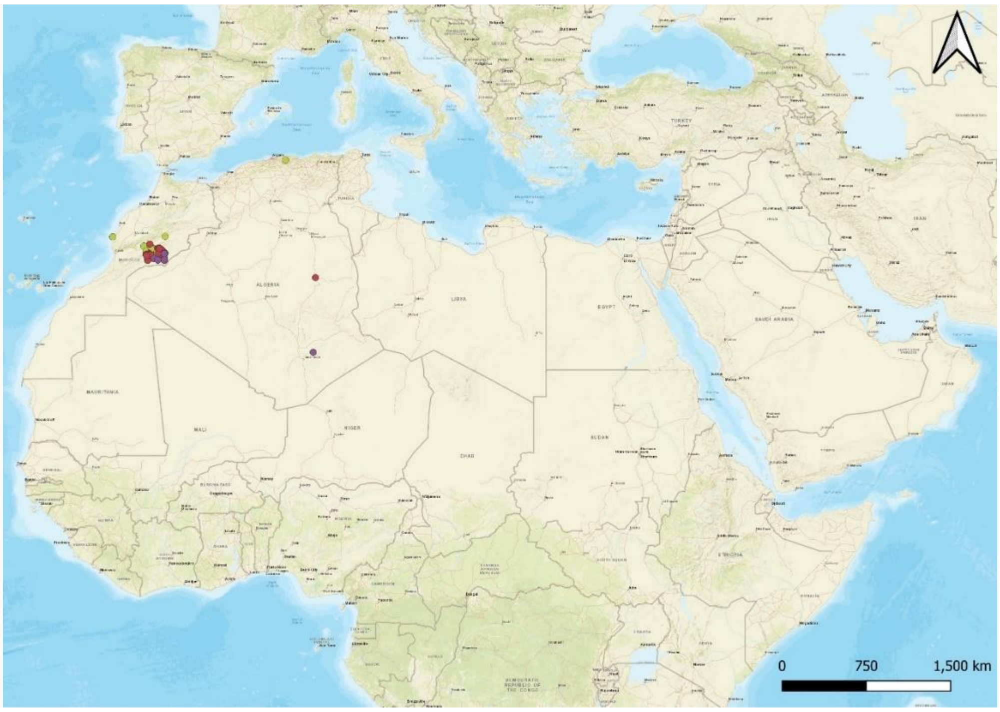

Figure 15. Distribution of relevés of vegetation group 11. The dots with different colours represent the relevés of the 3 vegetation types.

Type 44 is dominated by *Anastatica hierochuntica* and *Trichodesma calcaratum* and is restricted to Morocco. The characteristic species of type 45 are *Anvillea radiata*, *Plocama reboudiana*, *Morettia canescens*, *Ephedra alata*, and *Drimia noctiflora* which can be found in

Morocco and Algeria. Finally, type 46 is dominated by *Fagonia longispina*, *Lotus glinoides*, *Diplotaxis pitardiana*, *Reseda villosa*, *Gymnocarpos sclerocephalus*, and *Paronychia arabica* and also can be found in Morocco and Algeria. These three types can be assigned to the class *Asterisco graveolentis-Forsskaoletea tenacissimae* Quézel 1965, and within this class to the alliance *Atractylion babelii* Lemée 1952. They are bound to hamadas and rocky wadis.

Vegetation group 12 *Seriphidium herba-alba-Schismus barbatus*-group (types 47 - 48)

This group consists of two types with 195 relevés having many species in common, including *Seriphidium herba-alba*, *Carlina brachylepis*, *Schismus barbatus*, *Stipa parviflora*, *Picris hispanica*, *Filago congesta*, *Artemisia mesatlantica*, *Minuartia montana*, *Astragalus tribuloides*, *Echium humile*, *Teucrium mideltense*, and *Herniaria hirsuta*. *Carlina brachylepis* and *Schismus barbatus* are also found in groups 13, 14 and 15 with a relatively high percentage, while *Seriphidium herba-alba* can be found with a moderately high percentage in group 9. This group exhibits high homogeneity and is adapted to extremely arid environments, commonly found on desert plains and rocky deserts (hamadas) in Morocco (Fig. 16). The life forms are chamaephytes and therophytes, with chorotypes including Saharo-Arabian and Mediterranean elements.

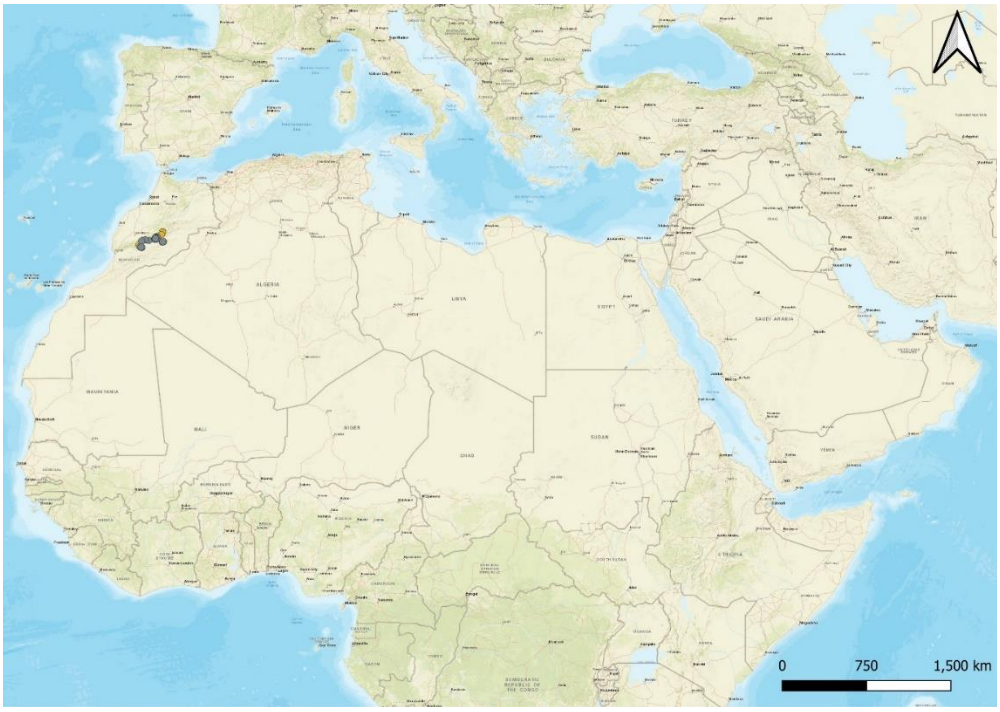

Figure 16. Distribution of relevés of vegetation group 12. The dots with different colours represent the relevés of the 2 vegetation types.

The difference between the two types is small and it is noticeable that *Seriphidium herba-alba* and *Carlina brachylepis* dominate the two types. Type 47 is dominated by *Carlina brachylepis, Bufonia tenuifolia, Stipa parviflora, Artemisia mesatlantica, Picris hispanica, Echium humile, Teucrium mideltense*, and *Helianthemum croceum*. Type 48 is dominated by *Seriphidium herba-alba*, *Schismus barbatus*, *Bromus rubens*, *Filago congesta*, *Bromus* *tectorum*, *Herniaria hirsuta*, *Minuartia montana*, *Astragalus tribuloides*, *Reseda phyteuma*, and *Erysimum incanum*.

This is a steppe vegetation group. The corresponding syntaxa for the two types is the class *Lygeo sparti-Stipetea tenacissimae* Rivas-Martínez 1978, order *Artemisietalia herbae-albae* Br.-Bl. & O. Bolòs 1958 and alliance *Artemision herbae-albae* Br.-Bl. & O. Bolòs 1958 (Taleb and Fennane, 2019).

Vegetation group 13 *Bromus rubens - Lactuca viminea*-group (type 49)

This group comprises one type with 40 relevés. The characteristic species are *Bromus rubens, Lactuca viminea, Bufonia tenuifolia, Salvia verbenaca, Taeniatherum caput-medusae, Centaurea debdouensis, Bromus tectorum, Stipa barbata, Filago micropodioides, Medicago polyceratia, Scorzonera pygmaea, Cladanthus scariosus, Dactylis glomerata, Alyssum simplex, Lasiopogon muscoides, Linaria simplex, Paronychia arabica, Minuartia funkii*, and *Echinaria capitata*.

This group has moderate homogeneity and a diverse mix of species. It is a little similar to the previous group except that it is adapted to transitional areas between desert and semi-desert, commonly found in semi-arid plains and sandy regions (regs) in Morocco (Fig. 17). The life forms include therophytes and hemicryptophytes, with chorotypes spanning Saharo-Arabian and Mediterranean regions.

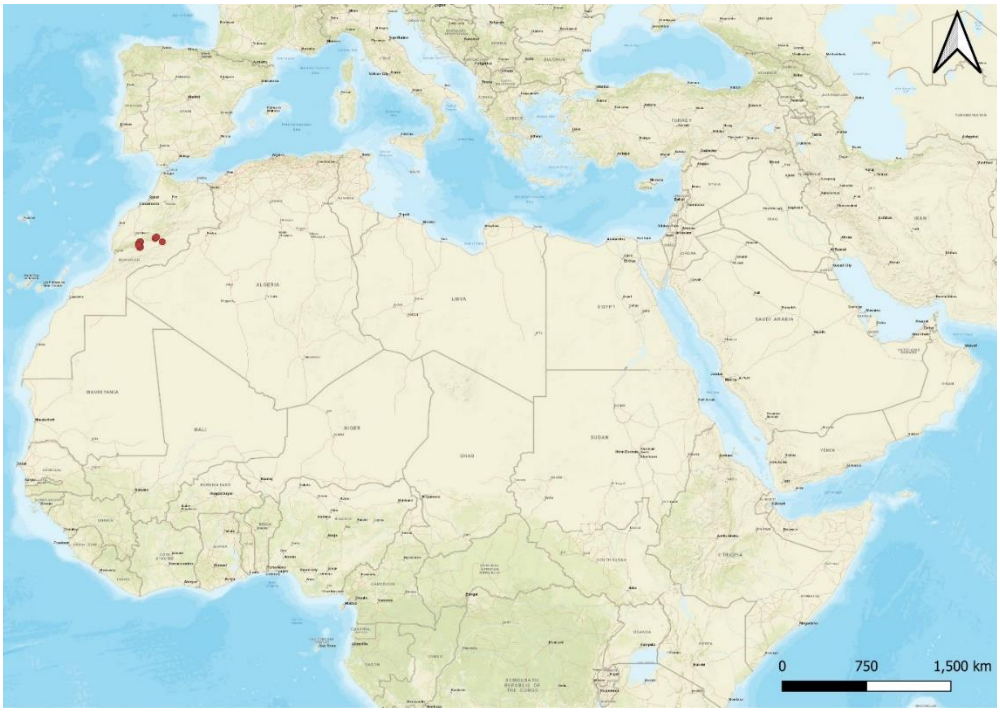

Figure 17. Distribution of relevés of vegetation group 13.

The proposed syntaxonomy for this group can be class *Lygeo sparti-Stipetea tenacissimae* Rivas-Martínez 1978, order *Stipetalia tenacissimae* Br.-Bl. 1931, alliance *Stipion tenacissimae* Br.-Bl. 1931.

Vegetation group 14 *Hormathophylla spinosa* (types 50 - 51)

This group comprises two types with 190 relevés. It is dominated by *Hormathophylla spinosa, Vella mairei, Euphorbia megalatlantica, Artemisia negeri, Bupleurum spinosum, and Cytisus balansae*.

It shows high homogeneity with few dominant species. It is found in high-altitude, rocky environments, inhabiting mountain slopes and high-altitude plains (hamadas) in Morocco (Fig. 18). The predominant life forms are hemicryptophytes and chamaephytes. Chorotypes include high-mountain and Mediterranean species.

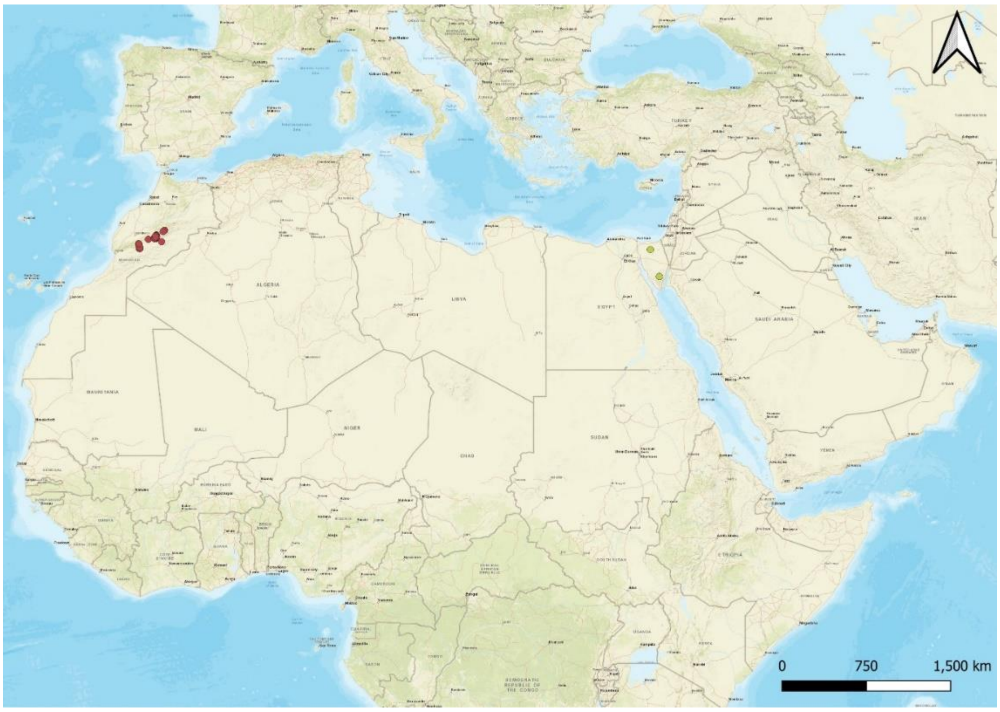

Figure 18. Distribution of relevés of vegetation group 14. The dots with different colours represent the relevés of the 2 vegetation types.

Type 50 is dominated by *Hordeum murinum, Sisymbrium runcinatum, Scorzonera laciniata, Euphorbia helioscopia, Adonis macrocarpa, Glaucium corniculatum*, and *Descurainia sophia*. Also this type can be assigned to the alliance *Artemision herbae-albae* within the class *Lygeo sparti-Stipetea tenacissimae* Rivas-Martínez 1978.

The characteristic species of type 51 are *Hormathophylla spinosa, Vella mairei, Euphorbia megalatlantica, Artemisia negeri, Bupleurum spinosum, Erinacea anthyllis, Cytisus balansae*, and *Lactuca reviersii*. This type reflects endemic high mountain vegetation of the Atlas Mountains in Morocco, which have been described as the association *Velletum mairei* Quézel 1952, which is part of the class *Ononido-Rosmarinetea* Br.-Bl. in O. Bolos y Vayreda 1950.

Vegetation group 15 *Filago pyramidata* (types 52 - 55)

This group has four types with 305 relevés. It is dominated by *Filago pyramidata*, *Hertia maroccana*, *Reseda nainii*, *Thymus saturejoides*, and *Genista scorpius*. This group has moderate homogeneity with a mix of shrubs and herbs. It is adapted to arid areas with some moisture availability, commonly found on plains and low-lying areas (regs) in Morocco and Algeria (Fig. 19). The life forms include chamaephytes and therophytes, with chorotypes spanning Saharo-Arabian and Mediterranean regions.

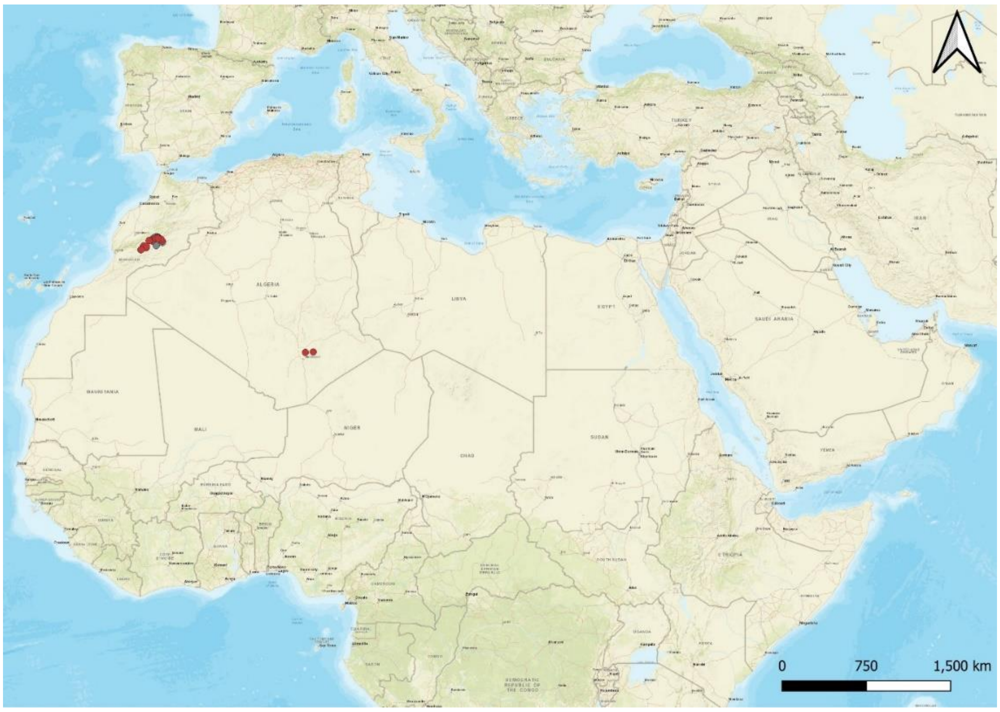

Figure 19. Distribution of relevés of vegetation group 15. The dots with different colours represent the relevés of the 4 vegetation types.

