The Farasan Archipelago: Progress towards an E-flora and conservation strategy

A thesis submitted by

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DECLARATION

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

Rahmah Al Qthanin

Zifaf Island, the Farasan Archipelago (2017)

"*All of the rocky and metallic material we stand on, the iron in our blood, the calcium in our teeth, the carbon in our genes, were produced billions of years ago in the interior of a red giant star. We are made of star-stuff. There are pieces of star within us all!*"

(The Cosmic Connection: An Extraterrestrial Perspective, Carl Sagan)

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ABSTRACT

This is the first time that a complete infrastructure has been presented that spans field biology, e-flora, multi-access keys, population genetics and conservation assessment for a complete flora. Such systems are ultimately a key step towards the achievement of the GSPC 2020 targets, particularly Targets 1, 2, 5 & 7. Positioned between Asia and Africa, the Farasan Archipelago has a high diversity of species given its small land area. This new online updated checklist of the Farasan Archipelago flora includes 245 species and subspecies of vascular plants. The replacement of traditional printed floras with online tools that are easily updated is part of target 1 of the GSPC. In this study, The web infrastructure to record the diversity and structure of the plant communities present in the Farasan Archipelago and to deliver this as an accessible and free flora for specialist and non-specialist users and for research and teaching purposes is demonstrated. This online flora includes the first multi-access key to Zygophyllaceae of the Farasan Archpeligoflora as an examplar with synoptic illustrations to allow confident identification of these difficult species. Appropriate management of plants of conservation concern requires genetic diversity assessment particularly for the threatened plant species that are ecologically and economically importance at a regional and global level. The assessment of mangrove species in the Farasan Archipelago confirmed that there is significant genetic structuring in natural populations along the coast. This study discusses the possible barriers that contribute to the separation of these populations. The consequence is that conservation action must be undertaken with populations as the basic units of protection. The conservation assessment and red listing of the Farasan Archipelago flora, according regional IUCN criteria and categories, reveals a high local extinction risk and thus the flora is of conservation concern, which is poorly recognized at present, both regionally and globally. This research is a first step towards the recognition of the dangers to the Farasan Archipelago plant diversity particularly the coastal zone plants. Industrial and tourist development are recognised as key threats. The conservation of the threatened species and the raising of public awareness at both regional and global levels is crucial to successful conservation. Overall, the most novel and important outcome of this research was the combination of these new techniques with field studies for the purpose of conservation prioritization for the Farasan Archipelago flora and to inform stakeholders and policy makers. This E-flora will become key to identifying and ameliorating the effects of the threats endangering the Farasan Archipelago plant diversity.

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Introduction

CHAPTER 1

1.1 General introduction

Since the time of Darwin and Wallace, island biotas have fascinated researchers in many ways relating to geological and biological history. Because of their isolation, with clearly delimited geographical boundaries, and lack of past connections to continents, the community structure is simpler than on the mainland, but it is easily threatened by human activities (Simberloff, 1995). For these reasons, islands have long served as an inspiration in the development in the fields of floristic studies, biogeography, ecology and evolutionary biology.

Islands can be divided into three types according to their geological origin and biological properties (Alfred Russel Wallace's classification): continental shelf islands, continental fragments and oceanic islands (Whittaker & Fernández-Palacios, 2007). Although the floristic content of continental or inshore islands can change in a short time and they lack a number of features that distinguish oceanic islands, they are significant in studying many aspects with at least equal resolution to purely oceanic islands. For example, dynamics of colonization and extinction, species numbers and species turnover between islands, dispersal means, and characteristics and morphological changes (Cody, 2006) and the equilibrium theory of island Biogeography which is "species richness decreases with decreasing island area and increasing isolation as these two variables influence immigration and extinction" (Macarthur and Wilson, 1967).

Continental islands such as the North and Baltic Sea, the eastern Atlantic and the Mediterranean (Lack, 1942, Russell *et al.*, 1995, Haila and Järvinen, 1983) have been wildly studies, however few studies on the continental islands in the Arabian Gulf and the Red Sea have been conducted (Akhani and Deil, 2012, Moawed and Ansari, 2015).

The Red Sea is a unique environment with a wide range of habitats and outstanding biodiversity, which confers a great scientific and ecological importance. The Red Sea has a narrow and relatively shallow connection to the Indian Ocean through Bab Al-Mandab in the southern part (Bailey, 2010a). It is characterised by the harsh conditions prevailing in the Sea such as high salinity 36-40 ppt (Parts per thousand), extreme water temperatures (21-40 °C), low rainfall and no permanent freshwater inputs (Bruckner *et al.*, 2012) with the desert surrounding both coasts in the Red Sea (Bailey, 2010b). The harsh environment has led to habitat fragmentation and low population density of plant species especially in the coastal habitats which have direct contact with the Red Sea (Kumar *et al.*, 2010).

Along the Asian Red Sea coast several inshore islands are found, some close to the coast and others farther away (Zahran, 1993). All of these islands share approximately the same geological age since they originated after the widening of Red Sea basin (Bosworth, 2015). Floristic studies of the Red Sea Islands are much less common than those of islands in the Indian Ocean (Renvoize, 1979, Gurib-Fakim and Brendler, 2004) , Atlantic Islands (Martins, 2000, Faria *et al.*, 2012) and Pacific Islands (Mueller-Dombois and Fosberg, 2013, Denslow *et al.*, 2009), however they are fundamental in the understanding of migration of flora between Arabia and Africa. So this thesis will focus on the biggest inshore Archipelago with the most biodiverse flora in the Asian Red Sea (The Farasan Archipelago).

The Farasan Archipelago lies on the Arabian continental shelf (**Figure 1.1)**, as a large group of islands (600km^2) located in the southcentral Red Sea, between Jizan coast in the southwestern part of Saudi Arabia (40 km) and the Dahlack Islands in Africa (~ 200 km). The archipelago consists between 36 and 176 islands (Muoftah, 1990). Most islands are low, coral islets, small islands with extensive areas of shallow, fringing coral reefs and sand shelves (Cooper and Zazzaro, 2014). There are seven islands of more than 10km^2: Farasan Alkabir (369 km^2), Sajid (149 km^2), Dissan (35.7km^2), Zifaf (33.2 km^2), Dushak (149 km^2) Qummah (15.2 km^2) and Dumsuq (12 km^2) (Hall *et al.*, 2010), which some authors, describe as the main islands (Alwelaie *et al.*, 1993, El-Demerdash, 1996). These big and small islands have an elevation of 20-70 m. Farasan Alkabir has the longest perimeter (215 km) and it composed, mainly, of fossil coral surfaces in the islands and eroded coral cliffs or coral sands along the coastal sides. However, soil formations like aeolean and alluvial soil deposits are also seen in some areas with thicker soil. Topographies of other islands such as Zifaf, Dushak and Dumsuq are also more or less same as that of Farasan Al-Kabir. However, in Zifaf, the fossil coral is in the form of ridges and folds with several wadis (Al Farhan *et al.*, 2005).

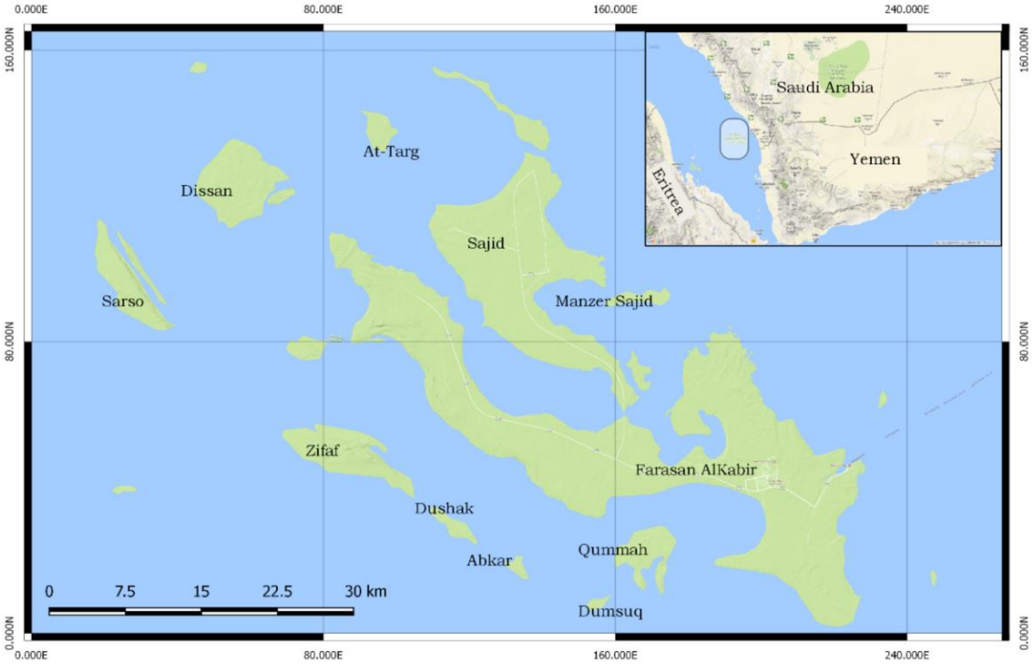

Figure 1.1 The location map of the main islands within the Farasan archipelago.

There are no long-term climatological records for the Farasan Islands. The available information of the nearest region to the study area is that of Jizan on the mainland. The climate is characterised by a long dry hot season (April- October) which is usually dominant, as shown in **Table 1.1** and a short mild one (November -March). Furthermore, the mean relative humidity ranges from 60% to 80% and the highest rainfall occurs in April. The precipitation is generally unpredictable in the southern part of Red sea (El-Demerdash, 1996).

Table 1.1 Monthly variation in air temperature (ºC), relative humidity (RH, %), wind speed (WS, km hr-1) and rainfall (RF, mm month-1) as recorded at Jizan meteorological station. The data are long term averages from Climatological Normal for KSA, 2009–2018 (Anonymous, 2018).

Month	Temperature (ºC)		RH	WS	RF
	Max.	Min.	%	(km hr-1)	(mm month-1)
January	29.14±1.231	18.57±1.158	70.79±4.136	7.21±0.975	121.14±279.040
February	30.36±1.082	19.14±1.027	72.14±4.276	7.07±1.328	2.36±6.640
March	32.50±1.019	20.14±1.167	70.50±3.898	7.64±1.151	112.36±282.024
April	35.00±0.877	22.50±0.760	67.43±3.694	7.14±0.663	170.57±329.407
May	37.43±1.158	24.14±1.099	66.36±3.272	7.50±0.760	0.07±.267
June	39.00±0.961	25.64±0.929	60.50±4.988	7.79±0.975	55.57±207.929
July	39.86±1.027	27.36±1.151	60.29±4.268	6.93±0.730	56.07±207.794
August	38.86±0.949	28.57±1.016	60.50±5.065	7.21±0.699	55.79±207.868
September	37.86±0.770	26.71±0.914	65.86±5.172	6.86±0.864	0.14±0.535
October	36.79±1.051	24.50±.760	75.79±4.061	5.57±.646	55.86±207.849
November	33.50±1.019	22.64±1.008	73.21±5.807	5.93±0.730	73.21±204.565
December	30.86±0.864	20.29±0.726	71.00±6.493	6.57±1.284	175.43±327.050
Total Mean	35.10±3.713	23.35±3.354	70.20±5.977	6.95±1.099	73.21±221.698

Geologically, there are a number of hypotheses proposed on the history of the Farasan Islands (Alwelaie *et al.*, 1993, Dabbagh *et al.*, 1984). Modern satellite imagery shows all of the islands are Pleistocene uplifted coral reefs that lie on the salt domes of the Miocene. It supports Dabbagh *et al*. (1984) and Baily *et al.* (2007) opinions, which argue there is no history of connection between the Farasan Islands and the mainland (Dabbagh *et al.*, 1984, Bailey *et al.*, 2007a). During the Pleistocene Epoch (2.6 Mya–11.7 ka), a pronounced sea-level change associated with glaciation has occurred repeatedly. The culmination of low sea levels was 115–130 m below the current level. The minimum level occurred during the Last Glacial Maximum (LGM) c. 17–19 ka (Ludt & Rocha, 2015). From the LGM to the early Holocene, sea levels rose drastically and rapidly (122 m). The islands assumed approximately their present configuration in the mid-Holocene 6,000 years before the present (BP) (Bailey et al., 2007; Ludt & Rocha, 2015).