Type 52 is dominated by *Filago pyramidata* and *Hertia maroccana*, while the characteristic species of type 53 are *Reseda nainii*, *Picris asplenioides*, *Carthamus duvauxii*, *Eryngium ilicifolium*, and *Cleome africana*. Type 54 is dominated by *Genista scorpius, Thymus saturejoides, Teucrium malenconianum, Centaurea gattefossei, Lotus maroccanus*, and *Carthamus fruticosus.* As for type 55 it is dominated by *Crucianella hirta, Leisera leiseroides, Ononis natrix*, and *Centaurea maroccana*. All types belong to the alliance *Artemision herbae-albae* (class *Lygeo sparti-Stipetea tenacissimae*).

Based on our comprehensive analysis of the vegetation data and comparison with existing literature, we propose a syntaxonomical scheme for the Saharo-Arabian desert region (Table 2). This scheme synthesizes the hierarchical relationships among the identified plant communities (55 types), from the class level down to the level of association where applicable. It encompasses seven major categories: saline desert communities, lowland desert communities, mountain desert communities, steppe and Mediterranean communities, pseudosavanna communities, ruderal communities, and wetland communities. Within this overview, we refer to 15 classes, which reflect the main patterns of biodiversity in the Saharo-Arabian region. Most of these classes represent the core of the desert vegetation, while others are transitional to other regions or represent azonal vegetation.

Table 2. Syntaxonomical scheme of Saharo-Arabian desert vegetation, including the described (55) vegetation types.
999

SALINE DESERT COMMUNITIES

***Halopeplido-Suaedetea* Knapp 1968 (syn. *Suaedetea fruticosae* Zohary 1973)**

- *Limoniastretalia guyoniani* Guinochet 1951
    - *Limoniastrion guyoniani* Quézel 1965 (type 6 p.p.)
    - *Zygophyllion albae* Géhu et al. 1990
        - *Zygophylletum albi* Zohary 1973 (type 10)
    - *Limoniastreto-Zygophyllion* Quézel 1965
        - *Tetraenetum gaetulum* Costa et al. 2016 (type 16)
- *Halopeplidetalia perfoliatae* Knapp 1968
    - *Zygophyllion qatarensis* all. nov. prov.
        - *Zygophylletum qatarensis* Deil et Müller-Hohenstein 1996 (type 8 p.p.)
        - *Halopeplidetum perfoliatae* Deil et Müller-Hohenstein 1996 99(type 8 p.p.)
    - *Zygophyllion simplicis* Deil et Müller-Hohenstein 1996 (type 6 p.p.)

***Nerio-Tamaricetea* Br.-Bl. et O. de Bolòs 1958**

- *Tamaricetalia africanae* Braun-Blanquet et Bolòs 1957
    - *Tamaricion africanae* Braun-Blanquet et Bolòs 1957 (type 7, 25 p.p., 28 p.p.)

LOWLAND DESERT COMMUNITIES

***Anabasietea articulatae* Zohary 1952 ex Danin et Solomeshch 1999 (syn. *Haloxylonetea salicornici* Zohary 1955)**

- *Anabasietalia articulatae* Zohary 1955 ex Danin et Solomeshch 1999 (type 5)
    - *Agathophoro-Anabasion articulatae* Danin, Orshan et Zohary 1975 ex Danin & Solomeshch 1999
        - *Anabasietum articulatae* Zohary 1973 (type 19)
    - *Astragalion eremophili-annulari* all. nov. prov. (type 1)
- *Aristidetalia pungentis* Guinochet 1951 (type 13)
    - *Aristidion pungentis* Géhu, Kaabèche & Gharzouli 1994
        - *Calligono comosi-Artemisietum monospermae* Mandaville 1990 (type 13 p.p.)
- *Zygophylletalia coccinei* ord. nov. prov.
    - *Zygophyllion coccinei* El Sharkawy et Fayed 1982 (type 11 p.p., 12)
- *Haloxylonetalia salicornici* Quézel 1964
    - *Haloxylonion salicornici* Quézel 1964 (type 17)
        - *Haloxylonetum salicornici* Zohary 1973 (type 18)

***Retametea raetam* Eig 1939**

- *Haloxylo-Retametalia raetam* Zohary 1973
    - *Artemision judaicae-Retamion raetam* all. nov. prov.
        - *Artemisietum judaicae* Zohary 1973 (type 22)
        - *Retamo raetam-Zilletum spinosae* Danin 1983 (type 20)
        - *Retametum raetam* Zohary 1973 (type 21)

***Asterisco graveolentis-Forsskaoletea tenacissimae* Quézel 1965**

- *Gymnocarpeto decandri-Atractyletalia babelii* Quézel 1965 (type 14)
    - *Aerveto-Fagonion* Quézel 1954 (type 35)
    - *Atractylion babelii* Lemée 1952 (type 44, 45, 46)
- *Senecietalia flavi* Quézel 1965
    - *Senecion flavi* Quézel 1965 (type 43 p.p.)

***Pergulario tomentosae-Pulicarietea crispae* Quézel 1965**

- *Pergularieto-Puliceraetalia* Quézel 1965
    - *Antirrhineto-Zillion macropterae* Quézel 1965 (type 41, 42 p.p., 43 p.p.)

MOUNTAIN DESERT COMMUNITIES
***Chiliadenetea iphionoidis* Zohary 1955 ex Danin et Solomeshch 1999 (syn. Varthemietea iphionoidis Zohary 1973)**

- *Artemisio sieberi-Chiliadenetalia iphionoidis* Danin, Orshan et Zohary 1975 ex Danin et Solomeshch 1999
    - *Tanaceto-Artemision herbae-albae* Zohary 1973 (type 40)
        - *Stachydetum aegyptiacae* Zohary 1973 (type 39 p.p.)
        - *Tanaceto sinaici-Phlomitetum aureae* Danin 1983 (type 38)
        - *Artemisio herbae-albae-Tanacetetum sinaici* Danin 1983 (type 37)

***Lavanduletea antineae* Quézel 1965**

- *Lavanduletalia antineae* Quézel 1965
    - *Lavandulion antineae* Quézel 1965 (type 15 p.p., 39 p.p.)

***Helianthemo-Paronychietea* Quézel 1965**

- *Helianthemeto-Paronchietalia* Quézel 1965
    - *Moricandio-Senecion hoggariensis* Quézel 1954 (type 42 p.p.)

***Juniperetea procerae* Zohary 1973**

- *Oleo-Juniperitalia procerae* Knapp 1968
    - *Oleo-Juniperion (somaliensis) procerae* Knapp 1968 (type 15 p.p.)

STEPPE AND MEDITERRANEAN COMMUNITIES
***Artemisietea sieberi* Zohary 1952 ex Danin et Solomeshch 1999**

- *Artemisietalia sieberi* Danin et Solomeshch ord. nov.
    - *Artemision sieberi* Eig 1946 em. Danin et Solomeshch 1998
        - *Noaeetum mucronatae* Eig 1946 (type 23)

***Lygeo sparti-Stipetea tenacissimae* Rivas-Martínez 1978**

- *Artemisietalia herbae-albae* Br.-Bl. & O. Bolòs 1958
    - *Artemision herbae-albae* Br.-Bl. & O. Bolòs 1958 (type 47, 48, 50, 52, 53, 54, 55)
- *Stipetalia tenacissimae* Br.-Bl. 1931
    - *Stipion tenacissimae* Br.-Bl. 1931 (type 49)

***Ononido-Rosmarinetea* Br.-Bl. in O. Bolos y Vayreda 1950**

- *Erinacetalia anthyllidis* Quézel 1952
    - *Arenarion pungentis* Quézel 1957
        - *Velletum mairei* Quézel 1952 (type 51)
    - *Platycapnion saxicolae* Quézel 1952 (type 9)

(PSEUDO)SAVANNA COMMUNITIES
***Acacietea tortilis* Knapp 1968**

- *Acacietalia tortilis* Knapp 1968
    - *Acacion tortilis* Eig 1946 (type 2, 3)
        - *Acacietum tortilis* Eig 1946 (type 11 p.p.)
    - *Panico turgidi-Acacion raddianae* Quézel (1954) 1965 (types 30, 31, 32 p.p., 33 p.p., 34 p.p.)
- *Acacietalia seyalis* Knapp 1968 (type 32 p.p., 33 p.p., 34 p.p., 36)

RUDERAL COMMUNITIES
***Chenopodietea* Br.-Bl. in Br.-Bl. et al. 1952** (type 26, 27, 28 p.p.)

WETLAND COMMUNITIES
***Phragmito-Magnocaricetea* Klika in Klika et Novák 1941** (type 24, 25 p.p., 29)
***Isoëto-Nanojuncetea* Br.-Bl. et Tx. in Br.-Bl. et al. 1952**

- *Mollugineto-Anticharidetalia* Quézel 1965 (type 4)

4.4.3 Discussion

The classification of the vegetation in the Saharo-Arabian desert region revealed 15 main groups comprising 55 vegetation types, highlighting the considerable diversity of plant communities in this arid environment. These groups range from saline communities, wadi and psammophytic assemblages to high mountain vegetation, with steppic, mediterranean and savanna-like communities in the transition zones towards other geographic regions. This diversity is notable, given the harsh climatic conditions, and supports previous assertions about the complexity of desert ecosystems (Ward, 2016). The use of a large dataset (6,748 relevés) and advanced clustering techniques has allowed for a more comprehensive overview of vegetation patterns compared to earlier studies in the region (e.g. Quézel, 1965; Zohary, 1973). The scheme provides a complete overview of the higher units of the desert vegetation of the Saharo-Arabian region, but on the lower levels, it is not complete because of gaps in data.

Ecologically, these groups exhibit distinct adaptations to specific environmental niches, reflecting the complex interplay of edaphic conditions, topography, and microclimatic variations. The spatial distribution of these vegetation groups reflects the influence of both climatic gradients and topographic features across the Saharo-Arabian region. For instance, the *Vachellia gerrardii* group (Group 1) is primarily confined to Saudi Arabia, while the *Erodium crassifolium* group (Group 4) is found in the cooler, high-altitude areas of the Negev in Israel. This pattern aligns with the biogeographical subdivisions proposed by Quézel (1978) and Le Houérou (1990), emphasizing the role of environmental factors in shaping vegetation composition.

The identification of several halophytic communities within the *Haloxylon salicornicum* group (Group 2) underscores the importance of saline habitats in desert ecosystems. These findings are consistent with previous studies highlighting the significance of salt-tolerant vegetation in arid regions (e.g. Batanouny, 2001). The presence of both coastal and inland saline communities within this group suggests a need for further investigation into the ecological drivers of halophytic vegetation distribution in desert environments.

The recognition of distinct mountain vegetation types, such as the *Teucrium polium* group (Group 9), emphasizes the role of topography in creating diverse habitats within the desert landscape. This group's association with rocky and stony habitats in Sinai and Algeria aligns with observations by Danin & Orshan (1999), regarding the unique plant assemblages found in desert mountain ranges. The high level of endemism often associated with these habitats (Moustafa & Zaghloul, 1996) underscores their importance for biodiversity conservation in arid regions.

The identification of several steppe vegetation types, particularly in the western part of the study area (e.g. Groups 12 and 13), highlights the transitional nature of some desert margins. These communities represent important ecotones between true desert and more mesic environments. The classification of these vegetation types within the *Lygeo sparti-Stipetea* *tenacissimae* class aligns with previous phytosociological studies in North Africa (Taleb & Fennane, 2019) and provides a foundation for understanding vegetation dynamics in semi-arid landscapes.

The presence of savanna-like communities, particularly in Group 7 (*Vachellia tortilis-Forsskaolea tenacissima* group), illustrates the complexity of vegetation structure in some parts of the Saharo-Arabian region. The classification of these communities within the *Acacietea tortilis* class is consistent with earlier descriptions of desert tree-dominated vegetation (Knapp, 1968). However, the observed variability within this group suggests that further research is needed to fully understand the ecological drivers and biogeographical patterns of savanna-like vegetation in desert environments.

The identification of numerous endemic and regionally restricted plant communities, particularly in mountain habitats, underscores the unique botanical character of the Saharo-Arabian region. This finding supports the designation of this area as a distinct floristic region (Takhtajan, 1986) and highlights its importance for global biodiversity conservation. The high level of endemism observed in some groups (e.g. Group 9 in Sinai) aligns with previous studies emphasizing the biogeographical significance of desert mountain ranges (Moustafa & Zaghloul, 1996; Hatim et al., 2021).

4.4 Conclusions

This comprehensive phytosociological study of the Saharo-Arabian desert region has significantly advanced our understanding of vegetation patterns in one of the world's largest arid areas. The identification of 15 main vegetation groups encompassing 55 distinct types demonstrates the remarkable diversity of plant communities in this seemingly homogeneous landscape. This classification provides a robust framework for future ecological research and conservation efforts in the region.

The integration of large-scale data analysis with traditional phytosociological methods has proven effective in capturing the complexity of desert vegetation. The use of modern clustering techniques and extensive relevé data (6,748 samples) has allowed for a more objective and statistically supported classification compared to earlier studies. This approach bridges the gap between classical vegetation science and contemporary data-driven methodologies, offering a model for future large-scale vegetation analyses in other biogeographic regions.

Our findings highlight the critical role of environmental heterogeneity in shaping desert plant communities. The distinct vegetation groups associated with specific habitats – such as saline depressions, mountain slopes, and wadi systems – underscore the importance of topographic and edaphic factors in driving botanical diversity in arid environments. This reinforces the need for a landscape-level approach to desert ecology and conservation, recognizing the mosaic nature of these ecosystems.

The syntaxonomical classification presented here provides a unified system for describing Saharo-Arabian vegetation, addressing inconsistencies in previous regional studies. By aligning our classification with the International Code of Phytosociological Nomenclature (Theurillat et al., 2021), we have created a standardized reference that facilitates comparisons across different parts of the Saharo-Arabian region and with other desert areas globally.

This study supports the recognition of the Saharo-Arabian region as a distinct floristic realm and highlights its importance for global biodiversity conservation.

While this study represents a significant step forward in our understanding of Saharo-Arabian vegetation, it also reveals areas requiring further investigation. The transitional nature of some vegetation types, particularly at the desert margins, suggests the need for more detailed studies of ecotonal communities. Additionally, the impact of anthropogenic factors on vegetation patterns, including grazing and climate change, remains an important area for future research.

4.5 Recommendations

We propose the following recommendations for future research and conservation efforts:

- Given the high levels of endemism observed in certain vegetation groups, particularly in mountainous regions (e.g. Group 9 in Sinai), we recommend targeted studies in these areas. Such research should aim to elucidate the evolutionary and ecological processes driving speciation and adaptation in these unique habitats. This information is crucial for developing effective conservation strategies for rare and endemic taxa.
- Establish a network of permanent plots across the identified vegetation types to monitor long-term changes in community composition and structure. This is particularly important in the context of climate change, which is expected to significantly impact arid ecosystems. Such monitoring efforts should incorporate both floristic and environmental data to track shifts in species distributions and community dynamics over time.
- Further investigation of the transitional vegetation types, such as those found in Groups 12 and 13, is needed to better understand the ecotonal dynamics between desert and adjacent biomes. These areas may serve as early indicators of climate-driven vegetation shifts and deserve special attention in future ecological studies.
- To complement the floristic approach used in this study, we recommend conducting comprehensive analyses of plant functional traits across the identified vegetation types. This would provide insights into the adaptive strategies of desert plants and help predict community responses to environmental changes.
- Given the importance of soil-plant interactions in arid environments, we suggest integrating soil analyses with vegetation studies. This could reveal important associations between plant communities and soil diversity, potentially uncovering key factors in desert ecosystem functioning.
- Conduct detailed studies on the effects of human activities, such as grazing, urbanization, and resource extraction, on the identified vegetation types. This information is crucial for developing sustainable land-use practices and effective conservation strategies in the region.
- Explore the potential of high-resolution remote sensing techniques to map and monitor the distribution of the identified vegetation types at a regional scale. This approach could provide valuable data on vegetation dynamics and help identify areas of conservation priority.

- Incorporate phylogenetic information into future vegetation analyses to better understand the evolutionary history and biogeographic patterns of Saharo-Arabian flora and plant communities. This approach could provide insights into the processes shaping desert biodiversity over evolutionary timescales.
- Promote the use of standardized sampling protocols and data sharing practices among researchers working in the Saharo-Arabian region. This would facilitate more comprehensive meta-analyses and improve our ability to detect large-scale patterns and trends in desert vegetation dynamics.
- Foster collaborations between vegetation scientists, climatologists, soil scientists, and conservation biologists to develop a more holistic understanding of Saharo-Arabian desert ecosystems. Such interdisciplinary approaches are essential for addressing complex ecological questions and informing effective management strategies in these sensitive environments.