The Farasan Archipelago has significant ecological interest because it is included in one of the main routes for bird migration and comprises a characteristic assemblage (El-Demerdash, 1996), and it is consequently registered as an important Bird area (Evans, 1994). For example, plovers and sooty gulls, which may have played a significant role in the early stages of the Farasan Islands' flora formation (Chaudhary, 2001b; AlRashidi et al., 2011), particularly of coastal plant species.The landscape of these islands comprises a wide range of habitats (**Figure 1.2, Figure 1.3, Figure 1.4)**, such as different type of coast (rocky, vegetated and sandy coast), mangroves, drought land, salt marshes, rocky habitats, coral rock, farmland, sand habitat and wadi channels that have resulted in a rich biological diversity and led to a natural variation in the island flora in the Farasan Archipelago (Mutairi *et al.*, 2012b). Not only the habitat, but also the soil moisture, salinity, organic carbon and silt are related to the vegetation distribution patterns (El-Demerdash, 1996). The large islands in the archipelago such as Farasan Alkabir retain higher diversity than an equivalent area of several smaller islands. This island also includes rare species and rare habitats such as coral rocks. However, the exotic tree *Prosopis juliflora* has invaded some of the unique habitats such as wadi channels and water catchments in Farasan Alkabir Island (**Figure 1.5)**, which negatively affected the native biodiversity in this island.

1.2 The Farasan Archipelago flora

The Farasan Archipelago is one of the most biodiverse sites in Saudi Arabia and The Red Sea Islands (Masseti, 2010, Hall *et al.*, 2010). The flora of the Farasan Archipelago lies within the Afro-Asian phytogeographical zone, with floral elements recorded from these islands having more affinities towards Arabian flora than the floras of Eritrea, Somalia or Ethiopia (Hassan and Al-Hemaid, 1996). About 60% of the surface of the Farasan Islands is a subtropical desert of fossil limestone (Bruckner *et al.*, 2012). Inland vegetation cover is sparse, except in gullies between fossil coral outcrops, and dominated by trees such as *Vachellia* ssp. especially *Vachellia flava.* The south-eastern area of Farasan Alkabir island, where the land is rugged, is the most densely vegetated. The Al-Muharraq area (**Figure 1.6)** includes species such as *Commiphora gileadensis, Salvadora persica, Indigofera oblongifolia, Ziziphus spina-christi, and Maerua oblongifolia*. Some *Asparagus flagellaris* are covered with the climbers: *Cissus quadrangularis, Pentatropis nivalis, Ipomoea obscura, Ipomoea hochstetteri* and *Kickxia corallicola.* The north-western unbroken plateau and the western facing shoreline are devoid of plants except for a few annual species (Alfarhan *et al.*, 2001). The most common in this area are *Capparis spinosa, Euphorbia collenetteae, Indigofera oblongifolia,* with occasional small trees of *Salvadora persica* and *Acacia ehrenbergiana*. *Abutilon pannosum* is dominant on silt and is especially evident in western Farasan Alkabir and southern Sajid Islands (**Figure 1.7)**. In some areas, such as the raised coral platform near Seir, in Farasan Alkabir the thickets of *Capparis spinosa* and *Euphorbia collenetteae* can become very dense (**Figure 1.8)** (Hall *et al.*, 2010).

Above the intertidal zone, beaches usually have a band of *Suaeda monoica, Halopeplis perfoliata, Limonium axillare,* and several species of *Zygophyllum* in the low- shore line (**Figure 1.9).** Sheltered coastal areas support extensive stands of *Avicennia marina* mangrove, and a large population occurs in Khawr Farasan near the port (Mandura and Khafaji, 1993). Northeast Farasan Alkabir is the only area which supports the patch of *Rhizophora mucronata* in this island, with an additional 20 ha (hectare) of *Rhizophora* mangrove on Zifaf Island (Hall *et al.*, 2010). These two mangroves (**Figure 1.10)** are the foremost factor that makes the Farasan group of islands unique. These are highly productive littoral biotopes important as a refuge for many small animals, such as birds and fish.

There are sixteen species in The Farasan Archipelago that were not thought to occur elsewhere in Saudi Arabia (Fisher *et al.*, 1998, Chaudhary and Al-Jowaid, 1999, Chaudhary, 2001 , Alfarhan *et al.*, 2001, Hall *et al.*, 2010, Tomas *et al.*, 2010). However, the revision of these taxa with relevant literature and herbarium specimens from the Royal Botanic Garden Edinburgh website has shown that five species from the list have been recorded in other parts of Saudi Arabia (Chaudhary, 2001, Al-Zahrani and El-Karemy, 2007, Al-Zahrani, 2010, Daur, 2012) and (Collenette, I.S. No. 4017 RBGE). In addition, as a result of the changing of the taxonomic status of *Commiphora erythraea* (Ehrenb.) to a synonym of widespread *C. kataf* (Forssk.) Engl (Roskov *et al.*, 2013), means this taxon has been excluded from the group. Thus, ten species (*Basilicum polystachion* (L.) Moench, *Cleome noeana* ssp. *brachystyla* Chamberlain & Lamond, *Dinebra somalensis* (Stapf) P.M.Peterson & N.Snow, *Euphorbia collenetteae* D.Al-Zahrani & El-Karemy, *Ficus populifolia* Vahl, *Ipomoea hochstetteri* House, *Micrococca mercurialis* (L.) Benth. *Nothosaerva brachiata* (L.) Wight, *Glossonema* sp. Aff. *boveanum* (Dence.) and *Vahlia digyna* (Retz.) O. Kuntze), can be considered as restricted taxa to the Farasan Archipelago.

Figure 1.2 Main habitat types in the Farasan Archipelago, A. Rocky beach B. vegetated beach C. sand beach D. Mangroves.

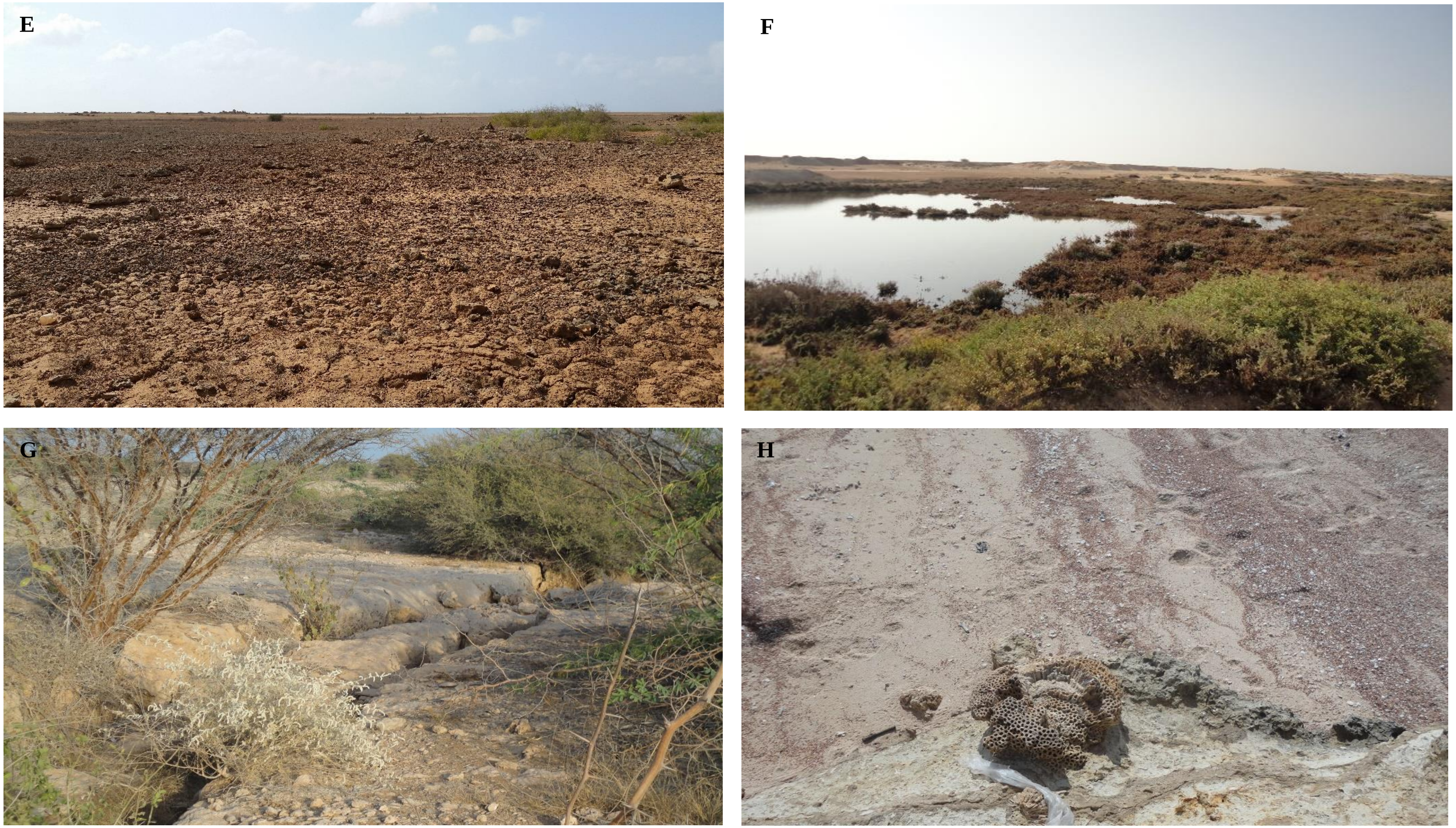

Figure 1.3 Continued main habitat types in the Farasan Archipelago, E. drought land F. salt marshes G.rocky habitat H. coral rock.

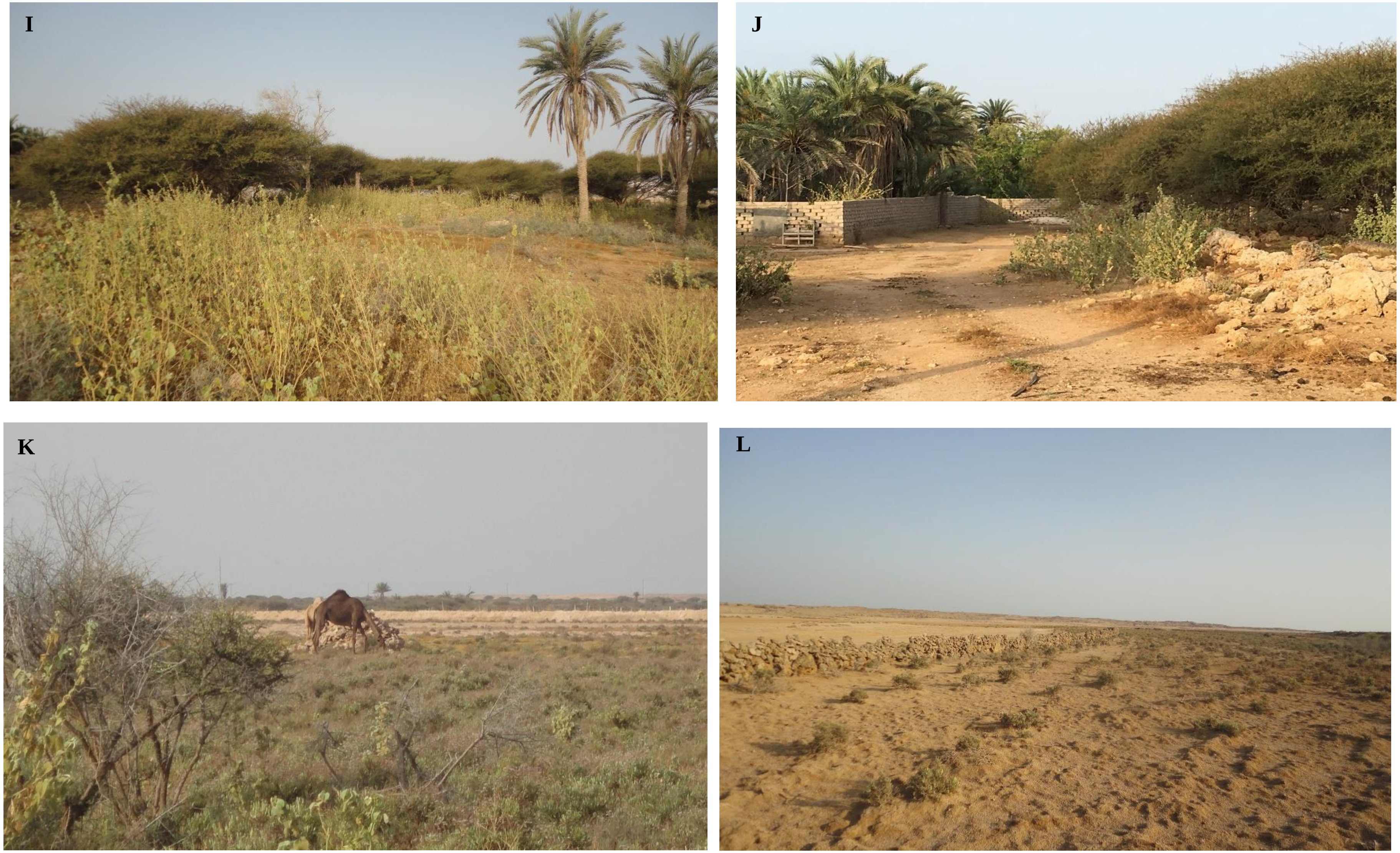

Figure 1.4 Continued main habitat types in the Farasan Archipelago, I.&J. farmland K.sand habitat. L. wadi channels.

Figure 1.5 The invasive species in the Farasan Archipelago, *Prosopis juliflora* is one of the main threats to plant biodiversity conservation on Farasan

Figure 1.6 Al-Muharraq area, south eastern of Farasan Alkabir Island, in the Farasan Archipelago.

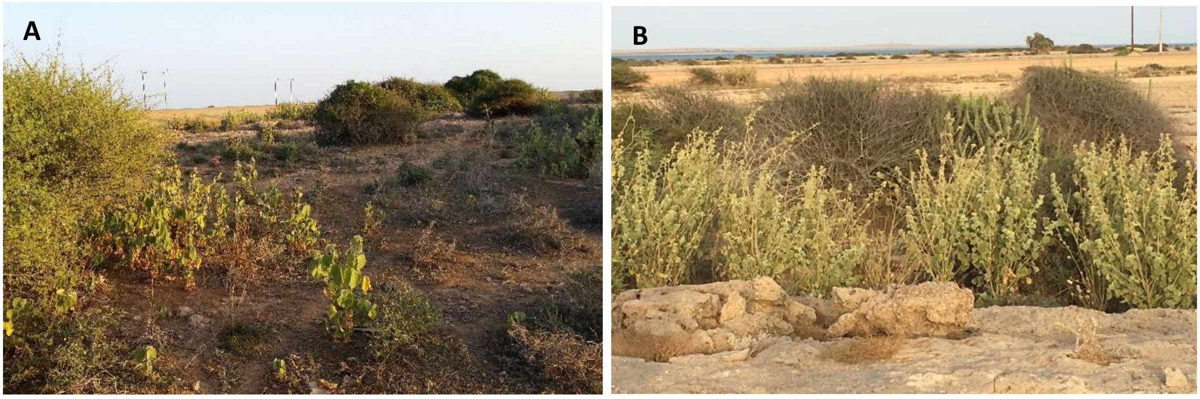

Figure 1.7 *Abutilon pannosum* community which is dominant on A. western Farasan Alkabir and B. southern Sajid islands.

Figure 1.8 A. *Capparis spinosa* and B. *Euphorbia collenetteae* dense community on Sair road in Farasan Alkabir Island.

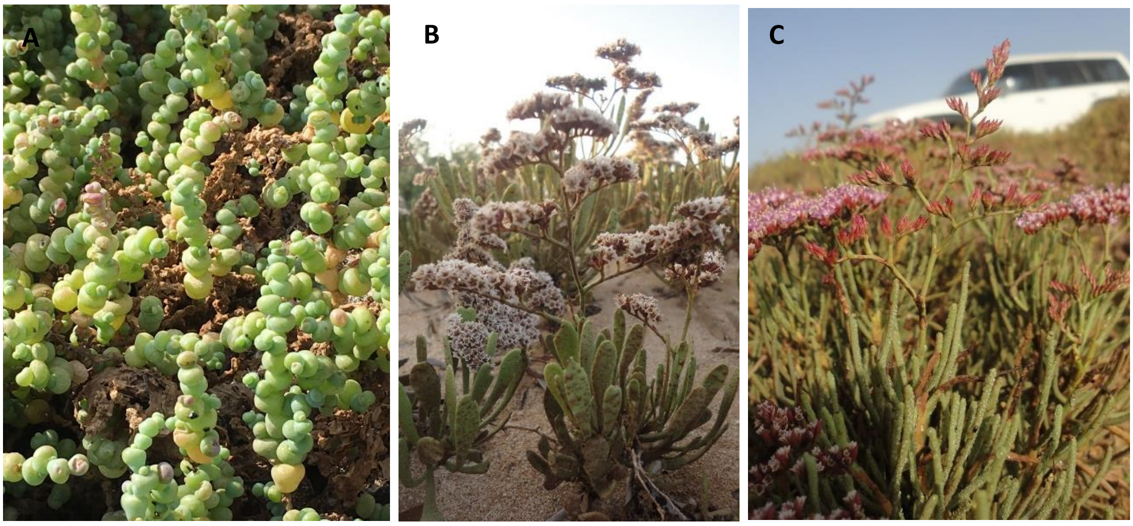

Figure 1.9 Populations of A. *Halopeplis perfoliata* B. *Limonium axillare* C. *Limonium cylindrifolium* in the Farasan Archipelago.

Figure 1.10 The largest population of combined *Rhizophora mucronata* and *Avicenna marina* in the Arabian Red Sea Regions Occur in the Farasan Archipelago.

The Farasan Archipelago flora has attracted attention and interest through history (Alfarhan *et al.*, 2001, Alfarhan *et al.*, 2005). According to previous studies which recorded the Farasan Archipelago flora, it contain 220 taxa of plants, in 50 families (Alwelaie *et al.*, 1993, El-Demerdash, 1996, Hassan and Al-Hemaid, 1996, Chaudhary, 1998, Chaudhary, 2000, Chaudhary, 2001, Collenette, 1999, Rahman *et al.*, 2002, Roskov *et al.*, 2013, Alfarhan *et al.*, 2001, Alfarhan *et al.*, 2005, Tomas *et al.*, 2010). Although these previous books and papers were a good record for the Farasan Archipelago flora, many of these studies focused only on the two main islands Farasan Alkabir and Sajid Islands, and did not mention plant geographical distribution among the main islands in the Farasan Archipelago. In addition, a lot of records were compiled from literature sources and herbarium specimens, not from field survey so there was no census of what was actually growing on the island at the time. These records of the Farasan Archipelago flora are now seriously out of date, and no modren checklist of the Farasan Archipelago exists. The current lists do not account for recent taxonomic changes to families as a result of the Angiosperm phylogeny group (APG, 2016).

Despite the importance of the Farasan Archipelago Flora, it is vulnerable to biodiversity loss due to its small size, isolation and fragility. The vegetation has faced anthropogenic, ecological and invasive plant species pressures. The islands are the home of 20000 people who derive much of their economic resourses and environmental value directly or indirectly from the rich natural resources in their immediate environment. In addition, from 4000 to 5000 tourists visit Farasan and Sajid Islands during vacation periods, with the most popular location being along the beach, leading to significant threats to the coastal vegetation (Gladstone, 2000). Although Coastal zones in the islands are characterized by highly diverse ecosystems that are important as a source of food and as habitat for many species and support a variety of economic activities which has led to a high rate of population growth and economic development, it is under intense threats from multiple drivers. Overgrazing, woodcutting, removal of shoreline sand for construction of hotels and resorts, tourism, drought, climate change, off-road driving, unsustainable exploitation, fishing , shipping of resources and pollution by domestic, tourist and industrial waste (Gladstone *et al.*, 1999, Gladstone *et al.*, 2003, Gladstone, 2009). In addition, the extent of this biodiversity deterioration varies from one island to another, however the Farasan Alkabir Island is becoming the most threatened (Mandura and Khafaji, 1993) because of the increasing number of tourists, urbanisation development of coastal area and construction of leisure centres.

As the flora of any region is a useful source of information for biogeographical, ecological and evolutionary studies (Peruzzi, 2018), floristic records and the analyses of plant species distribution across a geographic area are essential to provide suitable data for decision-making processes in biodiversity conservation and landscape planning (Thomson *et al.*, 2018, Heywood, 2017). Particularly, islands have long served as an inspiration for evolutionary hypotheses because their biotic assemblages and ecological processes are clearly delimited by geographical constraints (Macarthur and Wilson, 1967, Whittaker and Fernández-Palacios, 2007). Islands host peculiar and often unique and vulnerable floras (Nunn, 2004). So, the continued update of the flora will act as a starting point for assessing plant conservation, management, and ecological restoration, providing information on the need for additional surveys or data collection (Kier *et al.*, 2005, Costanza *et al.*, 2007), and aiding the understanding of the impact of climate changes on the islands.

A plant checklist is the result of careful and thorough field work, as well as long time bibliographic research and it works as the first step of updating any flora (Fischer *et al.*, 2010). Local checklists may become out of date in a few years because further exploration may lead to the discovery of new taxa. Lots of checklists have recently has been published using online platforms (Fischer *et al.*, 2010) such as the annotated checklist of the flowering plants of Nepal http://padme.rbge.org.uk/floraofnepal/ and a checklist of the Saudi Arabia flora http://www.plantdiversityofsaudiarabia.info. Mainly because of their length, an online checklist could give them a consistent added value and can be updated in real time, or at more or less regular intervals. However, the checklist of the Farasan Archipelago flora is out of date, which reduces their importance for audience especially in research and education.

As taxonomists develop a flora from a checklist they conduct field expeditions and must have access to and methods for searching through the vast store of biodiversity information contained in our libraries, museums, and botanical gardens (Bisby, 2000, Edwards *et al.*, 2000). Furthermore, it is important to publish all or at least part of the available information sources on taxonomy and plant-species distribution online, with the aim of opening this content to a wider audience, which can access the information for interest in biodiversity, professional needs, pedagogical scenarios, decision-making, etc. (Martellos and Nimis, 2015). The first target of the 2020 Global Strategy for Plant Conservation (GSPC) is to produce an online flora for all known plants of the world by 2020 (Jackson and Miller, 2015).

A lot of floras are now delivered online, such as the Flora of Gibraltar http://floraofgibraltar.myspecies.info/ and flora of Madagascar www.wildmadagascar.org/flora/, and these can easily and continuously be improved without incurring the same costs as for paper-published Floras (Victor *et al.*, 2014b). Additionally, they can be updated rapidly and dynamically in comparison to the time it takes to publish in hardcopy format. However, there will inevitably be costs involved in maintaining and updating an online Flora and online floras require internet reception.

New techniques being developed in areas of computer science such as graphics, modelling, image processing, and user interface design can help make this possible. Scratchpad is one of the resources available today which provides the necessary tools to allow you to mobilise and interlink the biodiversity data (Victor *et al.*, 2014a) and link data out worldwide. It can hold multiple descriptions of the same taxon and the descriptions can be in different languages. To date, there are 826 Scratchpads by 7,115 active users covering 158,335 taxa http://scratchpads.eu/stats.

Electronic keys are modern solutions for identifying plants. These have been available since computers began processing data on morphological characteristics (Stevenson *et al.*, 2003). Identification keys are based on characters (observable features such as colour), defined by character states (blue or yellow) (Hawthorne and Lawrence, 2013). Most computer-based keys are multi-access, meaning that the sequence of steps is not fixed in a particular order and multiple character states are available at each step (Farr, 2006). Electronic field guides included colour images and have been turned into electronic files to make identification of known taxa easier and faster. More high-level versions include electronic keys created through character databases such as Delta: https://www.delta-intkey.com/www/data.htm, OpenKey http://www.ibiblio.org/openkey/ and Lucid http://www.lucidcentral.com/. The most frequently used is Lucid key, some versions of this electronic key are now available online, that can continually be revised and updated such as the Lucid Key of the invasive terrestrial plants in Europe https://keys.lucidcentral.org/keys/v3/invasive_terrestric_plants/en/index.html published by (Duistermaat *et al.*, 2017). Others are available for downloading and can be used it without internet connection. Scratchpads support the integration of Lucid keys to identification (Smith *et al.*, 2011). However, no previous studies have produced a single electronic resource and electronic keys for the Farasan Archipelago Flora.

1.3 Population genetics for conservation assessment

Population genetic research is commonly used to provide important perspectives for conservation (Mcmahon *et al.*, 2014), allowing biologists to assess the genetic variation and genepool structure of species and to establish conservation management strategies (Allendorf *et al.*, 2007, Höglund, 2009). Anthropogenic activities have caused fragmentation of the natural populations due to habitat destruction (Haddad *et al.*, 2015).