5

Suitability maps of the Sinai desert vegetation

5.1 Introduction

Botanists have been intrigued by the remarkable occurrence and resilience of plants in desert environments throughout history. Sinai, positioned at the junction of three continents and renowned as a vital hub for biodiversity in the Middle East, holds significant global importance as a desert region. This significance is further highlighted by the ongoing climatic changes that have been observed in recent times (Ayyad et al., 2000).

The Sinai desert is known for its arid climate and low amount of precipitation, and as such, the vegetation in the region is limited to a relatively small number of species that have adapted to these conditions (Hatim et al., 2021). These include shrubs and small trees such as acacia, tamarisk, and jujube, as well as various types of grasses and succulents. These plants have developed deep roots, thick leaves, and the ability to store water, which allows them to survive in the desert environment.

The diversity of the vegetation of Sinai has been extensively described in Hatim et al. (2021), chapter 2 of this thesis. However, no comprehensive map of the spatial extent of the desert vegetation in the Sinai Peninsula has been compiled so far (Hussein et al., 2015). This lack of detailed mapping can be attributed to several factors, including the complexity of plant communities present in the region (with many areas with few species and low vegetation cover), the vast area of Sinai itself, and the inaccessibility of several parts of this politically instable region. Due to these challenges, accurately displaying vegetation patterns in the form of a map has proven to be a difficult task.

Danin (1983) acknowledged the complexity of Sinai vegetation and the limitations in producing accurate vegetation maps. He opted to present schematic diagrams instead, showing broad regions with different geomorphological characteristics (Fig. 1). These diagrams aimed to provide a generalized representation of vegetation by categorizing it into different types associated with the geomorphological districts of the peninsula. While these schematic diagrams offer broad insights into the vegetation patterns of Sinai, they do not provide a comprehensive map with precise details on distribution of plants and plant communities across the region, which may serve as a baseline for future monitoring of changes.

Still coping with the same challenges, in this chapter, we study the possibility of compiling a map of the spatial patterns of the Sinai vegetation by creating a model based on spatial maps of abiotic factors and a limited set of vegetation observations on the ground. This model results in so-called vegetation suitability maps: maps that indicate the chance a vegetation type occurs in a certain area. In this way, approved, cutting-edge methods in vegetation science are used to produce suitability maps of the Sinai desert vegetation based on our own data inventory (Hatim et al. 2021) and the different environmental data provided by open-access databases.

Vegetation suitability maps may serve different goals. First, they indicate the potential patterns of the different types of vegetation found in the harsh desert conditions. As the maps are based on models, these models can be adapted, for example, by changing temperature or drought parameters, which makes it possible to predict future changes in vegetation patterns.

Secondly, they are a useful tool for understanding the distribution and potential of different plant species in the area (Thuiller et al., 2008). In the case of the Sinai desert in Egypt, these maps provide information about the areas where certain desert plants are most likely to be found. In this way, vegetation suitability maps may provide information on sites about the potential to be used for different purposes, such as for grazing or the growth of medicinal plants.

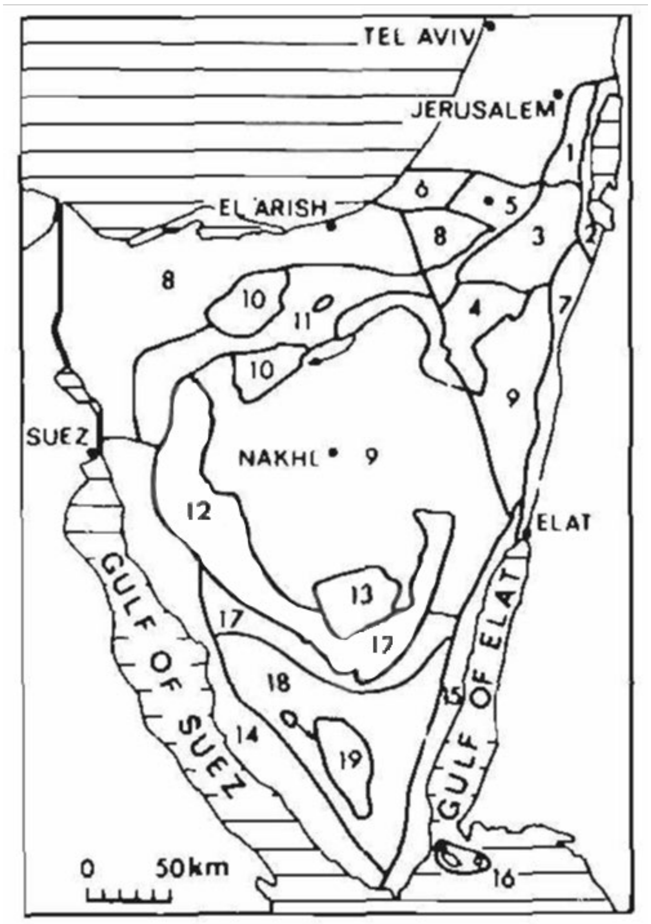

Figure 1. Schematic diagram of 19 geomorphological districts of Sinai (Danin, 1983).

Finally, vegetation suitability maps of the Sinai desert can also help identify areas particularly vulnerable to degradation and desertification, especially in the light of ongoing climatic changes. This is important for conservation and regreening efforts as it can help identify areas that need protection or restoration.

Through these different ways, suitability maps provide information that can be used to plan for sustainable land management in the region and help ensure that the desert ecosystems are protected for future generations. In the present time of the large-scale decline of biodiversity, excessive land use and exploitation, and climate change, we urgently need such information for important but vulnerable regions like the Sinai desert. The results of our study may serve as an improved basis for decision-making in Sinai nature conservation and environmental policy and further in-depth studies on Sinai vegetation.

5.1.1 Study area

The Sinai Peninsula is a triangular plateau in the northeast of Egypt. Bordered by the Mediterranean Sea in the North, it extends south to Ras Muhammad, where the eastern coast of the Suez Gulf meets the western coast of the Aqaba Gulf. The area of the Sinai Peninsula

(61,000 km^2) approximates 6% of that of Egypt. The core of the peninsula is situated near its southern end and consists of high and very rugged igneous and metamorphic rock formations (Fig. 2). The northern two-thirds of the peninsula is characterized by a tremendous northward-draining limestone plateau (El-Tih and Ugma Plateau), which rises from the Mediterranean coast, extends southwards, and terminates in a high escarpment on the northern flanks of the igneous core (Said, 1962). The Sinai Peninsula can be divided into three regions based on these geomorphological features: northern, central, and southern (Fig. 2). The elevation ranges from 0 m to 2,641 m at the highest peak of Saint Catherine mountain (Zahran & Willis, 2009), which forms district 19 of Figure 1.

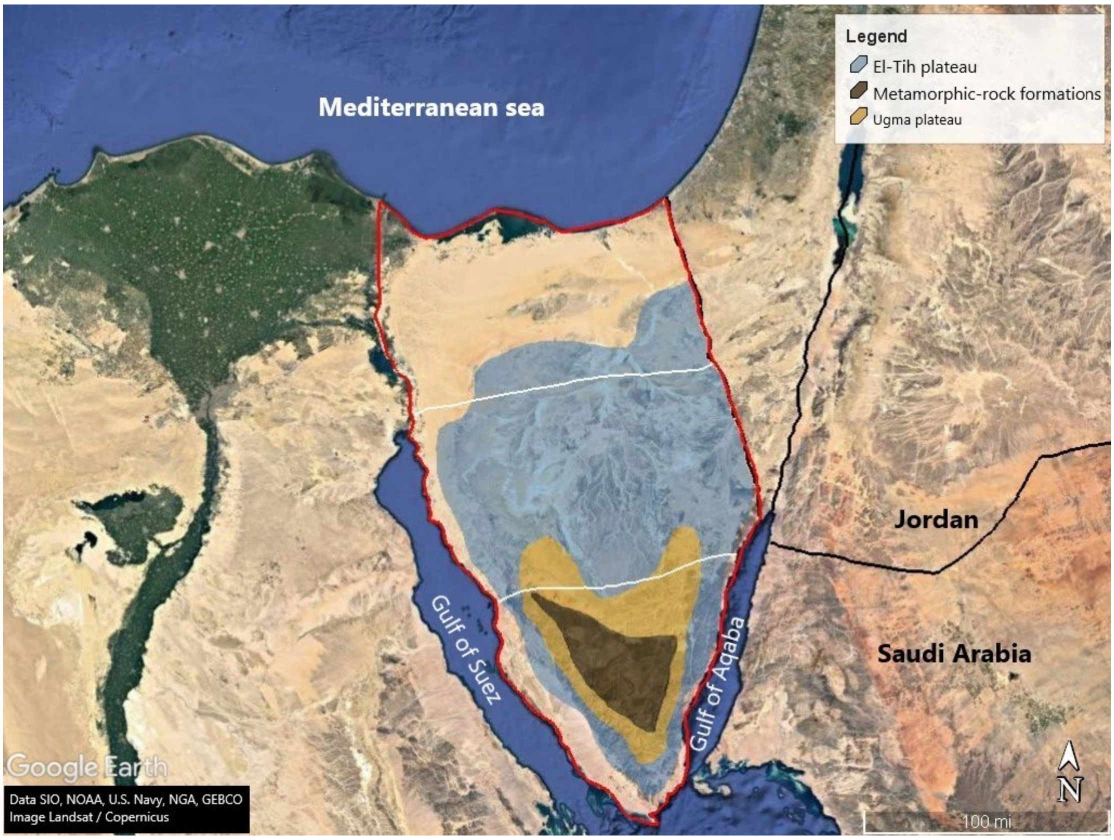

Figure 2. Map of Sinai showing the study area features. The Sinai region is bordered by the red line and divided by the two white lines into three regions, southern, central and northern Sinai (after Hatim et al., 2021). Some geomorphological features are indicated by colours and explained in the legend.

The Sinai Peninsula lies in the junction of three floristic regions: the Saharo-Sindian (which corresponds to Zohary's (1966) Saharo-Arabian region), the Irano-Turanian, and the Mediterranean region (Zahran & Willis, 2009). Most of the species in Sinai have a Saharo-Arabian distribution. Danin & Plitmann (1987) stated that species characterising the Mediterranean region decline from north to south in Sinai. The characteristic species of the Irano-Turanian region are common in the highlands of the Sinai desert. Species from a fourth region, the subtropical Sudanian region, are common in the lowlands of the Southern Sinai (Danin & Plitmann, 1987).

Climatically, the Sinai Peninsula belongs to the Saharo-Arabian region (Ayyad et al. 1986). It is distinguished into an arid zone in the Northern Sinai and a hyperarid zone in the Central and Southern Sinai. The arid zone is characterized by hot summers, mild winters, and rainfall during winter. According to Emberger (1963), this zone is further distinguished into two provinces: (i) the coastal belt province, which is under the maritime influence of the Mediterranean Sea, having relatively short dry period with annual rainfall ranging from 100 to 200 mm, and (ii) the inland province, with a relatively long dry period and annual rainfall of 20 to 100 mm. The hyperarid zone includes the central and southern regions of Sinai. It is further divided into two provinces: (i) the hyperarid province with hot summers, mild winters, and winter rainfall, which includes Central Sinai or the El-Tih Plateau, together with the western and eastern coasts of the Gulfs of Aqaba and Suez, and (ii) the hyperarid province with cold winters and hot summers, which occurs around the Sinai mountains in the southern region (Zahran & Willis, 2009).

Air temperature in Sinai is subject to significant spatial variations. The mean maximum summer temperature ranges from 20 °C at Saint Catherine (Southern Sinai) to more than 50 °C at El-Kuntilla (Central Sinai; Zahran & Willis, 2009). The mean minimum winter temperature ranges from 0 °C at Saint Catherine (Southern Sinai) to 9 °C at Nekhel (Central Sinai), 14 °C at El-Arish (Northern Sinai), 15 °C at El-Tor (Southern Sinai) to 19 °C at Sharm El-Sheikh (Southern Sinai).

The prevailing land use in Sinai is farming, especially in the Southern Sinai. According to Shaltout et al. (2019), the edaphic and moisture conditions in the Saint Catherine region (Southern Sinai) create habitats where farmlands can occur. The farmland vegetation can be found in catchment areas of the surrounding mountains or near Bedouin settlements where groundwater is available (El-Hadidi & Hosny, 2000). Sufficient groundwater, together with the natural protection of the locality against winds, provides suitable conditions for cultivation in many wadis in Southern Sinai (Shaltout et al., 2019). The farms are mainly cultivated with fruit trees and crops (Shaltout et al., 2019). Norfolk et al. (2013) estimated that there are about 600 farms in the Saint Catherine region (Southern Sinai). Bedouins run their farms on the principles of agroforestry, where the smaller orchard trees are widely spaced to grant light reaching the cultivated vegetables, thus giving space to the growth of native desert plant species between the trees (Norfolk et al., 2013). Grazing is an essential component of the land use in Sinai region, closely intertwined with farming and agroforestry practices managed by the Bedouin communities. These indigenous practices of livestock grazing, primarily involving goats and sheep, are sustainably integrated with agriculture, contributing to the ecosystem's health and the Bedouins' livelihoods. Grazing animals feed on natural vegetation and crop residues, aiding in soil fertility through manure deposition, while the mobility of livestock ensures the optimal use of scarce resources in this arid landscape (Alsheikh, 2013).

5.2 Methods

Making suitability maps requires geo-referenced ground data classified in a typology and spatial environmental data as predictive parameters. In a previous study, the desert vegetation of Sinai was described (Hatim et al., 2021), and a classification system was developed to categorize the vegetation into four main groups (M1 - M4) (Table 2) and 25 subgroups (Fig. 3). This classification summarises the diverse vegetation types found in the Sinai Peninsula. Classifying the diversity of vegetation into these distinct groups and subgroups enabled the description of the characteristics, distribution, and ecological significance of each vegetation type in the region (Hatim et al., 2021). This classification provides the framework used for this study, in which we modelled the four main groups.

Table 2. The four main groups of desert vegetation of Sinai (Hatim et. al, 2021).

Main group	Vegetation	Characteristic species
M1	Salt desert	*Tetraena alba*
M2	Lowland desert	*Zilla spinosa*
M3	Mountain desert	*Artimisia herba-album*
M4	Ruderal desert	*Convolvulus arvensis*

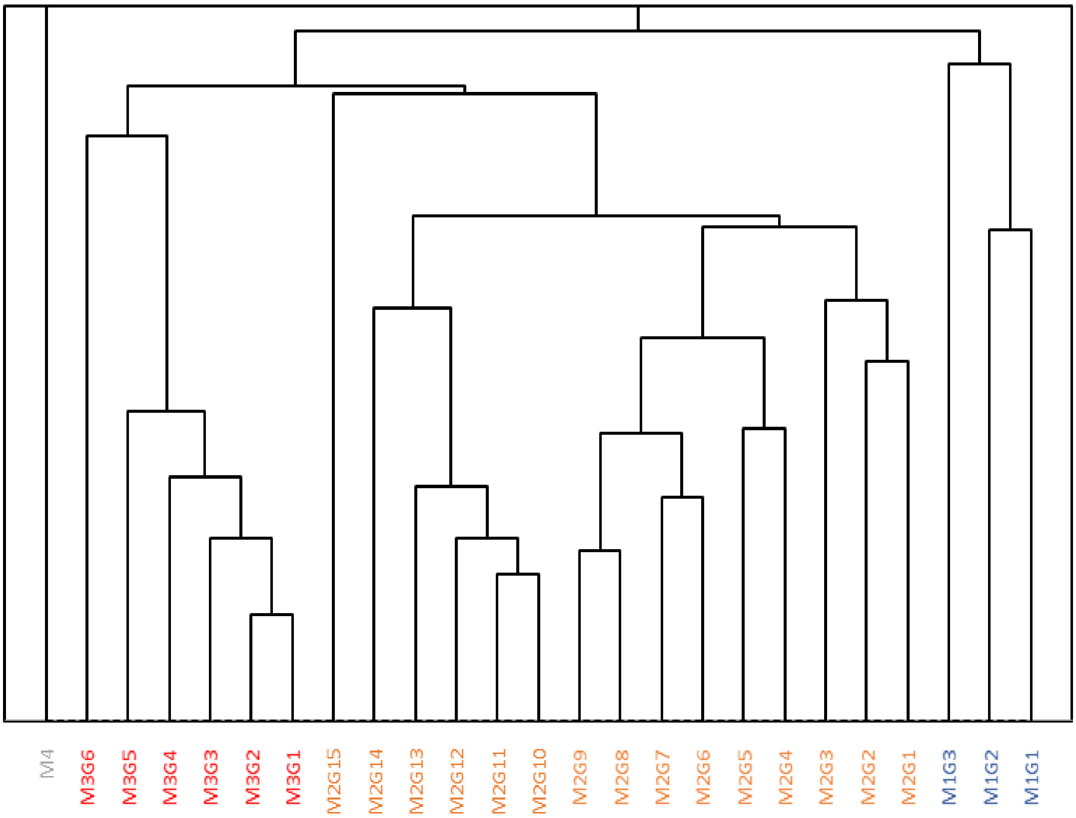

Figure 3. Schematic classification showing the 25 main groups of desert vegetation of Sinai (Hatim et. al, 2021).