Genetic diversity can be described as genetic variability between and within populations, and is a part and key component of species diversity (Hughes *et al.*, 2008). Genetic diversity caused by gene flow, mutations, genetic drift, and natural selection is important in the survival of species (Eriksson *et al.*, 2006, Frankham *et al.*, 2004, Frankham, 2005) and patterns of diversity reflect the role of these factors (Hedrick, 2011, Fu *et al.*, 2016).

In general a lot of island populations often harbour lower levels of gene diversity and higher levels of differentiation when compared with the mainland, and are at increased risk of extinction, possibly due to greater environmental and demographic stochasticity (Haddad *et al.*, 2015). A correlation between genetic variation within populations and differentiation among populations has been found with population size, fragmentation, and breeding system (Luijten *et al.*, 2000, De Vere *et al.*, 2009). Other studies have found negative relationships between population size and genetic diversity (Vergeer *et al.*, 2003). In general, in small isolated populations, species persistence is completely affected by enhanced random genetic drift, increased inbreeding, and as a consequence increased homozygosity (Ellstrand and Elam, 1993). Moreover, when the habitat is fragmented, populations lose their connectivity, and gene flow is interrupted (Chávez-Pesqueira *et al.*, 2014).

Because conservation genetic studies can provide important instruments for conservation, they are clearly applicable to populations of species found in Biodiversity Hotspots. In the Farasan Archipelago most species occur in fragmented populations due to habitat patterns. Currently, *Avicenna marina* and *Rhizophora mucronata* (**Figure 1.11, Figure 1.12)** are both rare and threatened in the Arabian Red Sea Region. Both of these two species occur in harsh environmental conditions and have some physical barriers which lead to variation in the amounts of genetic exchanges among the parts of the populations. Although the importance of mangrove species in helping the conservation of the flora and fauna is evidenced by a number of studies around the world, only one study of Red Sea mangroves mentions the genetic structure, in this case, of the north Red sea grey mangrove, *Avicennia marina* (Yoshimori *et al.*, 2015). Other studies have been focused different aspects such as the distribution patterns and growth attributes (Ahmed and Abdel-Hamid, 2007), ecological aspects (Almahasheer *et al.*, 2017, Saifullah, 1997, Simões *et al.*, 2015), conservation status aspects (Khalil, 2015, Khraiwesh *et al.*, 2013) and distribution mapping (Abdel-Hamid *et al.*, 2018).

Molecular marker technologies are commonly used in genetic diversity studies (Omondi *et al.*, 2016, Idrees and Irshad, 2014). Various molecular markers are being developed and used in mangrove genetic studies, including Simple Sequence Repeats (SSRs) in Ecuador (Basyuni *et al.*, 2017), East African (Nehemia and Kochzius, 2017) and Colombia (Salas-Leiva *et al.*, 2008); Inter Simple Sequence Repeat (ISSRs) in Qatar (Ahmed and Babssail, 2012) and China (Wang and Xie, 2010); Restriction Fragment Length Polymorphisms (RFLPs) in east and west coast of India (Lakshmi *et al.*, 2000); Random Amplification of Polymorphic DNAs (RAPDs) in the east coast of India (Hazarika *et al.*, 2013), Amplified Fragment Length Polymorphisms (AFLPs) in Brazil, Rio de Janeiro State (Lira-Medeiros *et al.*, 2015) and Single Nucleotide Polymorphisms (SNPs) in the Indo Malayan coast (Guo *et al.*, 2018). Among these, SSRs, also known as microsatellites, are good tool for studying the effects of gene flow, genetic drift and structure of population genetics (White *et al.*, 2007). SSRs are co-dominant highly polymorphic DNA markers, and more informative than the RAPDs or AFLPs (the dominant markers) especially for diploid organisms (Nadeem *et al.*, 2018). SSRs have a few advantages over SNPs using modern genotyping platforms, though they are low throughput and might cost more per unit. SSR markers have been commonly used in an extensive range of fundamental and applicable fields, for assessment of population structure, differentiation, genetic conservation, molecular breeding, and paternity testing. It is possible to track fingerprinting of each individual and investigate the evolutionary history of species after glaciations (Hoshino *et al.*, 2012). Thus, they are most useful co-dominant marker systems. The analysis of microsatellite variation can be done with agarose and acrylamide gels, but due to the high allelic variation analysis of dye-labelled fragments with capillary sequencing is more accurate.

Figure 1.11 *Rhizophora mucronata* population in the north eastern of Farasan Alkabir Island, AlQandal area.

Figure 1.12 *Avicenna marina* population in the north eastern of Farasan Alkabir Island, AlQandal area.

1.4 Regional IUCN Red listing for conservation assessment

The International Union for the Conservation of Nature (IUCN) conservation assessments are statements on the level of threat associated with particular species or habitats. IUCN curates the IUCN Red List of threatened species which is widely recognised as the most comprehensive and consistent way to evaluate conservation status (Rodrigues *et al.*, 2006, Miller *et al.*, 2007). IUCN Red Listing is the accepted standard for calculating the risk of species extinction (Hoffmann *et al.*, 2008), it is also used as an indicator for assessing ecosystem status (Rodríguez *et al.*, 2015) and also as an indicator for allocating funds and conservation efforts (Trousdale and Gregory, 2004).

Along with assessing the risk of species becoming globally extinct, Red Lists can also be compiled on continental, national or smaller regional scales (Collen *et al.*, 2013, Stojanović *et al.*, 2013). Within any region the species have different distribution histories, ranging from those that are endemics to the area to non-endemic or native species, and may some of these taxa are now extinct in the region but which are still extant in other parts in the world (Gärdenfors, 1996, Baillie *et al.*, 1995). Therefore, it is important to assess species at regional levels, where conservation policy is often implemented (IUCN, 2001).

Regional Red Listing is the first step needed to highlight the danger of extinction of species. This listing aids reporting to international conventions, such as target two of the Global

Strategy for Plant Conservation (GSPC) which calls for a preliminary assessment of the conservation status of all known plant species at national, regional and international levels (The Secretariat of the Convention on Biological Diversity, 2002). In addition, data collected from individual smaller regions may be critical for the assessment of the larger region, and have consequences for conservation planning (IUCN, 2012).

The IUCN Regional Application Working Group (RAWG), was formed under the SSC Red List Programme Subcommittee (Gärdenfors *et al.*, 1999), and a final revision of the guidelines was recommended for adoption by the IUCN Species Survival Commission in 2002. The regional and global IUCN assessments are largely complementary in terms of taxonomic and geographic coverage, however the combining of the regional and global Red listing assessment provides more support for GSPC targets on conservation of plants (Mounce *et al.*, 2018).

Any publication that results from a regional assessment process should include critical components such as the regional Red List Category, the global Red List Category, an estimate of the proportion (%) of the global population occurring within the region, and monitoring and evaluation of vulnerable species (Gärdenfors *et al.*, 2001). It is widely assumed that the regional Red List appears to be integrated in many aspects of conservation such as policy development and awareness raising (Hoffmann *et al.*, 2008, Rodrigues *et al.*, 2006). In addition, regional Red Listing has led to positive conservation results, though this has not been systematically measured (Milner-Gulland *et al.*, 2006, Garavito *et al.*, 2015). However, regional assessment has been carried out in a two-step process in comparison with the global assessment. In the first step, the criteria of the global IUCN Red List are applied to the regional population of the taxon as published in IUCN (2001), resulting in a preliminary categorization. In the second step, the existence and status of any conspecific populations outside the region that may affect the risk of extinction within the region should be investigated, particularly If the taxon is non-endemic to the region. Then, the regional Red List category should be changed to a more appropriate level that reflects the extinction risk as defined by criterion E (Gärdenfors *et al.*, 2001).

The Farasan Archipelago is potentially important for the preservation of regionally threatened species, habitats and assemblages (Hall *et al.*, 2008, Hall *et al.*, 2010). This Archipelago is potentially important not only for biodiversity conservation but also for the conservation of wilderness. However, no IUCN Red Listing for any taxonomic group of the Farasan Archipelago Flora has been done, and very little is being done about habitat protection, or raising public awareness of the threatened plant species particularly in the coastal zone (**Figure 1.13, Figure 1.14)** which appears to be the most threatened area in the Farasan archipelago.

1. 5 Aims and Outline

There are five core aims to this study:

1. To generate an updated checklist of the Farasan Archipelago Flora
2. To initiate a single, comprehensive, electronic documentation source for the plants in the Farasan Archipelago
3. To provide an exemplar system of electronic keys to the Farasan Archipelago flora
4. To assess genetic diversity within and between the populations of exemplar species in different islands.
5. To apply the red listing and conservation assessment on the status of some species under pressure in the coastal zone of the Farasan Archipelago

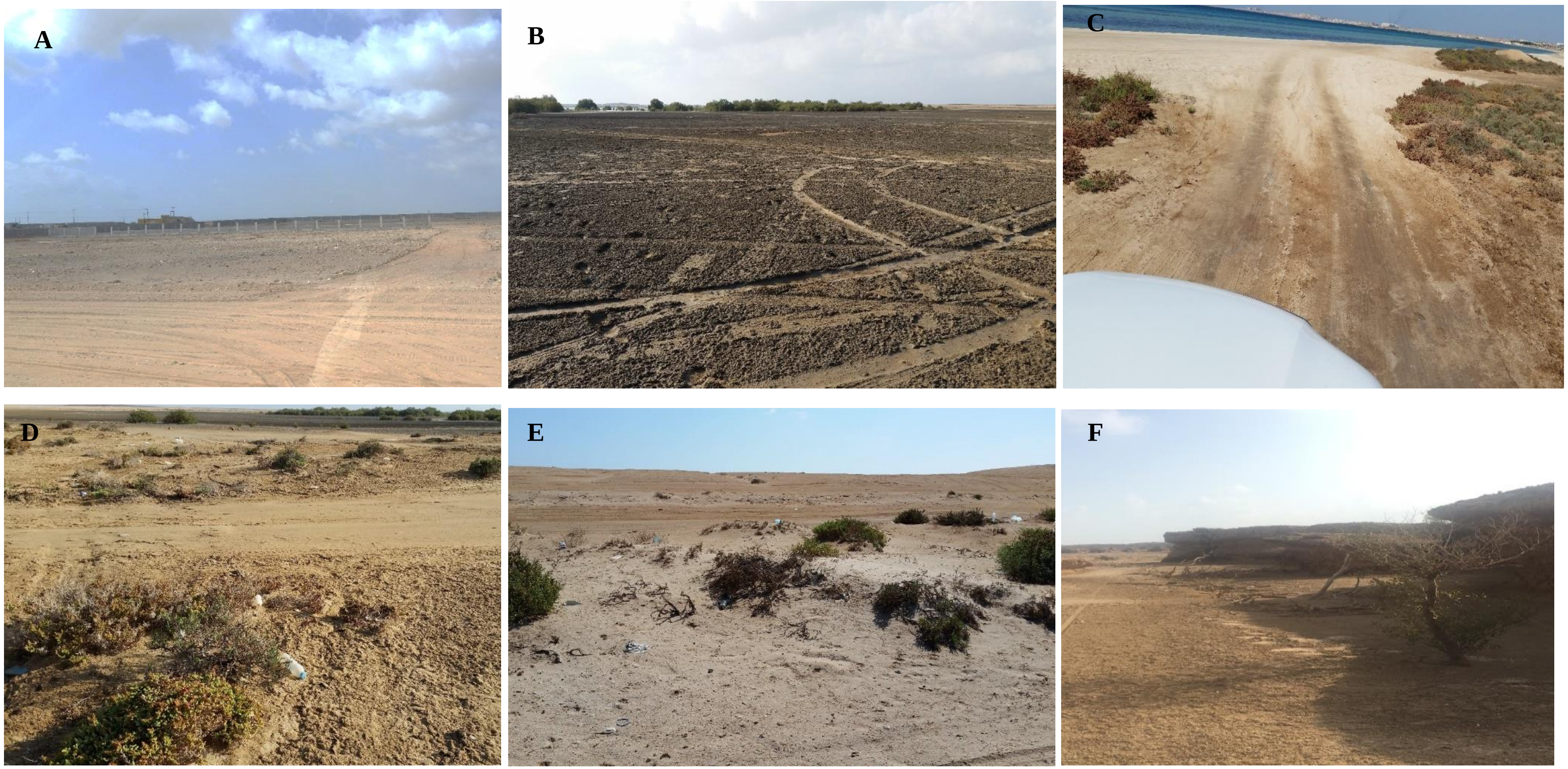

Figure 1.13 The threatened locations in the Farasan Archpeligoparticularly the coast zone. A. The construction area, B-C-D. Off-road driving in several vegetative beach in Farasan Alkabir Island, E. Off-road driving in Sajid Island, F. Mangroves mortality area, near the main port in Farasan Alkabir Island.

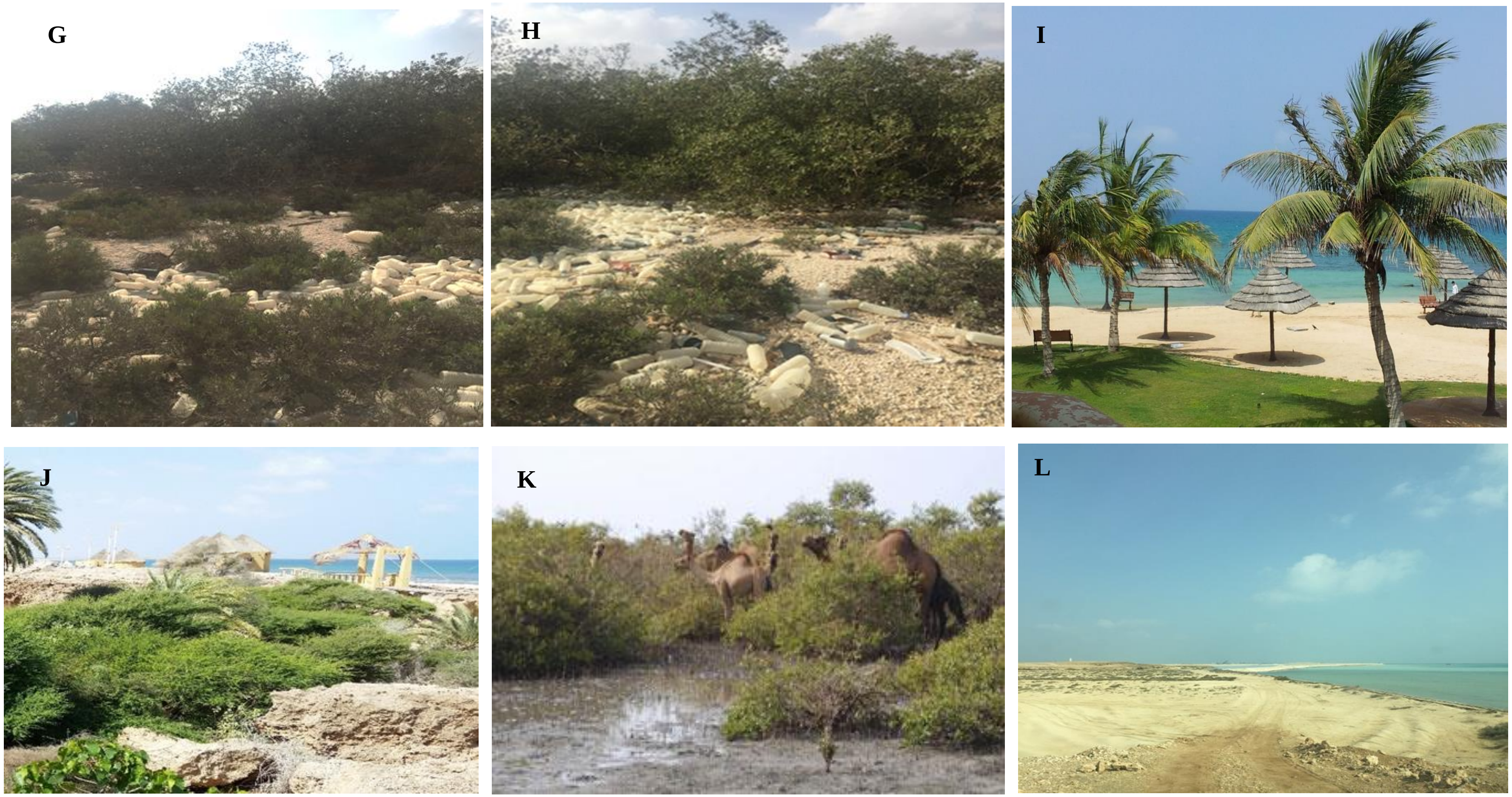

Figure 1.14 The threatened locations in the Farasan Archpeligo particulary the coast zone. G-H. Solid waste within mangrove populations in Farasan Alkabir Island, I-J. Hotels and resorts on beach in Farasan Alkabir Island, K. Camel grazing within *A.marina* population in Farasan Alkabir Island, L. Off road driving in the north beach of Farasan Alkabir Island.

CHAPTER 2

Progress towards an updated checklist of the Farasan Archipelago Flora

CHAPTER 2

Progress towards an updated checklist of the Farasan Archipelago Flora

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Abstract

The Farasan Archipelago is an Important Plant Area in the Arabian Peninsula. The islands are small, low lying and subject to considerable tourist and industrial development putting their native flora at risk. Here we report an updated checklist covering 52 families, including 152 genera and 245 species that is published online for the first time. This inventory was performed by baseline survey from literature followed by field surveys across the entire islands. Taxonomic updates result in four new family reports: Cleomaceae, Asphodelaceae, Loranthaceae and Asparagaceae. Forty percent of the flora has been reclassified at the family, genus or species level based on modern treatments, and the remaining sixty percent remain unchanged. This checklist will help to focus conservation efforts and provide a framework for research, conservation and policy development for The Farasan Archipelago flora.

ADDITIONAL KEY WORDS: flora checklist- taxonomy- the Farasan Archipelago- APG IV.

2.1 Introduction

Regional checklists provide the key for exploration of biodiversity, understanding of the dynamics and distributional structure of flora on the one hand, and to the administration and conservation of biodiversity on the other (Drake *et al.*, 2002, Galanos, 2015). The flora and plant communities of the Farasan Archipelago are of great significance as the islands occupy an environment totally dependent of the influence of other communities of the surrounding mainland (Alfarhan *et al.*, 2001), and are the result of an admixture of the elements of Asia, Africa and the Mediterranean (Alfarhan, 1999). The island coastline is a major area of highly productive littoral biotope important as a refuge for many animals, birds and fish (Mandura, 1997).

The Farasan Archipelago flora has long been recognised as an important plant area for conservation in the Red Sea (Hall *et al.*, 2010), according to the adapted Arabian assessment criteria (Al-Abbasi *et al.*, 2010). It contains seven main islands of more than 10 km² and has been managed by the Saudi Wildlife Commission (SWC) as a protected area since 1989 (Hall *et al.*, 2010). The islands are characterized by seven plant communities, each of which could easily be linked to a habitat type (Tomas *et al.*, 2010).

Group one is characterized by the dominant *Abutilon pannosum*, which occupies the wadi channels. Group two is characterized by a combination of *Phoenix dactylifera* and *Acacia ehrenbergiana* (now commonly treated as *Vachellia flava* (Forssk.) Kyal. & Boatwr.), and this group has the largest share of annual species in dry habitat. Group three is present in rocky plains, it has two codominant species: *Indigofera spinosa* and *Acacia tortilis* (= *Vachellia tortilis* (Forssk.) Galasso & Banfi). Group four is characterized by *Commiphora opoblassimum* and *Stipagrostis ciliata* which are co-dominant, and it is present in coral rock habitats. Group five is characterized by the dominance of the halophyte *Limonium axillare* in saltmarshes habitat and the occurrence of many xerophytic species, notably *Atriplex farinosa*, *Stipagrostis ciliata*, *Blepharis ciliaris* and *Aerva javanica in vegetated beach*. Group six is characterized by *Panicum turgidum* and *Zygophyllum coccineum*, which dominates the sand habitat with a very low moisture content. Group seven is characterized by the dominance of the mangrove habitat type *Avicennia marina* and

Rhizophora mucronata (Alfarhan *et al.*, 2001). The south-eastern area of Farasan Alkabir Island, where the land is rugged, has the highest diversity of the Farasan Archipelago vegetation (Alfarhan *et al.*, 2001).

The climate of the Archipelago is little understood because the absence of a weather station and is commonly compared with Jizan region (the nearest area of mainland). Due to the differences in topology the archipelago's environment may be different. In general, the climate in the coastal area of Jizan region which is nearly the same of the Farasan Archipelago is arid and subtropical with a long hot season from April to October and a short mild one from November to March (Ibrahim, 2008).

Several researchers and plant collectors have contributed towards the knowledge of the flora and vegetation of these remarkable islands. Since 1993 many revisions, checklists and vegetation notes have been recorded (Alwelaie *et al.*, 1993, Alfarhan *et al.*, 2001, Rahman *et al.*, 2002, Hall *et al.*, 2010). The flora comprises 219 species of plants in 52 families (Hall *et al.*, 2010). A detailed account on the major families of the Farasan Archipelago flora, has been given by several authors at ecological and floristic level, 13.8% Fabaceae and 12.6% Poaceae are the highest represented families and the most common annual species belong to other families: *Euphorbia prostrata* (Euphorbiaceae) with 11.5% and *Corchorus depressus* (Tiliaceae) with 8.6%. There are 14 species reported in the Farasan Archipelago, but not previously reported elsewhere in Saudi Arabia (Alfarhan *et al.*, 2001, Tomas *et al.*, 2010) .

Although previous floras provide a good reference from a taxonomic perspective, the flora of the Farasan Archipelago is now out of date. The most recent checklist on the Farasan Archipelago flora was in 2010 (Hall *et al.*, 2010), however the taxonomic systems have changed, the information about an exact number of taxa and their distribution patterns within Islands not recent reported and new species have been discovered. The Farasan Archipelago is a small land area in the most arid environment compared to mainland (Saudi Arabia), and there are not many islands belonging to Saudi Arabia. In addition, the Archipelago has been developed for tourism and industry, and has become a popular tourists destination for Saudi families, that is threatening the habitats (Gladstone *et al.*, 1999, Gladstone, 2000).

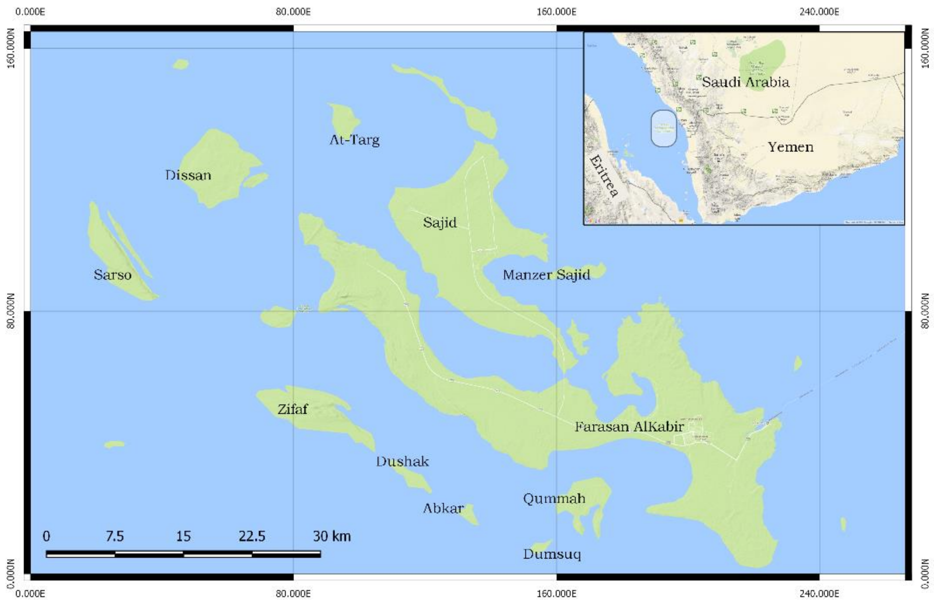

Figure 2.1. The Farasan Archipelago (Saudi Arabia), in the southern region of the Red Sea, approximately 50 km^2 from the Saudi Arabian city of Jizan.