Group M1 contains coastal and inland (sand) salt desert vegetation. In group M1 *Tetraena alba*, *Stipagrostis scoparia*, *Panicum turgidum* and *Nitraria retusa,* are amongst the dominant plant species (Hatim et al. 2021). These plant species have evolved mechanisms to tolerate high salinity levels and arid conditions, allowing them to thrive in these specific habitats (El-Bana et al., 2017). Chamaephytes are particularly common in group M1, while most species have a Saharo-Arabian distribution (Hatim et al. 2021).

Group M2 has *Zilla spinosa*, *Fagonia mollis*, *Zygophyllum coccineum* and *Artemisia judaica* as characteristic species, while also many annual species (therophytes) are present (Hatim et al. 2021). Most species are distributed mainly in the Saharo-Arabian region. This is the most diverse main group, consisting of 15 of the 25 distinguished, more detailed vegetation types. It covers vegetation types of lowland habitats, including sand and rock plains and slopes and sandy and rocky wadis.

In Group M3 *Artemisia herba-alba* is a characteristic plant species, together with many characteristic species of mountain desert vegetation of Sinai. The species of M3 have different distribution patterns, and include species from the Saharo-Arabian, Mediterranean, and Irano-Turanian regions (Hatim et al., 2021). The steppic scrub *Artemisia herba-alba* is a species of which the taxonomy is under discussion (Malik et al. 2017; see also chapter 4). Besides steppic communities, also endemic plant communities are found within this main group 3.

According to Hatim et al. (2021), the ruderal vegetation (M4 group) in Sinai is primarily characterized by hemicryptophytes. These plants have adaptations that allow them to persist in disturbed environments.

The study by Hatim et al. (2021) was based on ground data from the Sinai vegetation database, which also formed the source of the ground data in this study: observations with precise coordinates of the different vegetation groups. The database comprises 1,421 plots assigned to the four main groups and 25 more detailed vegetation types as distinguished by Hatim et al. (2021).

For the environmental parameters or the predictors, we selected climatic variables from the 1-km WorldClim 2 (Fick and Hijmans, 2017), soil data, vegetation greenness data, elevation and water bodies data. WorldClim variables were derived using a 1970-2000 climate baseline, remote sensing inputs and spatial interpolation methods. We used monthly averages of precipitation, maximum temperature and minimum temperature (e.g., “prec1” = precipitation, January), and annual averages of 19 bioclimatic variables enumerated in Table 1. 250-m ISRIC gridded soil data were derived from non-linear regression models (Heng et al. 2017). We particularly used seven soil variables listed in Table 1. Additionally, we used the Normalized Difference Vegetation Index (NDVI) derived from MODIS satellite, elevation data from SRTM V3 (Jarvis, 2008) and water bodies from Global Surface Water (Pekel et al., 2016). All datasets were in raster format, set under a common coordinate reference system (UTM Zone 36N, EPSG 32636) and resampled to 250 m pixel size. Further details of the predictors are shown in Table 1. Data access and pre-processing (masking, resampling and projection of rasters) were all implemented in R programming software.

Table 1. List of the environmental data inputs and their key details.

Data category	Name	Units	Description
Climate	bio01	°C	Annual mean temperature
Climate	bio02	°C	Mean diurnal range (mean of monthly (max temp – min temp))
Climate	bio03	%	Isothermality (bio02/bio07)
Climate	bio04	°C	Temperature seasonality (Standard deviation * 100)
Climate	bio05	°C	Max temperature of warmest month
Climate	bio06	°C	Min temperature of coldest month
Climate	bio07	°C	Temperature annual range (bio05-bio06)
Climate	bio08	°C	Mean temperature of wettest quarter
Climate	bio09	°C	Mean temperature of driest quarter
Climate	bio10	°C	Mean temperature of warmest quarter
Climate	bio11	°C	Mean temperature of coldest quarter
Climate	bio12	mm	Annual precipitation
Climate	bio13	mm	Precipitation of wettest month

Climate	bio14	mm	Precipitation of driest month
Climate	bio15	Coefficient of Variation	Precipitation seasonality
Climate	bio16	mm	Precipitation of wettest quarter
Climate	bio17	mm	Precipitation of driest quarter
Climate	bio18	mm	Precipitation of warmest quarter
Climate	bio19	mm	Precipitation of coldest quarter
Climate	tmin (1-12)	°C	Minimum temperature
Climate	tmax (1-12)	°C	Maximum temperature
Climate	prec (1-12)	mm	Precipitation
Soil	ocd	g/dm3	Organic Carbon Density 15-30cm
Soil	cfvo	cm3/dm3	Coarse fragments 15-30cm
Soil	phh20	pH * 10	pH water 15-30cm
Soil	cec	mmol©/kg	Cation exchange capacity (at ph 7) 15-30cm
Soil	sand	g/kg	Sand content 15-30cm
Soil	silt	g/kg	Silt content 15-30cm
Soil	clay	g/kg	Clay content 15-30cm
Elevation	srtm	m	Elevation (meters above sea level)
Vegetation	NDVI	0-1	Greenness index of vegetation
Water	water	0, 1	water and non-water class
Area	sinai_area	0, 1	study area and non-study area class

The map layers used in this study were adjusted to match the specific geographic region of Sinai, using the WSG 84/ UTM zone 36N projection. The maps span a period of 21 years, from 2000 to 2021. To facilitate the modelling process, the map layers (predictors) were clipped to cover the specific study area of Sinai. The resulting map layers were then exported as ASCI files, ensuring they could be easily integrated into the modelling process. These predictors and the coordinates of the vegetation plots were utilized in modelling the suitability maps for desert vegetation using Maxent V. 3.4.

The modelling process involved using 50% of the available ground data for modelling purposes and reserving the other 50% for validation, allowing for a rigorous evaluation of the model's accuracy and predictive capabilities. The Maxent model was employed to predict suitable locations for the vegetation groups. We set the threshold for location suitability at the 10th percentile of training presence, indicating areas with environmental conditions that match or exceed those where a group is most commonly found. This conservative threshold helps to focus on more confidently suitable habitats.

For the future climate change scenarios, we used Geographic Information System (GIS) techniques and remote sensing data to model the distribution of the main vegetation groups (M1-3) in the Sinai desert using Maxent V. 3.4. We excluded the M4 group from the modelling because we are interested in the zonal vegetation groups for the climate change scenarios. The data retrieved represent two distinct periods: 1970-2000 and 2021-2040. The data was retrieved from WorldClim 2 (Fick and Hijmans, 2017) for the current and future scenarios. For the future climate change scenario, we used the environmental data resulted from the MPI-ESM-LR Global Climate Model (GCM), as Kheireldin et al., (2020) concluded it is the more suitable model for predicting climate change parameters.

To produce the suitability maps, we first processed the environmental parameters (predictors), namely precipitation, minimum temperature, and maximum temperature, to match the spatial resolution and extent of our study area. The environmental variables were then analyzed using a species distribution modelling approach, which correlates known occurrences of vegetation with environmental variables to predict its distribution across the landscape. The modelling process involved the calibration of the model with historical data to accurately reflect the current distribution of the main vegetation groups, followed by the application of future climate scenarios to project changes in vegetation patterns. The output maps were then generated, with red pixels indicating the predicted presence of the main vegetation groups, allowing for a direct comparison between the historical and future distribution patterns.

5.3 Results and discussion

5.3.1 Modelling Suitability Maps

The produced suitability maps together do not cover the whole Sinai area. This may be the effect of the threshold values in the modelling process or it might be due to the presence of many regions in Sinai bare of vegetation.

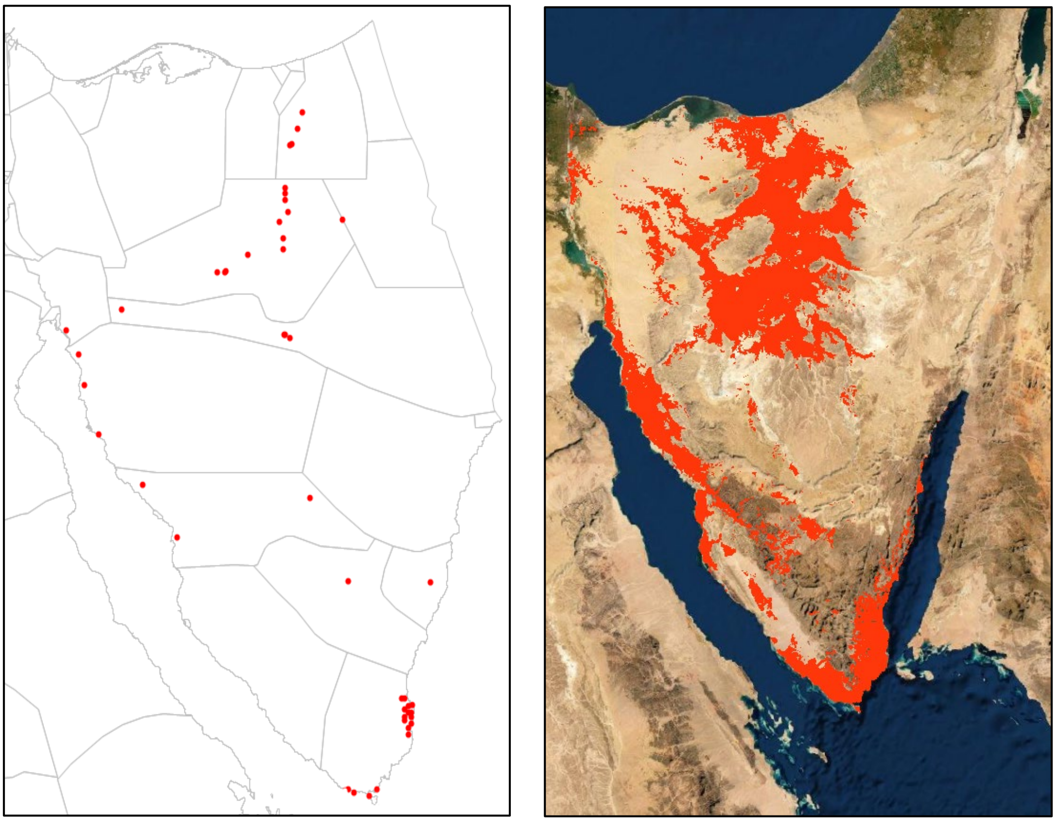

Figure 4. Maps showing the actual distribution of the relevés of M1 main group (on the left) and the predicted distribution of them (Suitability maps on the right).

According to the suitability map of main group M1, representing salt desert vegetation(Fig. 4), we found that the mean temperature of the coldest quarter plays a significant role in shaping the distribution patterns of the vegetation. Temperature plays a vital role in determining the suitability of certain areas for specific plant species (Suttle et al., 2007), and this is especially an issue in desert regions. Different plants have varying temperature requirements for optimal growth and survival, leading to variations in their distribution across the study area. Additionally, the pH of water at a depth of 15-30 cm was identified as an important parameter that influences the plants of the M1 group to thrive in specific areas. pH levels can affect the availability and uptake of essential nutrients by plants, ultimately influencing their growth and adaptation (Marschner, 2011). The variations in pH levels can create different microenvironments, favouring the establishment of particular plant species adapted to specific pH conditions (Marschner, 2011). Besides, the pH-value is strongly related to salinity, and this may be one of the dominant factors for group M1. Unfortunately, for soil salinity no spatial data were available.

The suitability map for lowland desert vegetation (main group M2) is shown in Figure 5. We found that annual precipitation was a crucial parameter affecting this vegetation pattern. Water availability through precipitation plays a vital role in determining the suitability of certain areas for specific plant species (Falkenmark & Rockström, 2006). Different plants have varying water requirements and adaptations to arid conditions, leading to variations in their distribution patterns across the study area (Falkenmark & Rockström, 2006). Group M2 was mapped in areas with low precipitation. Furthermore, the minimum temperature of the coldest month was a significant predictor.

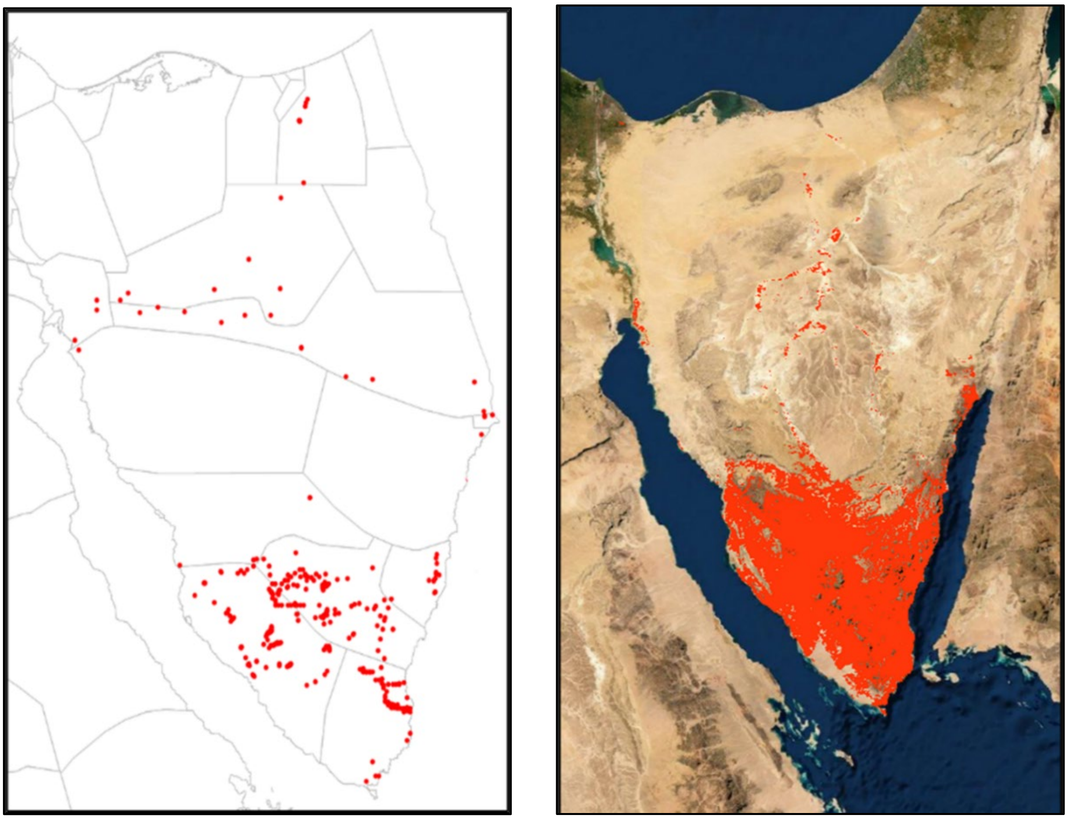

Figure 5. Maps showing the actual distribution of the relevés of M2 main group (on the left) and the predicted distribution of them (Suitability maps on the right).

In the third suitability map (Fig. 6), we predict the distribution of mountain desert vegetation (main group M3). The mean temperature of the driest quarter emerged as a critical parameter shaping the vegetation patterns. The temperature during the driest quarter is a crucial factor that influences the survival and growth of plant species in arid environments (Körner, 1999). Different plant species have varying temperature tolerances, which result in distinct vegetation patterns across the study area (Körner, 1999). Additionally, elevation played a significant role in mapping group M3. In the dry Sinai region, elevation is strongly related to precipitation and temperature (Qin et al., 2001), the first increasing with altitude, the latter decreasing.

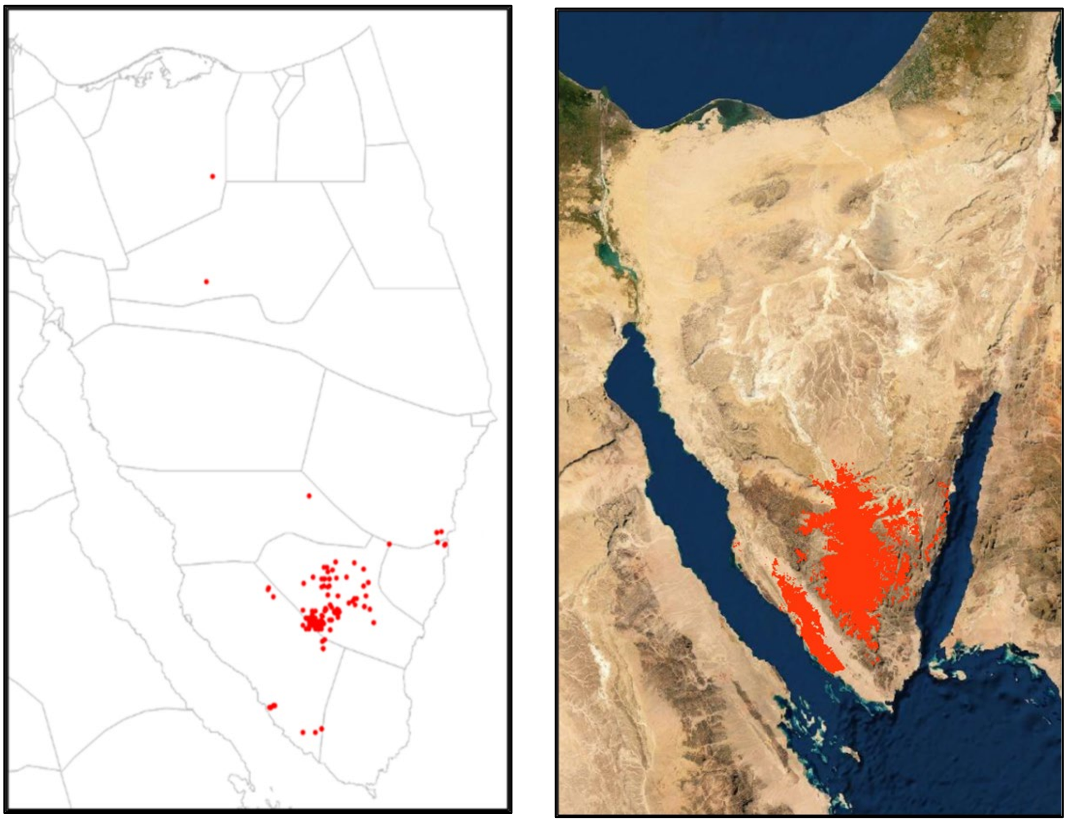

Figure 6. Maps showing the actual distribution of the relevés of M3 main group (on the left) and the predicted distribution of them (Suitability maps on the right).