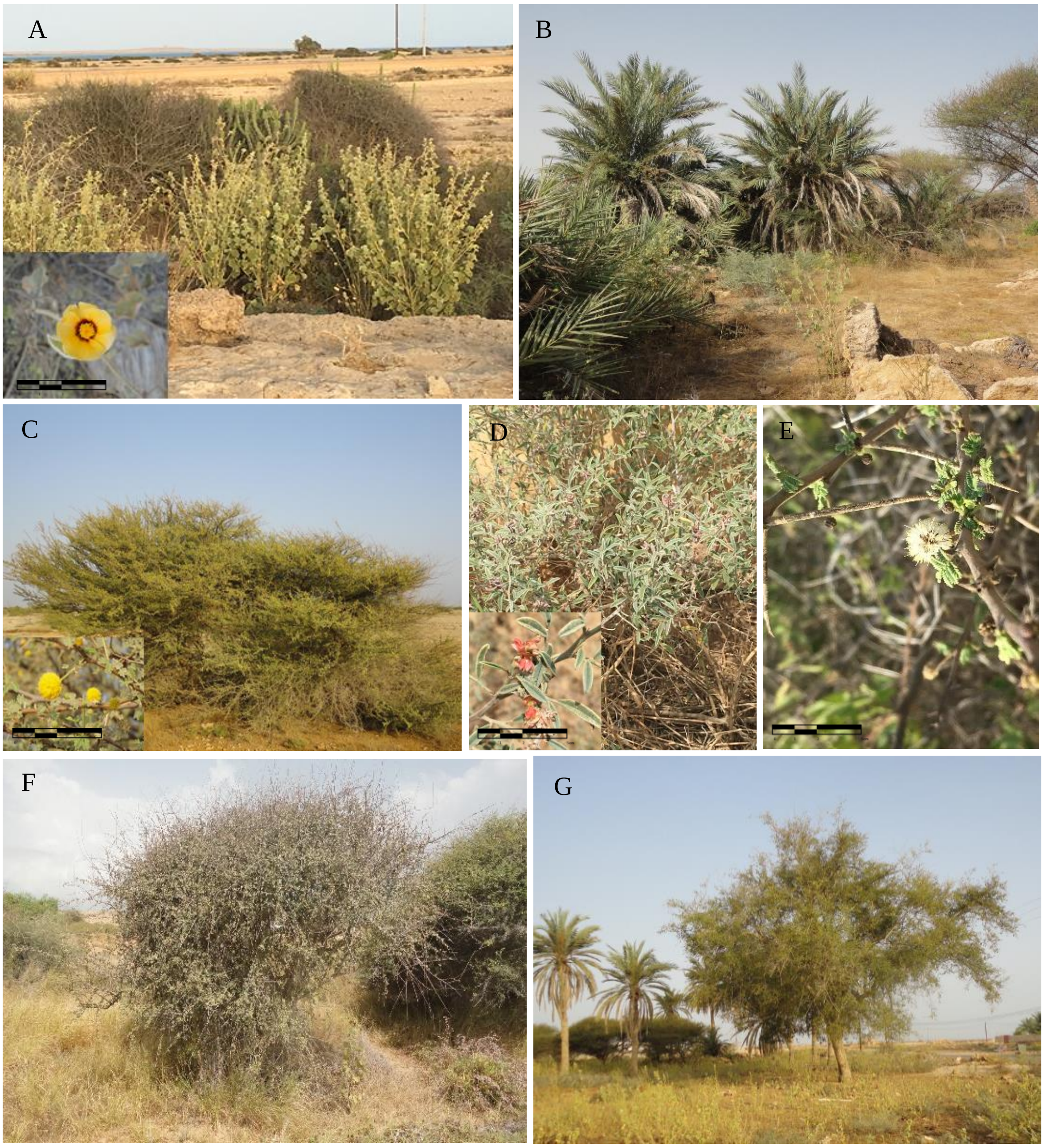

Figure 2.2. Plant communities related with habitat in the Farasan Archipelago A. *Abutilon pannosum* population in wadi channels habitat, B&C. *Phoenix dactylifera* and *Acacia ehrenbergiana* populations in dry and rocky habitat, D&E. *Indigofera spinosa* and *Acacia tortilis* in rocky habitat, F. *Commiphora opoblassimum* in coral rock habitat, and G. *Ziziphus spina-christi* in farmland field, Scale bar = 5cm.

Figure 2.3. Plant communities related with habitat in the Farasan Archipelago H&I. *Suaeda fruticosa* and *Limonium axillare* in saltmarshes habitat, J. *Euphorbia collenetteae* in rocky habitat, K-O. *Blepharis ciliaris, Limonium axillare, Tetraena coccinea, Tetraena simplex* and *Tetraena alba* var. *alba* in sand habitat and vegetated beach, P&Q. *Avicennia marina* and *Rhizophora mucronata* indicating the mangrove habitat types. Scale bar = 5cm.

Most of the natural vegetation in the Farasan Archipelago were medicinal and fodder plant. Their habitats are threatened by continued degradation. In addition, *Prosopis juliflora* has been introduced to the Farasan Islands as an ornamental plant, however the plant has escaped cultivation and invaded many areas in the island (**Figure 2.4)** where it out-competes native plant species.

To document the present vegetation abundance of the natural systems of the Farasan Archipelago it is important to maintain an up to date checklist of the flora of the Farasan Archipelago. This paper builds on previous Floras by updating those reports within the current circumscriptions of plant families, genera, species and lower taxa, and aims: 1) to verify previous checklists and to present an updated checklist for the Farasan Archipelago Flora, based on field observations and 2) to describe the distribution patterns of taxa on the islands from field survey to allow conservation planning.

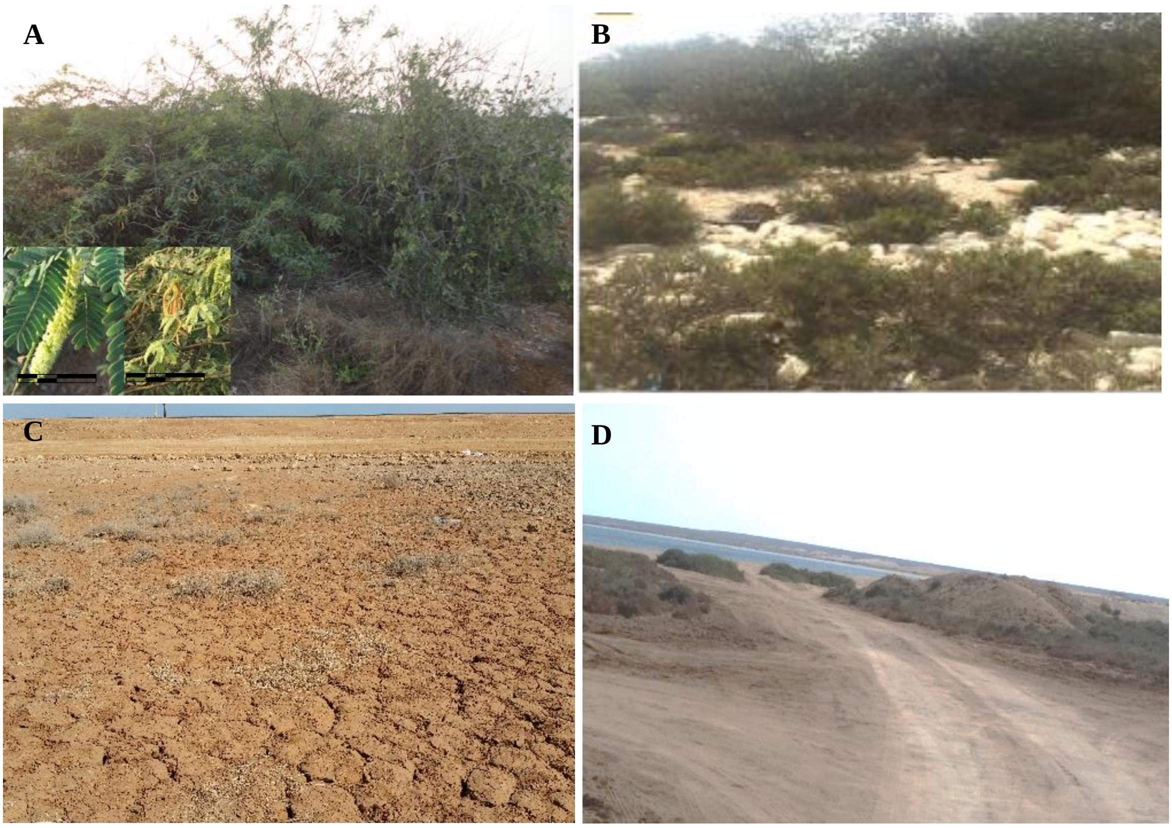

Figure 2.4. A. *Prosopis juliflora* is an aggressive invader of rangelands in Farasan Alkabir Island, B. mangrove population near the port of Farasan Alkabir Island have been converted to a disposal site, C. drought area in Farasan Alkabir Island, D. off road on the coast zone of Farasan Alkabir Island.

2.2 Material and methods

2.2.1 Construction of a working checklist

An Excel spreadsheet recording the number and the name of species, families, author and date of the documentation has been built from published literature and field trips. This primary checklist from multiple references has been used as the basic information to build an updated checklist for the Farasan Archipelago and as a guide for field trips conducted. From this, an update of the nomenclature and taxonomic circumscription by using the recent taxonomic treatment studies at species level, and the taxonomic databases for the currently accepted name of plants, has been done. The Plant List (TPL), International Plant Names Index (IPNI), Catalogue of Life, The Integrated Taxonomic Information System (ITIS), World Checklist of Selected Plant Families (WCSP, 2017), and Angiosperm Phylogeny Group APG IV (APG, 2016) were used to re-circumscribe and concerning the validity of the plant families.

2.2.2 Field trips

Three Field surveys were conducted in the Farasan Archipelago, in the period from 2015 to 2016, (**Table 2.1**). Permits to visit the islands and collect were obtained from the Saudi wildlife authority (SWA). Within the Archipelago the first field trip focused on the six islands over 10 km²: Farasan Alkabir (369 km²), Sajid (149 km²), Zifaf (33.2 km²), Qummah (15.2 km²), Dumsuq (12 km²) and Dushak (149 km²), however, the second and third field trips focused on the two main islands. Plant specimens were collected from these islands, from different sites representing various ecological habitats within the study area. Several species were photographed for later identification performed by the authors and generally checked afterwards with other local and foreign botanists. Then, data were deployed in the Scratchpad 'E-Flora of the Farasan Archipelago'.

Table 2.1. Details of the three field trips to confirm reported the Farasan Archipelago flora checklist.

The Field trips	**The visited islands**	**The period of each field trip**
First	Farasan Al-Kabir, Sajid, Zifaf, Qummah, Dumsuq and Dushak	15 th June to 15 th July 2016
Second	Farasan Al-Kabir, Sajid	12 th December 2016 to 29 th December 2016
Third	Farasan Al-Kabir, Sajid	25th December 2016 to 4th January 2017

2.3 Results

A total of 245 species belonging to 152 genera and 52 families from the islands were recorded from literature, (**Table 2.2)**. It was noticed that Farasan Alkabir and Sajid Islands have the highest number of species. Of these, 144 species were confirmed by field work (**Table 2.3)**, and the remaining 101 species are not confirmed however, seven species are new records for the islands. Two of the seven species did not match any previous recorded taxa and working is going to identify these species. No endemic taxa have been reported to occur in all the Farasan Archipelago, only nine species can be included that do not occur elsewhere in Saudi Arabia. The analysis of the life form spectra of the vegetation in the Farasan showed that Geophytes had the highest contribution in the study area, followed by chamaephytes, therophytes, phanerphytes, Epiphytes and the parasite species were the lowest percentage, (**Figure 2.6A**). 171 species recorded as perennials habits and 69 species are annuals (**Figure 2.6B**). Regarding the global phytogeographical distribution, the bi-regionals species were the highest (124 species), followed by mono-regional species (102 species) and pluri-regional (12 species) were the lowest (**Figure 2.7 A and B**).

Table 2.2. An updated checklist An Updated Checklist covering 52 families from the Farasan Archipelago flora contain 152 genera and 245 species. (**1**) the first field trip, (**2**) the second field trip, (**3**) the third field, (**-**) Species not reported on an Island, (**L**) literature review only, (*) New Species report, and species restricted to the Farasan Archipelago (**#**) within the flora of Saudi Arabia. Life forms: **Ch,** chamaephytes; **G,** geophytes; **P,** parasites; **Ph**, phanerophytes; **EP**, Epiphytes and **Th**, therophytes. Habit: **Per**, Perennial; **Ann**, Annual. Chorotypes: **SA**, Saharo-Arabian; **SU**, Sudano-Zambezian; **IT**, Irano-Turanian; **ME**, Mediterranean; **TR**, Tropical; **IN**, India and **Plu**, Pluriregional. The literature review coding as **A=** Kyalangalilwa *et al*., (2013), **B=**Thulin and Roalson (2017), **C=** Basahi& Masrahi (2019), **D=** Bruyns *et al*., (2017), **E=** Al-Zahrani (2010), **F=** Simmons et al., (2008), **G=** Collenette (1999), **H=** Collenette & Tsagarakis (2001), **I=** Alwelaie *et al*. (1993), **J=** Hassan & Al-Hemaid (1996), **K=** Atiqur Rahman *et al*. (2002), **L=** SWC field records, **M=** Chaudhary, (1999; 2001a; 2001b; 2001c), **N=** Alfarhan *et al*., (2005), **O=** Al-Zahrani, & El-Karemy (2007), **P=** Hall *et al*. (2010), **Q=** Aldhebiani (2010).

Family and Species	The Farasan Islands field trips						Chorotypes	Habit	Life form	Previous name	Literature review	Justification for name change
	Farasan Al Kabir	Sajid	Zifaf	Qummah	Dumsuq	Dushak						
1. Acanthaceae												
Avicennia marina (Forssk.) Vierh.	1&2	1&2	1	–	–	–	SU+SA	Per.	Ph		I, G, M, N	
Barleria hochstetteri Nees	L	–	–	–	–	–	SU+IN	Per.	Ch		G, M	
Blepharis edulis (Forssk.) Pers.	1	1&2	1	–	–	–	SA+SU	Per.	Ch		M	
Blepharis saudinses	3						Endemic in FA	Per.	Ch	*Blepharis sp.**	C	New record-morphology data
Ecbolium viride (Forssk.) Alston	L	–	–	–	–	–	SU	Per.	Ch		G, M	
Justicia flava (Forssk.) Vahl	1	–	–	–	–	–	SU	Per.	G		G, M, N	
2. Aizoaceae												
Trianthema portulacastrum L.	1	2	–	–	–	–	SU	Ann.	G		G, K	
Trianthema sheilae A.G.Mill. & J.Nyberg	1	1	–	–	–	–	SU	Ann.	G		G, K	
Zaleya pentandra (L.) C.Jeffrey	L	L	–	–	–	–	ME+IN+SU+SA	Per.	G		M	
3. Amaranthaceae												

Achyranthes brachiata L. #	L	L	-	-	-	-	SU	Per.	G		G, L, K, M	
Aerva javanica (Burm.f.) Juss. ex Schultes.	2	2	1	1	-	-	TR.	Per.	Ch		G, L	
Amaranthus graecizans L.	1	-	-	-	-	-	TR.	Ann.	Th		G, L, K, M	
Amaranthus spinosus.	1	-	-	-	-	-	TR.	Ann.	Th		G, M	
Arthrocnemum macrostachyum (Moric.) K. Koch.	L	L	-	-	-	-	TR.	Per.	Th		G, M	
Atriplex halimus L.	1	1	-	-	1	1	ME	Per.	Ch		G, M	
Atriplex farinosa Forssk.	1	1	-	-	1	1	SU+SA+ME	Per.	Ch		I, K, G, M	
Chenopodium murale	1	1	-	-	-	-	IT+ME	Ann.	Th		I, K, G, M	
Cornulaca ehrenbergii Asch.	L	L	-	-	L	L	SU+ME	Per.	Ch		I, K, G, M	
Digera muricata (L.) Mart.*	1	-	-	-	-	-	SU+ SA+IN	Ann.	G		I, K, G, M	
Amaranthus viridis (L.) Moq.	L	L	-	-	-	-	SU+SA	Ann.	G		I, K, G, M	
Halopeplis perfoliata (Forssk.)	1	1	-	-	-	-	SA+ME+IN	Per.	Th		G, M	
Suaeda aegyptiaca (Hasselq,) Zoh.	2	2	-	1	1	1	SA	Ann	G		I, K, M	
Suaeda fruticosa Forssk. Ex Grueter.	1&2	1&2	-	1	-	-	SA+IN	Per.	Ch		I, K, M	
Suaeda monoica Forssk.	3	3	-	1	-	1	SU+ME	Per.	Ch		I, K, M	
Suaeda vermiculata Forssk. ex J.F.Gmel.	L	-	-	-	-	L	SU+SA+ME	Per.	Ch		I, K, M	
4.Amaryllidaceae												
Pancratium maximum Forssk.	L	-	-	-	-	-	SU	Per.	G		H	
5. Apocynaceae												
Blyttia spiralis (Forssk.) D.V.Field & J.R.I.Wood.	L	-	-	-	-	-	SU	Per.	Ch		G, M	
Boucerosia edulis Edgew.	1	1	-	-	-	-	SU+IN	Per.	Ch	*Caralluma edulis* Edgew.	D	Phylogenetic study
Calotropis procera (Ait.) Ait.f.	1	2	-	1	-	-	SA	Per.	Ph		G, M	
Caralluma adscendens (Roxb.) Haw.	L	L	-	-	-	-	SA	Per.	Ch			

Desmidorchis acutangula Decne.	1	3	–	–	–	–	SU	Per.	Th	*Caralluma retrospiciens* (Forssk.) Plowes	D	Phylogenetic study
Desmidorchis penicillata (Defl.) D.C.H. Plowes.	1	–	–	1	–	1	SU	Per.	Th		G, M	
Glossonema boveanum subsp. boveanum (Decne.) Decne. #	L	–	–	–	–	–	ME+SU	Per.	Ch		G, M	
Glossonema boveanum (Decne.) Decne.	1	1& 2	–	–	–	–	ME+SU	Per.	Ch		G, M	
Leptadenia pyrotechnica (Forssk.) Decne.	L	L	–	–	–	–	SU	Per.	Ch		G, M	
Pentatropis nivalis (J.F.Gmel.) D.V.Field & J.R.I.Wood .	L	L	–	–	–	–	SU	Per.	Epiphyt es		G, M, I	
6.Arecaceae												
Hyphaene thebaica (L.) Mart.	1&2	1	–	–	–	–	SU+ME	Per.	Ph		G, M, N	
Phoenix dactilifera L.	1	1	–	–	–	–					G, M, N	
7. Aristolochiaceae												
Aristolochia bracteolata Lam.	1	–	–	–	–	–	IT +SA+TR	Per.	Ph		G, K	
8.Asparagaceae												
Asparagus flagellaris (Kunth) Baker	1	1& 2	–	–	–	–	ME	Per.	G		G, M, K	
Dipcadi erythraeum Webb & Berthel.	L	L	–	–	–	–	SA+ME+I N	Per.	G		G, M, K	
9. Asphodelaceae												
Aloe officinalis Forssk.	1	1	–	–	–	–	SA	Per.	Ch		K, I	
Aloe vera L.*	2	–	–	–	–	–	SA	Per.	Ch		Field trip	
10. Asteraceae												
Launaea intybacea (Jacq.) Beauverd	2	–	–	1	1	–	ME+SA	Per.	Ch		H, M	
Launaea procumbens (Roxb.) Ramayya & Rajagopal.	1	–	–	1	1	–	ME+SA	Per.	Ch		H, M	
Pluchea dioscoridis (L.) DC.	L	L	–	–	–	–	SA	Ann.	Th		H, M	
Pulicaria jaubertii E.Gamal-Eldin	L	L	–	–	–	–	SU	Per.	Ch		H, M	
11.Boraginaceae												
Euploca strigosa (Willd.) Diane & Hilger.	L	L	–	–	–	–	IT+IN+SU	Per.	G		G, M	

Heliotropium bacciferum Forssk.*	2*	2*	⁻	⁻	⁻	⁻	SA+IT	Per.	Ch		G, M	
Heliotropium longiflorum Hochst. & Steud.	1	2& 3	⁻	⁻	⁻	⁻	SU	Per.	G		G, M	
Heliotropium pterocarpum (DC. & A. DC.) Hochst. & Steud. ex Bunge	L	L	⁻	⁻	⁻	⁻	SU	Ann.	G		G, M	
Heliotropium ramosissimum (Lehm.) Sieb. ex DC.	3	3	⁻	⁻	⁻	⁻	SU+IN	Per.	Th		G, M	
Heliotropium zeylanicum (Burm. fil.) Lam.	L	L	⁻	⁻	⁻	⁻	SU	Per.	G		G, M	
12.Burseraceae												
Commiphora gileadensis (L.) C. Christ.	1	1	1	⁻	⁻	⁻	SU	Per.	Ph.	*Commiphora opobalsamum* (L.) Engl.	E	Systemic study
Commiphora kataf (Forsk.) Engl.	1	⁻	1	⁻	1	1	Endemic FA	Per.	Ph.	*Commiphora erythraea* (Ehrenb.) Engl.	E	Systemic study
13. Capparaceae												
Cadaba farinosa Forssk.	1	1	⁻	⁻	1	⁻	Plur.	Per.	Ph		H, M, N	
Cadaba glandulosa Forssk.	1	1	⁻	⁻	⁻	⁻	SU+IN	Per.	Ch		H, M, N	
Cadaba longifolia DC.	L	L	⁻	⁻	⁻	⁻	SU	Per.	Ch		H, M, N	
Cadaba rotundifolia Forsk.	L	L	L	⁻	⁻	⁻	SU	Per.	Ch		H, M, N	
Capparis decidua (Forssk.) Edgew.	1	1	⁻	⁻	⁻	1	SU+ME+IN	Per.	Ch		H, M, N	
Capparis spinosa var. *aegyptia* (Lam.) Boiss.	1	1	⁻	⁻	⁻	⁻	Plur.	Per.	Ph		H, M, N	
Capparis spinosa var. *mucronifolia.*	1	1	⁻	⁻	⁻	⁻	Plur.	Per.	Ph		H, M, N	
Maerua crassifolia Forssk.	1	1	⁻	⁻	1	⁻	SA+SU+ME	Per.	Ph		H, M, N	
Maerua oblongifolia (Forssk.) A.Rich.	1	1	⁻	⁻	1	⁻	SU	Per.	Ch		H, M, N	
14.Caryophyllaceae												
Polycarpaea repens (Forssk.) Asch. & Schweinf.	L	⁻	⁻	⁻	⁻	⁻	SU+SA+IN	Per.	G		G, M	
Polycarpaea spicata Arn.	1	⁻	⁻	⁻	1	1	IT	Ann.	G		G, M	
15. Celastraceae												

Gymnosporia parviflora subsp. *Parviflora.*	L	L	−	−	−	−	SU	Per.	Ch	*Maytenus parviflora* (Vahl) Sebsebe	F	Phylogeny study
Gymnosporia senegalensis (Lam.) Loes.	L	−	−	−	−	−	SA	Per.	Ch	*Maytenus senegalensis* (Lam.) Exell.	F	Phylogeny study
Gymnosporia somalensis Loes.	L	L	L	−	−	−	SU	Per.	Ch	*Maytenus somalensis* (Engl. ex Loes.) Cufod.	F	Phylogeny study
16. Cleomaceae												
Rordia gynandra L.	1	−	−	−	−	−	SU+SA	Ann.	G	*Cleome gynandra* L.	B	Molecular and morphology data
Rordia noeana subsp. brachystyla (Deflers) D.F.Chamb. & Lamond. #	L	−	−	−	−	L	SU+IT	Ann.	G	*Cleome noeana subsp. brachystyla* (Deflers) D.F.Chamb. & Lamond. #	B	Molecular and morphology data
Rordia vahliana Fresen.	L	−	−	−	−	−	SU	Ann.	G	*Cleome vahliana* Fresen.	B	Molecular and morphology data
Dipterygium glaucum Decne.	L	−	−	−	−	−	SU+IN	Per.	Th		G, M, H	
17.Commelinaceae												
Commelina benghalensis L.	L	−	−	−	L	L	SU	Per.	Th		H	
Commelina forsskaolii Vahl.	1	−	−	−	1	−	SU	Per.	Th		H	
18.Convolvulaceae												
Convolvulus arvensis L.	1&2	−	−	−	1	−	TR	Per.	Th		G, M, N	
Convolvulus glomeratus Hochst. ex Choisy.	1&2&3	2	−	−	1	−	SA	Per.	G		G, M, N	
Convolvulus pilosellifolius Desr.	L	−	−	−	−	−	SA+IT	Per.	G		G, M, N	
Convolvulus rhyniospermus Choisy.	1	3	−	−	−	−	SA	Per.	G		G, M, N	
Cressa cretica L.	1	1	−	−	−	−	SU	Ann.	G		G, M, N	