Figure 7 shows the suitability map for the main group M4, which comprises ruderal plant communities, associated with grazing areas and farmland. *Convolvulus arvensis* is a characteristic plant species within the ruderal vegetation of Sinai (Hatim et al. 2021). Elevation is a crucial factor in this pattern. Different elevations in Sinai exhibit distinct plant communities due to variations in environmental conditions such as temperature, precipitation, and soil characteristics (Hatim et al., 2021). Apparently, the higher elevated areas, with higher precipitation and lower temperature, are most suitable for farming.

The analysis indicates that precipitation during the warmest quarter is a crucial factor for the ruderal vegetation of the Sinai region. This relationship is indirect; higher elevations often receive more precipitation, making the land more suitable for agricultural practices and grazing. The dataset for this main group is somewhat limited, as illustrated in Figure 7, where relatively few ground samples were available, potentially affecting the robustness of the analysis for this group.

5.3.2 Modelling Future Climate Change Scenarios

The modelling process revealed a change in the distribution of the main vegetation groups (M1-3) in the Sinai region over two distinct periods: 1970-2000 and 2021-2040 (Figures 8, 9 and 10). The red pixels represent the presence and density of these vegetation groups, providing a visual quantification of the spatial distribution and potential shifts due to climatic and environmental changes over 50 years.

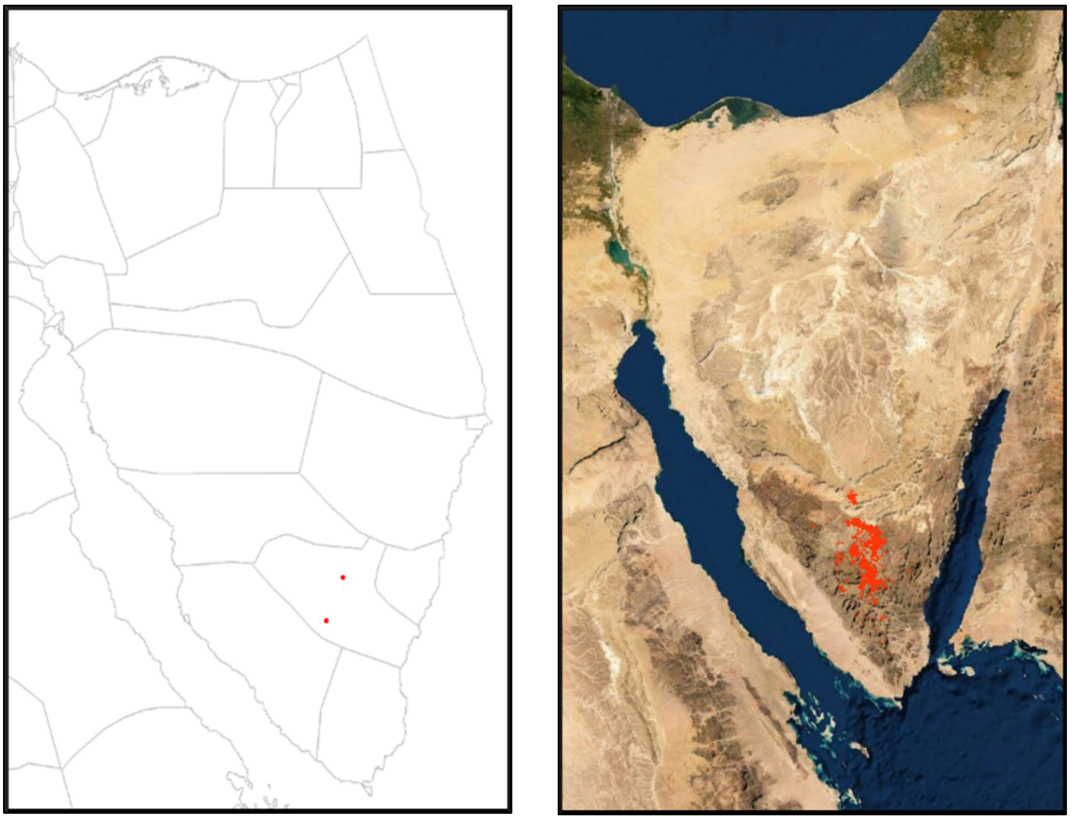

Figure 7. Maps showing the actual distribution of the relevés of M3 main group (on the left) and the predicted distribution of them (Suitability maps on the right).

During 1970-2000, the M1 group (salt desert vegetation) exhibited a widespread distribution across the Sinai, as indicated by the red pixels in the left image. The coverage appears dense in certain areas, suggesting that these locations offer the most suitable conditions for M1 vegetation.

Projecting into the future , the right image for the same M1 group shows a different scenario. The red pixels are significantly reduced in number and are more fragmented, indicating a contraction in the distribution of this vegetation group. This suggests that the changing climatic conditions between the two periods become less favourable for M1, due to decreased precipitation, increased temperatures, and possibly other environmental drivers.

Similarly, the M2 (lowland desert vegetation) and M3 (mountain desert vegetation) groups exhibit notable changes when comparing the left images (1970-2000) and the right images (2021-2040). While M2 shows a lesser reduction and fragmentation than M1, indicating a degree of resilience or adaptability to changing conditions, M3 distribution appears to be the least affected of the three groups. This relative stability could be the result of the M3 group being located in montane areas, which apparently are less affected by climate change (Dhimal et al., 2021). The variety of microclimates, created by complex topographies in the mountainous regions, offers diverse habitats that can shelter species from broad climatic shifts (Chen et al., 1999). Additionally, the altitudinal gradient present in mountains facilitates species migration to higher elevations, allowing them to escape higher temperatures. The natural isolation and resulting adaptations of mountain flora, including tolerance to variable conditions and ecological niche specialization, further enhances their ability to withstand climate change (Kumar & Vats, 2017).

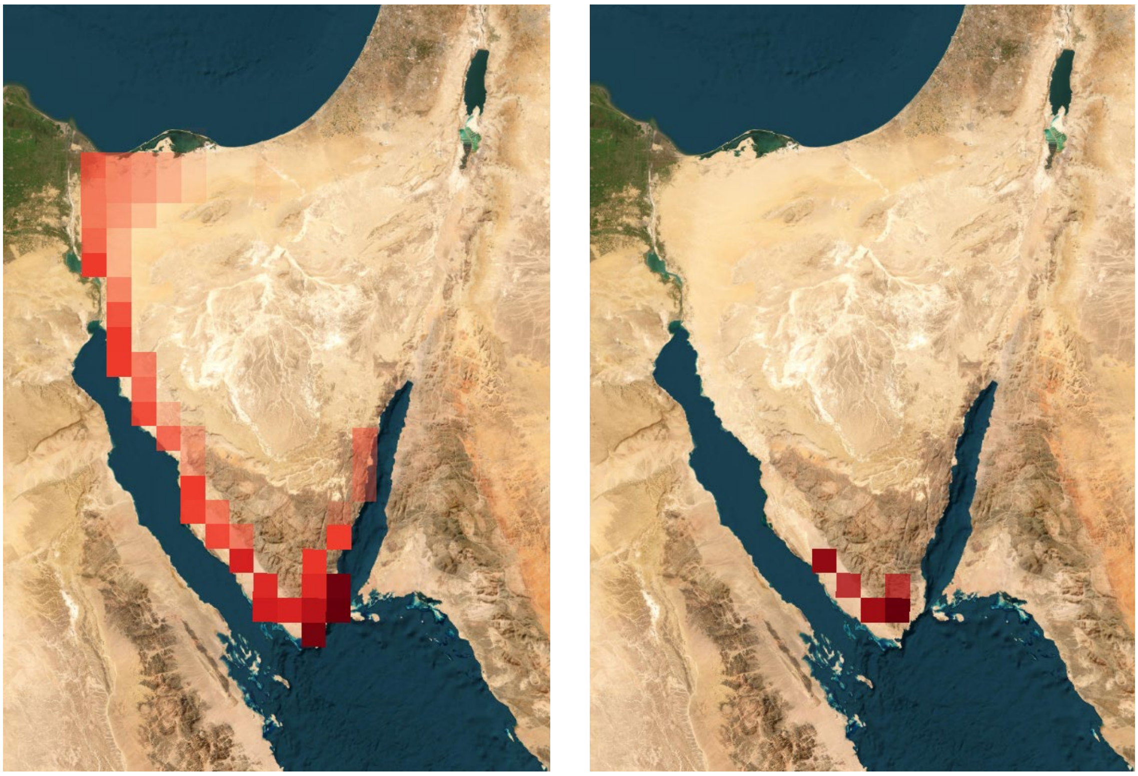

Figure 8. Maps showing distribution of Vegetation Group M1 in the Sinai, contrasting the modelling outcome showing historical (1970-2000, left) with projected future coverage (2021-2040, right).

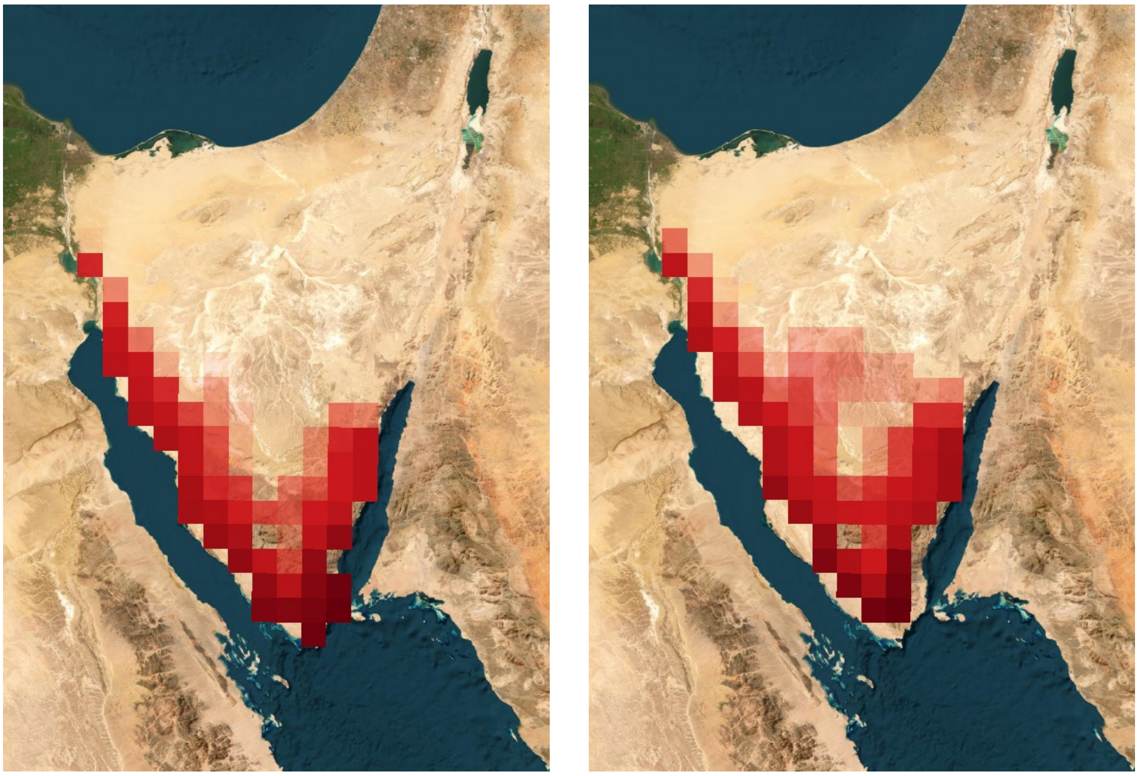

Figure 9. Maps showing distribution of Vegetation Group M2 in the Sinai, contrasting the modelling outcome showing historical (1970-2000, left) with projected future coverage (2021-2040, right).

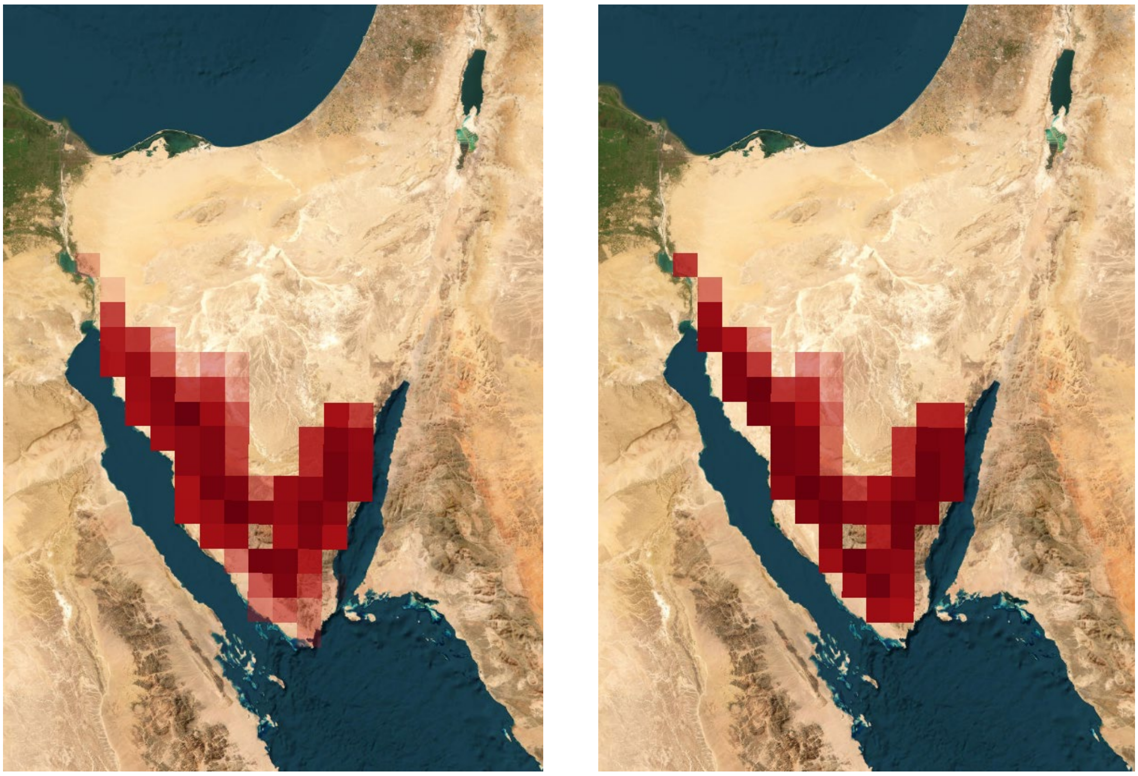

Figure 10. Maps showing distribution of Vegetation Group M3 in the Sinai, contrasting the modelling outcome showing historical (1970-2000, left) with projected future coverage (2021-2040, right).

5.4 Conclusions

The study aims to develop distribution maps of the Sinai desert vegetation by modelling the relationship between ground samples and explanatory variables on climate, soil, vegetation productivity, elevation and water bodies. The findings revealed valuable insights into the distribution patterns and ecological characteristics of the four main vegetation groups (M1-M4) in Sinai and allowed the modelling of potential vegetation changes based on changing climate and land use.

For the M1 main group (inland and coastal saline desert), the mean temperature of the coldest quarter and water pH at a depth of 15-30 cm were identified as crucial factors shaping vegetation patterns. It is likely that pH is strongly related to the salinity of the soil, as the vegetation is indicative of saline or brackish soils (Hatim et al. 2021). Unfortunately for the soil salinity, no predictive environmental maps were available. In the case of the M2 main group, lowland desert vegetation, annual precipitation, and the minimum temperature of the coldest month were found to influence vegetation patterns significantly. This is the most diverse of the four main groups, and therefore the most relevant one for further exploring of the subtypes. The distribution of M3 main group, representing mountain desert vegetation, is strongly determined by the mean temperature of the driest quarter and by elevation. Finally, for the M4 main group, elevation and precipitation during the warmest quarter played significant roles in shaping vegetation patterns. The suitability maps of the Sinai desert vegetation provide valuable information for conservation efforts and land management in the region. Based on the findings, the following recommendations are proposed:

(i) To identify and protect areas with high vegetation suitability to preserve the unique desert ecosystems of Sinai. These areas should be prioritized for conservation efforts and restoration projects to prevent degradation and desertification.

(ii) Together with the findings of chapter 2, the information from vegetation suitability maps can be utilized to develop sustainable land management practices in Sinai. This includes identifying areas suitable for grazing and the potential cultivation of medicinal plants. By implementing appropriate land management strategies, the region's resources can be utilized while ensuring the long-term sustainability of the desert ecosystem.

The comparative analysis of modelling the distribution of vegetation groups M1, M2, and M3 over the periods 1970-2000 and 2021-2040 reveals a sad picture of the impact of climate change on desert ecosystems. The marked reduction and fragmentation in the distribution of the salt desert vegetation (M1) are indicative of a continuously changing environment, likely driven by reduced precipitation and elevated temperatures. Although displaying greater resilience, the lowland desert vegetation (M2) is not immune to these changes, suggesting a potential threshold of adaptive capacity that could be tested as climate change progresses. With its relative distribution stability, the mountain desert vegetation (M3) highlights the complex interplay between topography, microclimate, and vegetation resilience. However, it is crucial to recognize that the observed stability does not guarantee immunity to future climatic extremes. These predictions ensure the urgent need for conservation strategies that boost the resilience of these ecosystems, safeguarding their ecological functions and the services they provide to local communities. The continued observation and modelling of these vegetation groups will be essential in anticipating and mitigating the adverse effects of ongoing climate change.

The insights gained from modelling vegetation distribution are highly relevant to the efforts to regreen the Sinai desert, like Lake Bardawil and Sinai Regeneration Initiative (The Weather Makers, 2022). The detailed understanding of how the distribution of vegetation groups has changed over time allows for a strategic approach to restoration and conservation. Specifically, the data can guide selecting sites where regreening efforts will likely be most successful and sustainable.

For instance, areas where the salt desert vegetation (M1) was once prevalent but is now showing signs of reduction, could be targeted for soil improvement and the introduction of salt-tolerant plant species that can thrive under current and projected future conditions. The resilience of the lowland desert vegetation (M2) suggests that these areas could serve as strongholds for biodiversity and could be prioritized for establishing protected areas or implementing sustainable land management practices.

Moreover, the relative stability of the mountain desert vegetation (M3) allows for exploring these regions as potential refugia for species that are losing their habitats at lower elevations due to climate change. These areas could be key in preserving genetic diversity and serving as seed sources for regreening efforts in surrounding regions.

Incorporating the modelling results into regreening projects also makes these initiatives more adaptive. By understanding the specific conditions that each vegetation group requires, regreening projects can implement adaptive management strategies that can be adjusted over time as conditions change. This could include using drought-resistant species, changing planting strategies as rainfall patterns shift, or even using technology to create microclimates supporting more diverse vegetation.

The predictive modelling of vegetation group distribution under future climate scenarios ultimately provides a roadmap for regreening efforts in the Sinai desert. It offers a scientific basis for making informed decisions that aim not only to restore vegetation but to do so in a way that anticipates and mitigates the impacts of climate change, ensuring the long-term success of these regreening efforts.

6

General Discussion

6.1 Background

The Saharo-Arabian region, encompassing the vast deserts of North Africa and the Arabian Peninsula, represents one of the most extreme and biodiverse arid landscapes on earth (Hoelzmann et al., 2001). This thesis provides a comprehensive understanding of the plant communities within this region, focusing on their distribution in relation to environmental and landform conditions. By identifying diverse plant communities, analyzing their floristic composition and structure, and exploring how different environmental factors and landforms influence vegetation patterns, this study significantly advances our knowledge of ecological interactions in arid environments.

The importance of this research extends beyond the geographical boundaries of the study area, contributing to our understanding of arid ecosystems, which cover approximately one-third of the earth's land surface (Reynolds et al., 2007). As climate change continues to alter precipitation patterns and temperature regimes worldwide, the insights gained from this study of desert vegetation dynamics and adaptations become increasingly relevant to other regions experiencing aridification (Huang et al., 2016).

The Saharo-Arabian region plays a crucial role in global climate systems, and its vegetation has far-reaching effects. One of the most significant impacts is the production and transport of mineral dust. The sparse vegetation cover in many parts of the Sahara makes it the world's largest source of atmospheric dust, with annual emissions estimated at 500-1000 million tons (Goudie & Middleton, 2001). This dust transport has multiple global implications, including nutrient cycling even in distant ecosystems like the Amazon rainforest, climate regulation through effects on the earth's radiation balance, and impacts on marine ecosystems in the Atlantic Ocean (Yu et al., 2015; Kok et al., 2018; Jickells et al., 2005).

The study's findings on vegetation responses to climate change in the Saharo-Arabian region have particular relevance for Europe. The proximity of North Africa to southern Europe means that ecological changes in the Sahara can directly impact European environments, affecting biodiversity (particularly migratory birds), climate modulation, and the potential spread of invasive species (Vickery et al., 2014; Prospero & Lamb, 2003; Walther et al., 2009).

Moreover, this research contributes to global biodiversity conservation efforts by highlighting the ecological value of desert flora and identifying strategies to protect these vulnerable ecosystems from the threats posed by climate change and human activities (Nathaniel et al., 2020). The detailed vegetation mapping and future projections provided by this study can inform conservation strategies and adaptive management practices not only in the Saharo-Arabian region but also in other arid areas globally.

The methodologies and findings of this study contribute to our understanding of how arid ecosystems might respond to global environmental change. This is crucial as many regions worldwide are predicted to experience increased aridity due to climate change (Huang et al., 2016). The vegetation classification and distribution modelling approaches used in this study can be adapted and applied to other arid regions, facilitating global comparisons and synthesis of desert ecology research.

Furthermore, the study's insights into plant adaptations to extreme environments in the Saharo-Arabian region have potential applications in agriculture and biotechnology. As global food security faces challenges from climate change, understanding how desert plants cope with water scarcity and high temperatures could inform the development of more resilient crop varieties (Mickelbart et al., 2015).

6.2 Outline of the thesis

This thesis presents a comprehensive exploration of desert vegetation in North Africa and the Middle East through four interconnected chapters, each addressing specific aspects, scales, and regions.

Chapter 2 focuses on the Sinai desert in Egypt, a global flora hotspot, providing an in-depth phytosociological overview of its vegetation. Utilizing robust vegetation plot data from literature and field surveys, the chapter employs advanced analytical methods, including modified TWINSPAN, Hopkins' test, and the Silhouette algorithm. The analysis results in the identification of nine main vegetation classes and 25 groups, revealing significant diversity in life forms and chorotypes. Significant findings include:

- The identification of salt desert, lowland desert, mountain desert, and ruderal vegetation as main groups;
- The dominance of therophytes (41.8%) and chamaephytes (28.8%) in life forms;
- The prevalence of Saharo-Armenian (33.6%) and Mediterranean (22.4%) chorotypes;
- The distinction of seven new plant communities not previously described in the literature.

Chapter 3 extends the research to the Hijaz Mountains' foothills and adjacent coastal zones in Saudi Arabia, an underexplored region of floristic interest. The study, conducted along coastal and inland transects, identifies seven distinct plant communities, further classified into three vegetation clusters based on latitude and altitude variations. Significant findings include:

- The dominance of therophytes in the life-form spectrum;
- The prevalence of Saharo-Arabian, Sahel-Sudano-Zambezian, and Tropical African chorotypes;
- The identification of annual precipitation and minimum temperature of the coldest month as key factors influencing vegetation patterns;
- The observation that mountain vegetation shows greater resilience to environmental changes.

Chapter 4 broadens the scope to a comprehensive examination of the Saharo-Arabian region, the world's largest hot desert. This chapter addresses the syntaxonomical systems of desert vegetation, employing sophisticated techniques to categorize the vegetation into distinct classes and lower syntaxa. Significant findings include:

- The identification of 15 main groups encompassing 55 vegetation types;
- The development of a preliminary syntaxonomical scheme for the region;
- The recognition of the role of environmental factors such as temperature extremes, precipitation patterns, and topography in shaping vegetation distribution;
- The identification of potential climate refugia in mountainous areas.

Chapter 5 applies the data from previous chapters to predict future vegetation patterns in the Sinai desert under climate change scenarios. This modelling approach creates suitability maps and forecasts vegetation trends. Significant findings include:

- Projected reduction and fragmentation in the distribution of salt desert vegetation and lowland desert vegetation;
- Greater resilience observed in mountain desert vegetation;
- The identification of elevation and precipitation during the warmest quarter as crucial factors for ruderal vegetation;
- The potential for significant shifts in vegetation distribution over the next few decades.

Each chapter contributes to a comprehensive understanding of desert ecosystems, integrating insights crucial for the conservation and ecological management of these unique landscapes. The thesis highlights the complex interplay between environmental factors, human activities, and plant adaptations in determining desert vegetation patterns. It also underscores the vulnerability of these ecosystems to climate change and anthropogenic disturbances, while identifying areas of resilience and potential conservation importance.

6.3 What is desert vegetation?

Historically, the definition of desert vegetation has evolved alongside our understanding of arid ecosystems. In the early 20th century, desert vegetation was often simplistically characterized as sparse, water-stressed plant communities in areas receiving less than 250 mm of annual precipitation (Shreve, 1942). This definition, while useful for broad classifications, failed to capture the complexity and diversity of plant life in arid regions.

As ecological research progressed, definitions of desert vegetation became more nuanced. Evenari et al. (1985) emphasized the importance of not just precipitation but also its distribution and frequency, as well as temperature extremes, in defining desert environments and their associated vegetation. They highlighted that desert vegetation is characterized by adaptations to water scarcity, such as deep root systems, reduced leaf surface area, and specialized photosynthetic pathways (C4 and CAM).

In recent decades, the definition of desert vegetation has expanded to include consideration of spatial heterogeneity and temporal variability. Noy-Meir (1973) introduced the concept of ‘pulse-reserve’ dynamics in desert ecosystems, where vegetation responds rapidly to infrequent rainfall events. This understanding has led to definitions that emphasize the dynamic nature of desert vegetation and its resilience to extreme variability in resource availability.

In the context of this thesis, particularly drawing from the phytosociological survey presented in Chapter 4, desert vegetation in the Saharo-Arabian region is defined more comprehensively. It is characterized not just by aridity, but by a complex interplay of environmental factors, including temperature extremes, soil characteristics, topography, and human influences. The classification into 15 main groups and 55 types reflects this complexity, acknowledging that desert vegetation comprises a mosaic of distinct communities adapted to specific local conditions (Hatim et al., 2021).

This thesis adopts a definition of desert vegetation that recognizes its diversity and adaptability. For instance, it includes not only the typical xeric communities of sandy and rocky deserts (ergs and hamadas) but also specialized vegetation types such as salt-tolerant communities in coastal and inland saline areas, mountain vegetation at higher elevations, and even ruderal communities associated with human disturbance (Hatim et al., 2021).

Furthermore, the thesis expands the definition of desert vegetation to include its dynamic nature in response to environmental changes. As evidenced by the modelling of future climate scenarios in Chapter 5, desert vegetation is not static but rather in a state of continuous adaptation to changing conditions. This perspective aligns with modern ecological thinking that views ecosystems as dynamic entities rather than fixed assemblages (Pickett et al., 2009).

The definition also incorporates the concept of functional diversity within desert vegetation. Rather than focusing solely on species composition, it considers the various ecological roles and adaptations of plants in these arid environments. This includes the range of life forms (from annual herbs to perennial shrubs and trees), physiological adaptations (e.g. drought tolerance mechanisms), and ecological strategies (e.g. rapid growth during brief wet periods) (Ward, 2016).

6.4 Changes in the Vegetation of the Saharo-Arabian Region

The Saharo-Arabian desert region has experienced significant changes in vegetation cover and composition over geological and historical timescales. As discussed in Chapter 4, , the current vegetation patterns are the result of long-term climatic and anthropogenic influences.

During the Holocene, particularly between 11,000 and 5,000 years ago, the region experienced the ‘African Humid Period’, characterized by increased rainfall and more extensive vegetation cover (Demenocal et al., 2000). Palynological and archaeological evidence suggests that much of what is now desert was savanna or grassland during this period, supporting diverse plant communities that likely included species of *Vachellia* (= *Acacia*) and various grasses (Kroepelin et al., 2008).

The transition to current arid conditions occurred gradually over several millennia, driven by orbital forcing that altered monsoon patterns, leading to a progressive decrease in precipitation (Claussen et al., 1999). As aridity increased, there was a marked shift in vegetation composition, with drought-tolerant species becoming increasingly dominant. This shift is reflected in the vegetation classifications presented in Chapter 4, which identify numerous plant communities adapted to arid conditions.

In more recent history, human activities have played an increasingly significant role in shaping the vegetation of the Saharo-Arabian region. As noted in Chapters 2 and 3, which focus on the vegetation of Sinai in Egypt and the Hijaz Mountains in Saudi Arabia respectively, the introduction of domesticated animals, particularly goats and camels, has profoundly impacted plant communities through grazing pressure and trampling (Le Houérou, 1996). This has led to the reduction of palatable species and the propagation of unpalatable or thorny plants in many areas, such as *Zilla spinosa* and various *Astragalus* species (Batanouny, 1983).

Agricultural practices, particularly in oases and along wadis, have also altered local vegetation patterns. The introduction of non-native species for agriculture and landscaping has changed the composition of plant communities in some areas, sometimes leading to the displacement of native species (El-Keblawy & Al-Rawai, 2007). This is particularly evident in the ruderal vegetation communities, as identified in Chapter 2, which include species like *Convolvulus arvensis* and *Cynodon dactylon*.

In the 20th and 21st centuries, climate change has emerged as a significant driver of vegetation change in the region. As demonstrated in Chapter 5, which presents suitability maps and future climate scenarios, rising temperatures and altered precipitation patterns have led to shifts in the distribution of plant species and communities. The models predict a reduction and fragmentation in the distribution of salt desert vegetation, dominated by species like *Haloxylon salicornicum*, and, to a lesser extent, lowland desert vegetation, which includes wadi communities dominated by *Vachellia* species. Mountain desert vegetation, characterized by species such as *Artemisia herba-alba* s.l. and *Teucrium polium*, shows greater resilience (Hatim et al., 2021).

Anthropogenic factors continue to play a significant role in vegetation change. As discussed in Chapters 2, 3, and 4, urbanization, infrastructure development, and resource extraction have led to habitat fragmentation and loss in some areas (Lambin et al., 2001). Conversely, conservation efforts and regreening initiatives in some parts of the region aim to restore native vegetation and combat desertification (Reij & Garrity, 2016). These efforts often focus on replanting native species such as *Vachellia tortilis* and *Panicum turgidum*.

The cumulative effect of these changes over time has been a general trend towards increased aridity and reduced vegetation cover across much of the Saharo-Arabian region, with local variations due to topography, human activities, and conservation efforts. However, as emphasized in the conclusions of Chapters 4 and 5, desert ecosystems are dynamic and resilient, and some plant species have shown remarkable adaptability to changing conditions. For example, species like *Zygophyllum simplex* and *Fagonia indica* have demonstrated the ability to thrive in a wide range of desert habitats (Ward, 2016), while many annual species may survive as seeds for long periods and reappear suddenly after rains.

Understanding these historical and ongoing changes, as synthesized across all chapters of this thesis, is crucial for predicting future trends and developing effective strategies for conservation and sustainable land management in this unique and challenging environment. The recommendations provided in the final chapter emphasize that long-term monitoring programs and continued research into plant adaptations and community dynamics will be essential for informing these efforts in the face of ongoing climate change and human pressures (Sala et al., 2000). This includes studying the responses of key species such as *Haloxylon salicornicum*, *Vachellia tortilis*, and *Artemisia herba-alba* s.l. to changing environmental conditions.

6.5 Insights from the syntaxonomical review

The phytosociological survey of the Saharo-Arabian desert region, as presented in this thesis, reveals a complex hierarchical structure of vegetation units, reflecting the diverse ecological conditions of the area. The classification system, following the Braun-Blanquet approach, identifies several classes, orders, alliances, and associations, each representing distinct ecological conditions and vegetation types.

One of the prominent classes identified is the *Halopeplido-Suaedetea* Knapp 1968, which represents halophytic vegetation communities. This class is typically found in coastal areas and inland salt flats, indicating environments with high soil salinity (Hatim et al., 2021). The presence of this class underscores the importance of salt-tolerant plant communities in the Saharo-Arabian region, which play a crucial role in stabilizing saline soils and providing habitat for specialized fauna (Zahran & Willis, 2009). The class *Nerio-Tamaricetea* Br.-Bl. et O. de Bolòs 1958, dominated by *Tamarix* species, is a second class of brackish and saline soils, which occurs in a wider area than the desert region.

The mountain vegetation in the Saharo-Arabian region is represented by several (near) endemic classes, which encompass isolated plant communities adapted to high-altitude rocky habitats. The class *Chiliadenetea iphionoidis* Zohary 1955 ex Danin et Solomeshch 1999 is restricted to mountainous areas of the Sinai Peninsula, characterized by cooler temperatures and higher precipitation compared to surrounding lowlands (Hatim et al., 2021). In the Hoggar and Tibesti mountains of the Central Sahara the classes *Lavanduletea antineae* Quézel 1965 and *Helianthemo-Paronychietea* Quézel 1965 are described for endemic plant communities in high-altitude and rocky habitats, while in Saudi Arabia the *Juniperus* scrubs of the higher and relatively moist habitats dominate northern outliers of a (sub)tropical class *Juniperetea procerae* Zohary 1973. The presence of endemic species within these communities underscores the importance of mountain habitats as centers of plant diversity and endemism in arid regions (Moustafa & Zaghloul, 1996). These mountain vegetation types play a crucial role in soil stabilization on steep slopes, water retention, and providing unique habitats for specialized fauna, thus contributing significantly to the overall biodiversity and ecosystem functioning of the Saharo-Arabian region (Ward, 2016).

A significant class in the desert lowlands is the *Retametea raetam* Eig 1939, which encompasses various psammophytic communities adapted to sandy desert conditions. This widespread class is particularly important in dune stabilization and as an indicator of less extreme desert conditions where some drought-resistant shrubs can thrive (Danin, 1983). In more extreme arid conditions, the class *Anabasietea articulatae* Zohary 1952 ex Danin et Solomeshch 1999 (synonym: *Haloxylonetea salicornici* Zohary 1955) is prevalent. This class, typically found in sandy soils, represents highly drought-resistant plant communities adapted to survive in areas with minimal precipitation and high temperatures (Danin & Orshan, 1999). The low desert vegetation of stony and gravelly plains, slopes and wadis (ergs, hamadas) is represented by two classes, the *Asterisco graveolentis-Forsskaoletea tenacissimae* Quézel 1954 from the Sahara, and the class *Pergulario tomentosae-Pulicarietea crispae* Quézel 1965 which is restricted to Morocco.

The identification of the *Acacietea tortilis* Knapp 1968 class is particularly noteworthy, as it represents the desert savanna ecosystems. This class, associated with wadis and other areas with occasional water accumulation, plays a crucial ecological role in providing habitat for a diverse range of desert fauna and contributing to soil stabilization in these harsh environments (Kürschner, 1998). It is likely that the communities of this class form relict vegetation of the more widespread savanna at the beginning of the Holocene.

The class *Artemisietea sieberi* Zohary 1952 ex Danin et Solomeshch 1999, represented by communities dominated by steppe species, indicates areas with a slight increase in moisture availability, often found in the transition zones between true desert and steppe regions (Zohary, 1973). This class of steppe plant communities is ecologically significant as it often represents areas where pastoralism is practiced, highlighting the interface between natural vegetation and human land use in arid regions.

On the northern edges of the study area plant communities were found that belong to the Mediterranean shrub class *Ononido-Rosmarinetea* Br.-Bl. in O. Bolos y Vayreda 1950 and the steppe class *Lygeo sparti-Stipetea tenacissimae* Rivas-Martinez 1978.

In oases and other water bodies vegetation of widespread wetland classes were encountered, belonging to the classes *Phragmito-Magnocaricetea* Klika in Klika et Novák 1941 and *Isoëto-Nanojuncetea* Br.-Bl. et Tx. in Br.-Bl. et al. 1952 and.

Finally, the strongly human influenced communities on farmland and other heavily grazed sites are considered part of the worldwide ruderal plant communities of the class *Chenopodietea* Br.-Bl. in Br.-Bl. et al. 1952.

The recognition of these syntaxonomic units is not merely a classificatory exercise but provides valuable insights into the ecological functioning of desert ecosystems. Each class, order, and alliance represents a unique set of environmental conditions and plant adaptations. For instance, the presence of certain alliances can indicate specific soil conditions, microclimatic variations, or particular disturbance regimes. The overview of classes indicates the main species diversity which is the result of climate, environment and land use, and – specifically in the high-mountain, plant species dispersal abilities.

Furthermore, this hierarchical classification allows for a better understanding of vegetation dynamics and potential responses to environmental changes. For example, shifts in the distribution or composition of these syntaxonomic units could serve as indicators of climate change impacts or anthropogenic disturbances in desert ecosystems (Thomas et al., 2012). In the context of conservation and land management, this detailed syntaxonomic classification provides a framework for identifying areas of high ecological value or uniqueness. It can guide conservation efforts by highlighting communities that may be particularly vulnerable to environmental changes or human impacts (Le Houérou, 1996). Understanding the distribution and ecology of these vegetation units is crucial for restoration ecology in arid regions. Knowledge of the specific environmental requirements and species compositions of different alliances and associations can inform the selection of appropriate species and techniques for habitat restoration projects (Reij & Garrity, 2016).

6.6 Suitability of Vegetation Data Analysis Methods for Desert Vegetation Studies

The application of vegetation data analysis methods to desert ecosystems presents challenges and opportunities, particularly given that many of these techniques were originally developed with more temperate, European vegetation types in mind. This context necessitates a critical evaluation of their suitability for studying and surveying desert vegetation.

Modified TWINSPAN (Two-Way Indicator Species Analysis), as employed in this thesis, represents an advancement over the original TWINSPAN method developed by Hill (1979). The modified version addresses some of the limitations of the original algorithm, particularly its tendency to produce misclassifications in datasets with many zero values (Roleček et al., 2009), which is common in desert vegetation surveys due to the sparse nature of plant communities. This adaptation makes Modified TWINSPAN more suitable for analyzing desert vegetation data, where species occurrences are often rare and community composition can be highly variable across small spatial scales.

However, even with these improvements, challenges remain in applying these methods to desert vegetation data analyses. As experienced in this study, the initial classification derived from the modified TWINSPAN algorithm produced groups containing relevés that were misclassified. To address this issue, a mathematical method, the Silhouette Analysis, was implemented to reallocate misclassified relevés to their appropriate groups. This additional step highlights the need for a flexible and adaptive approach when applying vegetation analysis methods to desert ecosystems, often requiring a combination of computer techniques and expert knowledge to achieve accurate and ecologically meaningful results.

The Braun-Blanquet approach (Braun-Blanquet, 1964), a cornerstone of European phytosociology, has been widely applied in desert vegetation studies despite its already mentioned origin in more mesic environments. Its strength lies in its ability to capture both floristic composition and vegetation structure, which is particularly valuable in desert ecosystems where plant cover is often low and species interactions may be less apparent (Kent, 2012). However, the method's reliance on expert knowledge for the final classification of vegetation units can be challenging in desert environments, where species identification and ecological relationships may be less well understood compared to European systems.

Kassas (1952, 1953), in his studies on Egyptian desert vegetation, highlighted several limitations of applying the Braun-Blanquet method to arid ecosystems. He noted that the open character of desert plant communities does not allow dominant species to exert a controlling influence, challenging the concept of clearly defined, homogeneous plant associations. Kassas also emphasized the high spatial heterogeneity and temporal variability of desert vegetation, which are not easily captured by the static nature of Braun-Blanquet relevés. He advocated for adapting the method to incorporate more detailed information on soil characteristics, microtopography, and other environmental factors crucial in shaping desert vegetation patterns.

To address some of these limitations, researchers studying desert vegetation have increasingly combined traditional phytosociological methods with more quantitative approaches. For instance, the use of numerical classification techniques, such as cluster analysis and ordination methods (e.g. Detrended Correspondence Analysis or Non-metric Multidimensional Scaling), in conjunction with Braun-Blanquet sampling, has proven effective in identifying and characterizing desert plant communities (van der Maarel, 1979; Peet & Roberts, 2013).

The application of these methods to desert vegetation requires careful consideration of scale. Desert ecosystems often exhibit high spatial heterogeneity, with plant communities changing dramatically over short distances due to microtopographic variations and patchy resource distribution (Shupe, 2005). This characteristic necessitates adapting sampling strategies and analysis methods to capture this fine-scale variability effectively.

Moreover, the temporal variability of desert vegetation poses additional challenges. Many desert plants have ephemeral life cycles, appearing only after rare rainfall events (Noy-Meir, 1973). This temporal dynamism can lead to significant differences in community composition depending on the timing of surveys, potentially affecting the results of classification analyses. To address this, some researchers have advocated for repeated sampling over multiple seasons or years to capture the full range of species diversity in desert ecosystems (Whitford, 2002).

The use of multivariate statistical techniques, such as Canonical Correspondence Analysis (CCA) or Redundancy Analysis (RDA), has proven valuable in desert vegetation studies by allowing researchers to directly relate community composition to environmental variables (ter Braak & Prentice, 1988). This approach is particularly relevant in desert ecosystems where abiotic factors often play a dominant role in shaping plant community structure and distribution.

In recent years, the integration of remote sensing data and GIS techniques with traditional vegetation sampling methods has greatly enhanced our ability to study desert vegetation at larger spatial scales (Rocchini et al., 2013). These technologies allow for the extrapolation of ground-based observations to larger areas, providing a more comprehensive understanding of vegetation patterns and their relationships with environmental factors across desert landscapes.

Despite these advancements, it is crucial to recognize that many vegetation analysis methods may not fully capture the unique characteristics of desert ecosystems. For instance, traditional diversity indices may underestimate the ecological importance of rare species, which are prominent in desert environments (Gotelli & Colwell, 2001). Similarly, measures of beta diversity may need to be adapted to account for the high turnover rates and patchy distribution of desert plant communities (Anderson et al., 2011).

6.7 The significance of this thesis

This thesis represents a significant advancement in our understanding of the desert vegetation of the Saharo-Arabian region, offering a more comprehensive and nuanced perspective compared to many previous studies. One of the key contributions is the extensive geographical scope of the research, which encompasses a wide range of desert environments across multiple countries, including Saudi Arabia, Egypt, Chad, Niger, Tunisia, Algeria, Mauritania, and Morocco. This broad spatial coverage allows for a more holistic understanding of vegetation patterns and their relationships with environmental gradients across the entire region, a perspective that was often lacking in more localized studies.

Another significant contribution of this thesis is discovering and documenting new vegetation communities in the Sinai region in chapter 2. These newly distinguished communities, characterized by unique species compositions and environmental conditions, indicate gaps in the study of desert vegetation. It also highlights the presence of Mediterranean and ruderal elements within desert vegetation, which were not as prominently featured in earlier studies, challenging traditional definitions of desert vegetation and illustrating the region complex biodiversity. These findings underscore the importance of continuous field surveys and the application of updated methodologies to uncover the full extent of biodiversity in desert regions.

The phytosociological approach employed in this thesis, particularly as carried out in Chapter 4, provides a more detailed and hierarchical classification of desert vegetation than previous works. By identifying 15 main groups and 55 types of vegetation communities, which represent 16 vegetation classes, this study offers a finer resolution of vegetation units compared to broader classifications used in earlier research (Zohary, 1973; Danin & Orshan, 1999). This detailed classification allows for a more precise understanding of the ecological niches occupied by different plant communities and their responses to environmental factors.

Moreover, the integration of advanced statistical methods, such as modified TWINSPAN analysis and Silhouette value analysis, represents a methodological improvement over traditional phytosociological approaches. This combination of expert knowledge with robust statistical techniques enhances the objectivity and reproducibility of the vegetation classification, addressing some of the criticisms levelled at purely subjective classification methods.

Another significant contribution of this thesis is the development of suitability maps for different vegetation groups in the Sinai Peninsula, as presented in Chapter 5. By employing species distribution modelling techniques, this study provides spatially explicit predictions of vegetation distribution that go beyond the point-based observations typical of many vegetation surveys. This approach allows for a better understanding of the potential distribution of vegetation types across the landscape and their relationships with environmental variables. The inclusion of future climate change scenarios in vegetation modelling represents a forward-looking aspect that is often absent in traditional vegetation studies. By projecting potential changes in vegetation distribution under different climate scenarios, this thesis provides valuable insights for conservation planning and adaptive management strategies in the face of global change.

By proposing and refining syntaxonomic units (classes, orders, alliances, and associations) and updating the names of the plants and plant communities recorded according to the latest International Code of Phytosociological nomenclature (Theurillat et al., 2021), the thesis provides a more structured and ecologically meaningful classification system compared to many previous studies. This syntaxonomic framework facilitates comparisons with vegetation types in other arid regions globally and contributes to the ongoing development of a unified vegetation classification system for arid lands (Mucina et al., 2016).

Lastly, the multidisciplinary approach of this thesis, integrating traditional field surveys with modern geospatial analysis and climate modelling, provides a more holistic view of desert ecosystems than many previous studies. This integrated approach allows for a better understanding of the complex interactions between vegetation, climate, topography, and human activities in shaping desert landscapes.

6.8 Conclusions

This comprehensive study of the Saharo-Arabian desert vegetation has yielded several conclusions that may contribute to our understanding of arid ecosystem ecology, phytosociology, and conservation biology.

Firstly, the phytosociological survey revealed a complex and diverse vegetation structure within the Saharo-Arabian region. The classification highlighting the intricate mosaic of plant communities adapted to various microhabitats within this seemingly homogeneous desert landscape. This fine-scale classification underscores the importance of considering local environmental variations in desert ecology studies and conservation planning.

The study demonstrated the effectiveness of combining traditional phytosociological methods with advanced statistical techniques in desert vegetation analysis. The use of modified TWINSPAN, supplemented by Silhouette Analysis for refining classifications, proved to be a robust approach for dealing with the sparse and heterogeneous nature of desert vegetation data. This methodological framework provides a valuable template for future studies in arid ecosystems worldwide.

The research highlighted the critical role of environmental factors in shaping desert vegetation patterns. Factors such as temperature extremes, precipitation patterns, soil characteristics, and topography were found to be key determinants of plant community distribution and composition. These findings emphasize the need for a multifaceted approach to understanding and predicting vegetation dynamics in arid environments.

The development of suitability maps for different vegetation groups in the Sinai Peninsula represents a significant advancement in spatial ecology for arid regions. These maps provide a powerful tool for predicting potential vegetation distribution and identifying areas of high conservation value. Moreover, the incorporation of future climate scenarios in these models offers valuable insights into the potential impacts of climate change on desert ecosystems, facilitating proactive conservation planning.

The thesis also contributes to our understanding of the global significance of Saharo-Arabian desert vegetation. The research highlights the role of these ecosystems in global processes such as dust production and transport, which have far-reaching effects on nutrient cycling, climate regulation, and marine productivity. This underscores the importance of desert conservation not just for local biodiversity, but for global environmental health.

Furthermore, the study revealed the vulnerability of certain desert vegetation types to climate change and human activities. The projected shifts in vegetation distribution under future climate scenarios emphasize the need for adaptive conservation strategies. This is particularly crucial for endemic and rare species that may have limited capacity to migrate or adapt to changing conditions.

The research also highlighted the potential of desert plants for applications in agriculture and biotechnology. The unique adaptations of these plants to extreme conditions could inform the development of more resilient crop varieties, an increasingly important consideration in the face of global climate change.

6.9 Recommendations

Based on the comprehensive findings of this study on the Saharo-Arabian desert vegetation, several key recommendations can be made for future research, conservation efforts, and environmental management:

1. Given the high spatial and temporal variability of desert ecosystems revealed in this study, it is recommended to establish long-term ecological monitoring programs across the Saharo-Arabian region. These should include regular vegetation surveys using standardized protocols, complemented by continuous environmental data collection (e.g., microclimatic measurements, soil analyses). Such programs would provide invaluable data for tracking vegetation changes over time, especially in the context of climate change.
2. While this study has provided a detailed classification of Saharo-Arabian desert vegetation, further refinement is recommended. Future research should focus on integrating molecular phylogenetic data with traditional morphological and ecological

characteristics to develop a more robust and evolutionarily informed classification system. This approach could reveal cryptic diversity and provide insights into the evolutionary history of desert plant communities.

3. Based on the suitability maps and future projections developed in this study, it is recommended to prioritize conservation efforts on areas identified as current and future hotspots of plant diversity. Special attention should be given to regions that are predicted to serve as climate refugia, as these areas may be crucial for the long-term persistence of desert biodiversity.

4. In light of the projected vegetation shifts under climate change scenarios, it is crucial to develop and implement adaptive management strategies. These should include flexible protected area networks that can accommodate species range shifts, and restoration efforts that consider future climate conditions rather than historical baselines.

5. Future research and conservation efforts should strive to integrate traditional ecological knowledge of local communities with scientific approaches. This can provide valuable insights into sustainable land-use practices and historical vegetation changes, enhancing our understanding of desert ecosystem dynamics.

6. To fully understand the complex interactions within desert ecosystems, it is recommended to promote interdisciplinary research collaborations. These should involve ecologists, climatologists, soil scientists, remote sensing specialists, and social scientists to address the multifaceted challenges of desert conservation and management.

7. While this study has made significant progress in modelling desert vegetation distribution, further improvements are recommended. Future models should incorporate finer-scale environmental data, consider biotic interactions, and account for species' dispersal abilities to produce more accurate predictions of vegetation responses to environmental change.

8. It is recommended to conduct comprehensive assessments of the ecosystem services provided by different desert vegetation types identified in this study. This would help in quantifying the economic and ecological value of these ecosystems, potentially strengthening arguments for their conservation.

9. Based on the detailed vegetation classification and environmental associations identified in this study, it is recommended to develop tailored restoration strategies for degraded desert areas. These should consider the specific ecological requirements of different vegetation types and aim to enhance ecosystem resilience to future environmental changes.

10. Finally, it is recommended to develop educational programs and public outreach initiatives to increase awareness about the ecological importance and vulnerability of Saharo-Arabian desert ecosystems. This could help in garnering public support for conservation efforts and promoting sustainable land-use practices.

7

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8

Summaries and End matter

Summary (English)

In this comprehensive study, we provided an in-depth analysis of the desert vegetation in the Saharo-Arabian region, spanning from the western coasts of North Africa to the eastern shores of the Arabian Peninsula. We employed a multifaceted approach, combining traditional phytosociological methods with advanced statistical techniques and geospatial analysis, to elucidate the complex patterns and dynamics of plant communities in this vast arid landscape.

We started our investigation with a detailed phytosociological survey of the Sinai desert in Egypt, a recognized global hotspot for flora (Chapter 2). Utilizing a robust database of 1,421 vegetation plots, we applied modified TWINSPAN analysis, complemented by Hopkins' test and Silhouette algorithm, to classify the vegetation into nine main classes and 25 distinct groups. Our classification revealed significant diversity in life forms and chorotypes, with therophytes and chamaephytes dominating the life form spectrum, and Saharo-Arabian and Mediterranean elements prevailing in the chorological spectrum. Notably, we identified seven new plant communities not previously described in the literature, underscoring the value of comprehensive field surveys in uncovering hidden biodiversity in arid ecosystems. A key insight from this chapter was our recognition of four main vegetation groups: salt desert, lowland desert, mountain desert, and ruderal desert, each with distinct ecological characteristics and species compositions.

Expanding our geographical scope, we then focused on the understudied Hijaz Mountains' foothills and adjacent coastal zones in Saudi Arabia (Chapter 3). Through meticulous vegetation surveys along coastal and inland transects, supported by exhaustive soil analyses, we identified seven distinct plant communities, further classified into three vegetation clusters. We found that the distribution of these communities was largely dictated by latitudinal and altitudinal gradients, with annual precipitation and minimum temperature of the coldest month emerging as key determinants of vegetation patterns. This chapter provided valuable insights into the biogeographical patterns of the region, highlighting the influence of the Saharo-Arabian, Sahel-Sudano-Zambezian, and Tropical African floristic elements. We also revealed the importance of topography in creating diverse microclimates that support a range of plant communities, from coastal halophytic vegetation to montane woodlands.

Building on these localized investigations, we then broadened our perspective to encompass the entire Saharo-Arabian region (Chapter 4). In this comprehensive overview, we integrated various syntaxonomical systems, addressing the inherent difficulties in reconciling them with universally accepted nomenclature. We identified 15 main vegetation groups encompassing 55 distinct types, representing a diverse array of desert plant communities adapted to various microhabitats. Our classification provided a nuanced understanding of the ecological gradients and environmental factors shaping vegetation distribution across the region, from coastal salt marshes to inland sand dunes and mountain slopes. A significant contribution of this chapter was our development of a unified syntaxonomical scheme for the Saharo-Arabian

region, which included 16 vegetation classes. This scheme not only facilitated comparisons between different parts of the region but also provided a framework for understanding vegetation dynamics in response to environmental changes.

The final empirical component of our study focused on developing suitability maps for the desert vegetation of Sinai, employing species distribution modeling techniques (Chapter 5). By integrating current vegetation data with climate projections, we provided spatially explicit predictions of potential vegetation shifts under future climate scenarios. Our models revealed a projected reduction and fragmentation in the distribution of salt desert and lowland desert vegetation, while mountain desert communities showed greater resilience to climate change. This forward-looking analysis offered valuable insights for adaptive conservation strategies and land management planning in the face of global environmental change. We also highlighted the potential of these suitability maps in guiding restoration efforts and identifying climate refugia for desert biodiversity.

Throughout our study, we emphasized the critical role of environmental factors in shaping desert vegetation patterns. We found that temperature extremes, precipitation patterns, soil characteristics, and topography emerged as key determinants of plant community distribution and composition. Our research also highlighted the vulnerability of certain desert vegetation types to climate change and human activities, underscoring the urgent need for conservation efforts tailored to these unique ecosystems.

A valuable insight from our research was the recognition of desert mountains as potential refugia for plant diversity in the face of climate change. We demonstrated that mountain vegetation showed greater resilience to projected climate changes compared to lowland communities, likely due to the presence of diverse microclimates and the possibility for altitudinal migration of species (Chapters 3 and 5).

We also provided important perspectives on the role of human activities in shaping desert vegetation. We identified ruderal communities associated with human disturbance and agricultural practices, particularly in the Sinai region (Chapter 2). This highlighted the need to consider anthropogenic factors in conservation planning and the potential for sustainable land use practices that can support both human needs and biodiversity conservation.

Our comprehensive investigation significantly advanced the understanding of Saharo-Arabian desert vegetation, providing a robust scientific foundation for biodiversity conservation, climate change adaptation, and sustainable land management in arid regions. Our multidisciplinary approach, combining traditional field surveys with cutting-edge analytical techniques, set a new standard for desert ecology research. Furthermore, the insights we gained from this study have broader implications for global ecology, offering valuable perspectives on plant adaptations to extreme environments and the potential responses of arid ecosystems to global change. Our research underscored the importance of long-term ecological monitoring, interdisciplinary collaboration, and the integration of traditional ecological knowledge with scientific approaches in future desert research and conservation efforts.

Samenvatting

In deze uitgebreide studie hebben we een diepgaande analyse gemaakt van de woestijnvegetatie in de Saharo-Arabische regio, die zich uitstrekt van de westelijke kusten van Noord-Afrika tot de oostelijke kusten van het Arabische schiereiland. We gebruikten een veelzijdige aanpak, waarbij we traditionele fytosociologische methoden combineerden met geavanceerde statistische technieken en geospatiale analyse, om de complexe patronen en dynamiek van plantengemeenschappen in dit uitgestrekte aride landschap te verduidelijken.

We begonnen ons onderzoek met een gedetailleerde fytosociologische studie van de Sinaï-woestijn in Egypte, een erkende mondiale hotspot voor flora (Hoofdstuk 2). Met behulp van een robuuste database van 1.421 vegetatieplots pasten we gemodificeerde TWINSPAN-analyse toe, aangevuld met Hopkins' test en het Silhouette-algoritme, om de vegetatie in negen hoofdklassen en 25 afzonderlijke groepen te classificeren. Onze classificatie onthulde een aanzienlijke diversiteit in levensvormen en chorotypes, waarbij therofyten en chamaefyten het spectrum van levensvormen domineerden, en Saharo-Arabische en Mediterrane elementen overheersten in het chorologische spectrum. Opmerkelijk is dat we zeven nieuwe plantengemeenschappen identificeerden die niet eerder in de literatuur waren beschreven, wat het belang onderstreept van uitgebreide veldonderzoeken bij het ontdekken van verborgen biodiversiteit in aride ecosystemen. Een belangrijk inzicht uit dit hoofdstuk was onze herkenning van vier hoofdvegetatiegroepen: zoutwoestijn, laaglandwoestijn, bergwoestijn en ruderale woestijn, elk met onderscheidende ecologische kenmerken en soortensamenstelling.

Bij het uitbreiden van ons geografische bereik richtten we ons vervolgens op de weinig bestudeerde uitlopers van het Hijaz-gebergte en aangrenzende kustgebieden in Saudi-Arabië (Hoofdstuk 3). Door middel van nauwgezette vegetatieonderzoeken langs kust- en binnenlandse transecten, ondersteund door uitvoerige bodemanalyses, identificeerden we zeven verschillende plantengemeenschappen, verder ingedeeld in drie vegetatieclusters. We ontdekten dat de verspreiding van deze gemeenschappen grotendeels werd bepaald door breedtegraad- en hoogtegradiënten, waarbij jaarlijkse neerslag en minimumtemperatuur van de koudste maand naar voren kwamen als belangrijke determinanten van vegetatiepatronen. Dit hoofdstuk leverde waardevolle inzichten op in de biogeografische patronen van de regio, waarbij de invloed van de Saharo-Arabische, Sahel-Sudano-Zambezische en Tropisch Afrikaanse floristische elementen werd benadrukt. We onthulden ook het belang van topografie bij het creëren van diverse microklimaten die een reeks van plantengemeenschappen ondersteunen, van kusthalofytische vegetatie tot montane bossen.

Voortbouwend op deze lokale onderzoeken verbreedden we vervolgens ons perspectief om de gehele Saharo-Arabische regio te omvatten (Hoofdstuk 4). In dit uitgebreide overzicht integreerden we verschillende syntaxonomische systemen, waarbij we de inherente moeilijkheden aanpakten om deze te verzoenen met universeel aanvaarde nomenclatuur. We identificeerden 15 hoofdvegetatiegroepen die 55 verschillende typen omvatten, die een diverse reeks woestijnplantengemeenschappen vertegenwoordigen die zijn aangepast aan verschillende microhabitats. Onze classificatie bood een genuanceerd begrip van de ecologische gradiënten en milieufactoren die de vegetatieverspreiding in de regio vormgeven, van kustzoutmoerassen tot binnenlandse zandduinen en berghellingen. Een belangrijke bijdrage van dit hoofdstuk was onze ontwikkeling van een verenigd syntaxonomisch schema voor de Saharo-Arabische regio, dat 16 vegetatieklassen omvatte. Dit schema vergemakkelijkte niet alleen vergelijkingen tussen verschillende delen van de regio, maar bood ook een kader voor het begrijpen van vegetatiedynamiek in reactie op milieuveranderingen.

Het laatste empirische onderdeel van onze studie richtte zich op het ontwikkelen van geschiktheidskaarten voor de woestijnvegetatie van Sinaï, waarbij we gebruik maakten van technieken voor het modelleren van soortenverspreiding (Hoofdstuk 5). Door huidige vegetatiegegevens te integreren met klimaatprojecties, leverden we ruimtelijk expliciete voorspellingen van potentiële vegetatieverschuivingen onder toekomstige klimaatscenario's. Onze modellen onthulden een voorspelde afname en fragmentatie in de verspreiding van zoutwoestijn- en laaglandwoestijnvegetatie, terwijl bergwoestijngemeenschappen een grotere veerkracht toonden tegen klimaatverandering. Deze toekomstgerichte analyse bood waardevolle inzichten voor adaptieve natuurbehoudsstrategieën en landbeheersplanning in het licht van wereldwijde milieuverandering. We benadrukten ook het potentieel van deze geschiktheidskaarten bij het sturen van herstelactiviteiten en het identificeren van klimaatrefugia voor woestijnbiodiversiteit.

Gedurende onze studie benadrukten we de cruciale rol van milieufactoren bij het vormgeven van woestijnvegetatiepatronen. We ontdekten dat temperatuurextremen, neerslagpatronen, bodemkenmerken en topografie naar voren kwamen als belangrijke determinanten van de verspreiding en samenstelling van plantengemeenschappen. Ons onderzoek benadrukte ook de kwetsbaarheid van bepaalde woestijnvegetatietypen voor klimaatverandering en menselijke activiteiten, wat de dringende behoefte aan natuurbehoudsinspanningen onderstreept die zijn toegesneden op deze unieke ecosystemen.

Een waardevol inzicht uit ons onderzoek was de erkenning van woestijnbergen als potentiële toevluchtsoorden voor plantendiversiteit in het licht van klimaatverandering. We toonden aan dat bergvegetatie een grotere veerkracht vertoonde tegen voorspelde klimaatveranderingen in vergelijking met laaglandgemeenschappen, waarschijnlijk vanwege de aanwezigheid van diverse microklimaten en de mogelijkheid voor hoogtewaartse migratie van soorten (Hoofdstukken 3 en 5).

We leverden ook belangrijke perspectieven op de rol van menselijke activiteiten bij het vormgeven van woestijnvegetatie. We identificeerden ruderale gemeenschappen geassocieerd met menselijke verstoring en landbouwpraktijken, met name in de Sinaï-regio (Hoofdstuk 2). Dit benadrukte de noodzaak om antropogene factoren in aanmerking te nemen bij natuurbehoudplanning en het potentieel voor duurzame landgebruikspraktijken die zowel menselijke behoeften als biodiversiteitsbehoud kunnen ondersteunen.

Concluderend heeft ons uitgebreide onderzoek het begrip van Saharo-Arabische woestijnvegetatie aanzienlijk bevorderd, waarbij we een robuuste wetenschappelijke basis hebben geleverd voor biodiversiteitsbehoud, aanpassing aan klimaatverandering en duurzaam landbeheer in aride regio's. Onze multidisciplinaire aanpak, die traditionele veldonderzoeken combineerde met geavanceerde analysetechnieken, zette een nieuwe standaard voor woestijnecologisch onderzoek. Bovendien hebben de inzichten die we uit deze studie hebben verkregen bredere implicaties voor de mondiale ecologie, waarbij we waardevolle perspectieven bieden op plantaanpassingen aan extreme omgevingen en de potentiële reacties van aride ecosystemen op wereldwijde veranderingen. Ons onderzoek onderstreepte het belang van ecologische monitoring op lange termijn, interdisciplinaire samenwerking en de integratie van traditionele ecologische kennis met wetenschappelijke benaderingen in toekomstig woestijnonderzoek en natuurbehoudsinspanningen.

About the author

Mohamed Zakaria Hatim, known as Zakaria, took a bachelor's in Botany Sciences from the Faculty of Science, Tanta University, Egypt and ranked First in his department; thus, he was appointed as a Teaching Assistant and then Assistant Lecturer in the same faculty. He conducted research and education for several years there.

He got his master's degree from Tanta University and Wageningen University and Research in Plant Ecology and Vegetation Communities. In parallel he got several diplomas and degrees in Computer Sciences, Programming and Data Analysis from IBM, Google and Udacity.

His main interest is deserts; he started doing research there in 2004 when he joined the Medicinal Plants Conservation Project in Sinai, funded by UNDP and GEF. Then, he did his Master's thesis about Sinai desert vegetation, and finally, his PhD on the desert vegetation of North Africa and the Middle East.

He was involved in several projects, including sPlot for the Global Vegetation Database by iDive, Trees and shrubs natives of North Africa Project (IUCN), Lake Bardawil and Sinai Initiative by the Weather Makers, New Horizon Project, The New Polder in Emeshaven, Dogerbank Rewildining, and finally, Impact of Evaporation Technologies by WETSUS.

He is married to a beautiful wife, Omnia, and has two gorgeous kids, Amira and Malek. He likes to play Chess regularly and holds the title of Chess Champion of Wageningen University. He loves reading different types of books and also writing and drawing.

Publications

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PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 30 ECTS (= 20 weeks of activities)

Review/project proposal (6 ECTS)

- Overview of the desert vegetation of the Saharo-Arabian region

Post-graduate courses (5.5 ECTS)

- Nature in a Crowded Country, Joop Schaminée (2020)
- GIS in Practice, PE&RC (2019)

Invited review of journal manuscripts (1 ECTS)

- European Journal of Forest Research, Vegetation Diversity (2024)

Competence, skills and career-oriented activities (2.5 ECTS)

- The Essentials of Scientific Writing and Presenting, WGS (2020)
- Effective behaviour in your professional surroundings, WGS (2020)

Scientific Integrity/Ethics in science activities (0.9 ECTS)

- Ethics in Plant and Environmental Sciences, WGS (2023)
- Scientific Integrity, WGS (2020)

PE&RC Annual meetings, seminars and PE&RC weekend/retreat (1.5 ECTS)

- PE&RC Weekend – First year edition (2019)
- PE&RC Weekend – Last year edition (2022)

National scientific meetings, local seminars, and discussion groups (12.8 ECTS)

- Innovative research ideas (2022-2023-2024)
- MENA Working Group (2023)
- LLM Focus Group (2024)
- What Design Can Do (2024)
- PhD, how are you doing? (2021-2022-2023-2024)
- WUR Digital Demonstrators (2021)
- Ecoinformatics Seminars, Sohag, Egypt (2022)

International symposia, workshops and conferences (12.5 ECTS)

- 28th European Vegetation Survey Workshop, Madrid, Spain (2019)
- World Biodiversity Forum, Davos, Switzerland (2020)
- ESA Annual Meeting. Virtual conference, USA (2021)
- 30th Conference of the European Vegetation Survey: Plant communities in changing environment, Bratislava, Slovakia (2022)
- BES Annual Meeting, Edinburgh, Scotland (2022)

Societally relevant exposure (4.5 ECTS)

- Do we do the vegetation data clustering analysis right? (Nature Communities Blog, 2020)
- High plant diversity often found in smallest of areas (press article – WUR News, 2022)
- Grote plantendiversiteit vaak in kleinste gebieden (2022)

Lecturing/supervision of practicals/tutorials (1.8 ECTS)

- Ecology of Communities, Ecosystems and Landscapes: Field Excursions (2021 – 2022)
- Ecology of Communities, Landscapes and Ecosystems – Theory: Tutorials (2022 – 2023)

BSc/MSc thesis supervision (6 ECTS)

- Research topic 1: Traits and Potential Utilization of Salt-Tolerant Vegetation in North Sinai
- Research topic 2: Vegetation ecology of the Coastal desert of Wadi Watir, Sinai, Egypt
- Research topic 3: ACT Group 3176-B- Greening the desert: nature-based solutions to fight desertification in Botswana

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