Evolvulus alsinoides (L.) L.	L	–	–	–	–	–	SU	Per.	G		G, M, N	
Ipomoea eriocarpa R.Br.	L	–	–	L	–	–	SU+SA+TR+IN	Ann.	G		G, M, N	
Ipomoea hochstetteri Hous. #	1	–	–	L	–	–	IN	Ann	G		G, M, N	
Ipomoea obscura (L.) Ker Gawler	L	–	–	–	–	–	SU+SA+TR	Per.	G		G, M, N	
Ipomoea sinensis subsp. blepharosepala (Hochst. ex A. Rich.) Verdc. ex A. Meeuse	L	–	–	–	–	–	SU+IN	Ann.	G		G, M, N	
Seddera latifolia Hochst. & Steud.	L	L	–	–	–	–	SU+IN	Per.	Th		G, M, N	
Seddera virgata Hochst. & Steud. ex Hochst.	L	L	–	–	–	–	SU	Per.	Th		G, M, N	
19. Cucurbitaceae												
Citrullus colocynthis (L.) Schrad.	1	1&2	–	–	–	–	SU+SA+IT+ME	Per.	Ch		G, H, K, N	
Ctenolepis cerasiformis (Stocks) Naudin.	L	L	–	–	–	–	SU+IN	Ann	Epiphytes		G, H, K, N	
Cucumis melo var. *agrestis Naudin*.	L	–	–	–	L	–	SA	Ann.	Epiphytes		G, H, K, N	
Cucumis prophetarum L.	L	–	–	–	–	–	SA	Per.	Epiphytes		G, H, K, N	
Cucumis prophetarum subsp. *prophetarum* L.	L	–	–	–	–	–	SA	Per.	Epiphytes		G, H, K, N	
Kedrostis gijef (Forssk. ex J.F.Gmel.) C. Jeffrey.	L	L	–	–	–	–	SU	Per.	Epiphytes		G, H, K, N	
Zehneria anomala C. Jeffrey.	1	–	–	–	–	–	SU	Per.	Epiphytes		G, H, K, N	
20.Cyperaceae												
Cyperus articulatus L.	L	–	–	–	–	–	SU	Per.	G		M, N	
Cyperus bulbosus Vahl.	1	1	–	–	–	–	SU+IT+IN+SA+TR	Per.	G		M, N	
Cyperus conglomeratus Rottb.	1&2&3	1	1	–	1	1	Endemic FA	Per.	G		M, N	

Cyperus jeminicus Rottb.	1	1	–	–	–	–	SU+SA+ME	Per.	G		M, N	
Cyperus rubicundus Vah.	1	3	–	–	–	–	TR	Per.	G		M, N	
21. Ericaceae												
Erica arborea L.	L	L	–	–	–	–	SU+ME	Per.	Ph		M	
22.Euphorbiaceae												
Acalypha indica L.	1	1	–	–	–	–	SA	Ann.	G		G, M, N	
Chrozophora oblongifolia (Delile) A.Juss. ex Spreng.	L	–	–	–	–	–	SA+SU	Per.	G		G, M, N	
Dalechampia scandens var cordofana (Hochst. ex Webb) Müll.Arg.	L	L	–	–	–	–	SU+IN	Per.	G		G, M, N	
Euphorbia ammak Schweinf.	1	–	–	–	–	–	SU	Per.	G		P	
Euphorbia collenetteae Al-Zahrani & El-Karemy #	1&2	2	–	–	L	–	SU	Per.	Ch		O	
Euphorbia fractiflexa S. Carter & JRI Wood.	1	1	–	–	–	1	SU	Per.	Ch		P	
Euphorbia granulata Forssk.	1	1	–	–	–	–	SA+SU+IT +ME	Ann.	G		P	
Jatropha glauca Vahl.	1	–	–	–	–	–	SU	Per.	Th		G, M, N	
Micrococca mercurialis (L.) Benth. #	L	L	–	–	–	–	SU+IN+TR	Ann.	G		G, M, N	
23.Fabaceae												
Alysicarpus glumaceus (Vahl) DC.	1	–	–	–	–	–	SU	Ann.	G		G, M, N	
Argyrolobium arabicum (Decne.) Jaub. & Spach.	3	–	–	–	–	–	SU	Per.	Th		G, M, N	
Astragallus sp.	–	L	–	–	–	–	SU				M, I	
Crotalaria microphylla Vahl.	1	1	–	–	–	–	TR	Per.	Th		G, M, N	
*Indigofera sp.**	–	2	–	–	–	–	SU				Field trip	
Indigofera coerulea Roxb.	1&2	2	–	–	–	–	SU+IN	Per.	Th		G, M, N	
Indigofera coerulea var. *coerulea* Roxb.	1	1	–	–	–	–	SU+IN	Per.	Th		G, M, N	
Indigofera hochstetteri Bak.	1	1	–	–	–	–	SU+IN+TR	Ann.	G		G, M, N	
Indigofera linifolia (L.f.) Retz.	1	2&3	–	–	1	–	SU+IN+TR	Ann.	G		G, M, N	
Indigofera oblongifolia Forssk.	1&2	1	L	–	L	–	SU+SA+IN	Per.	Th		G, M, N	
Indigofera semitrijuga Forssk.	L	L	–	–	–	–	SU	Ann.	G		G, M, N	

Indigofera spinosa Forssk.	L	L	–	–	–	–	SU	Per.	Th		G, M, N	
Indigofera spiniflora	2	2	–	–	–	–	TR	Per.	Ch		G, M, N	
Prosopis juliflora (SW.) DC.	1	1	–	1	–	–	SU	Per.	Ph		G, M, N, K	
Rhynchosia minima (L.) DC.	1	–	–	–	–	–	SU+TR	Per.	Epiphytes		G, M, N, K	
Rhynchosia pulverulenta Stocks.	1	1&2	–	–	–	–	SU+IN	Per.	G		G, M, N, K	
Senna alexandrina Miller.	1	1	–	–	–	–	SA+SU	Per.	Th		G, M, N, K	
Senna holosericea (Fresen) Greuter.	1	1	–	–	–	–	SA+SU	Per.	Th		G, M, N, K	
*Sesbania leptocarpa.**	1	–	–	–	–	–	SU	Ann.	G		Field trip	
Taverniera cuneifolia (Roth) Ali.	L	–	–	L	–	–	SA+IN	Per.	Th		G, M	
Taverniera lappacea (Forssk.) DC.	L	–	–	–	–	–	SA+IN	Per.	Th		G, M	
Tephrosia purpurea (L.) Pers.	1	–	–	–	1	–	SA+SU+TR	Ann.	G		G, M	
Tephrosia subtriflora Hochst. ex Bak.	1	1	–	–	–	–	SU+IN+TR	Ann.	G		G, M	
Tephrosia uniflora Pers.	1	1	–	–	–	–	SU+IN+TR	Per.	G		G, M	
Tephrosia uniflora subsp. petrosa (Blatt. & Hallb.) J.B.Gillett & Ali.	L	L	–	–	–	–	SU+IN+TR	Per.	G		G, M	
Vachellia flava (Forssk.) Kyal. & Boatwr.	1	2	–	–	–	–	SU	Per	Ph	*Acacia ehrenbergiana* Hayne	A	Phylogenetic position
Vachellia tortilis (Forssk.) Galasso & Banfi.	1&2	1	–	–	–	1	SU	Per.	Ph	*Acacia tortilis (Forssk.)* Hayne.	A	Phylogenetic position
24.Juncacea												
Juncus rigidus Desf.	1	–	–	–	–	–	SU+SA+IT+ME	Per.	G		K, I	
25. Lamiaceae												
Ajuga arabica P.H.Davis.	L	–	–	–	–	–	Endemic in FA	Per.	Th		G, M, K, N	
Basilicum polystachion (L.) Moench. #	L	–	–	–	–	–	TR+IN	Per.	G		G, M, K, N	

Leucas urticifolia (Vahl) Sm.	1	1	–	–	–	–	SU+IN+ME	Ann.	G		G, M, K, N	
Ocimum basilicum L. *	2	3									Field trip	
Orthosiphon pallidus Royle ex Benth.	L	L	–	–	–	–	SU+IN+ME	Per.	Th		G, M, K, N	
Premna resinosa (Hochst.) Schauer.	L	–	–	–	–	–	SU	Per.	Ch		G, M, K, N	
26. Loranthaceae »												
*Plicosepalus curviflorus**	1	1	–	–	–	–	SA	Per.	Ch		Field trip	
27. Lythraceae	–	–	–	–	–	–						
Ammannia baccifera L.	L	–	–	–	–	–	Plur.	Ann.	G		I	
28. Malvaceae												
Abutilon bidentatum A. Rich.	L	–	–	–	–	–	IT+IN	Per.	Ch		G, L, M, N	
Abutilon fruticosum Guill. & Perr.	1	–	–	–	–	–	SU+ME+IN	Per.	Th		G, L, M, N	
Abutilon pannosum (Forst. fil.) Schltdl.	1	1&2	1	–	–	–	SA+IT+SU	Per.	Ch		G, L, M, N	
Abutilon pannosum var. figarianum (Webb) Verdc.	1	1	1	–	–	–	SU+SA	Per.	Th		G, L, M, N	
Corchorus depressus (L.) Stocks.	1&2	1	–	–	1	–	SA	Per.	G		G, L, M, N	
Corchorus olitorius L.	L	–	–	–	–	–	SA+SU	Ann.	G		G, L, M, N	
Corchorus trilocularis L.	L	–	–	–	–	–	SA+SU	Ann.	G		G, L, M, N	
Gossypium hirsutum L.	1	1	–	–	–	–	Plur.	Per.	|Th		G, L, M, N	
Grewia erythraea Schweinf.	1	1	–	–	–	–	SU+SA	Per.	Ch		G, L, M, N	
Grewia tenax (Forssk.) Fiori.	1	1	–	–	–	–	SA	Per.	Ch		G, L, M, N	
Hibiscus micranthus L.	L	–	–	–	–	–	TR	Per.	Ch		G, L, M, N	

Pavonia arabica Hochst. & Steud.	1	–	–	–	–	–	SU+SA	Per.	Th		G, L, M, N	
Roifia dictyocarpa (Webb) Verdc.	L	–	–	–	–	–	SU	Per.	G		G, L, M, N	
Senra incana Cav.	1	–	–	–	–	–	SU+IN	Per.	Th		G, L, M, N	
Sida spinosa L.	1	1	–	–	–	–	TR	Per.	Th		G, L, M, N	
29. Menispermaceae												
Cocculus pendulus (J.R.Forst. & G.Forst.) Diels.	L	–	L	–	L	–	SA	Per.	Epiphyte		H	
30. Molluginaceae												
Glinus lotoides L.	1	1	–	–	–	–	SU+TR	Ann.	G		H	
Mollugo nudicaulis Lam.	1	1	–	–	–	–	SU	Ann.	G		H	
31. Moraceae												
Ficus cordata subsp. salicifolia (Vahl) C. C. Berg.	1	1	–	–	–	–	TR	Per.	Ph		M, N	
Ficus glumosa Del.	3	–	–	–	–	–	SU	Per.	Ph		M, N	
Ficus populifolia Vahl. #	1&3	2&3	–	–	–	–	SU	Per.	Ph		M, N	
32.Nyctaginaceae												
Boerhavia diffusa L.	L	–	–	–	–	–	SU	Per.	Ch		H, K	
Commicarpus helenae (J. A. Schult.) Meikle.	1	1	–	–	–	–	SU+SA+IN +ME	Per.	G		H, K	
33.Orobanchaceae												
Cistanche phalypaea	L	L	–	–	–	–	ME	Per.	G		G, H, M	
Cistanche tubulosa (Schenk) Wight.	L	L	–	–	–	–	ME	Per.	G		G, H, M	
Striga gesnerioides (Willd.) Vatke.	L	–	–	–	–	–	SU+SA+IN	Ann	Parasite.		G, H, M	
34. Phyllanthaceae												
Andrachne aspera Spreng.	L	L	–	–	–	–	SU	Per.	Th		G, H, M	
Flueggea leucopyrus Willd.	L	–	–	–	–	–	IN	Per.	Ch		G, H, M	
Flueggea virosa (Roxb.) ex Willd.) Royle.	L	–	–	–	–	–	IN+IT	Per,	Ch		G, H, M	
Phyllanthus fraternus G.L.Webster.	L						SU+IN.	Ann	G		G, H, M	
Phyllanthus maderaspatensis L.	L	L	–	–	–	–	SU+IN	Ann.	G		G, H, M	

Phyllanthus rotundifolius Klein ex Willd.	1	1	–	–	–	–	SU+IN	Ann.	G		G, H, M	
35. Plantaginaceae												
Kickxia corallicola D.A. Sutton.	1	1& 2	–	–	–	–	Endemic in FA	Per.	G		M, N	
Lindenbergia indica Vatke.	1	–	1	–	–	–	SU+ME	Per.	G		M, N	
Nanorrhinum hastatum (R.Br. ex Benth.) Ghebr.	1	1	–	–	–	–	SU	Ann.	G		M, N	
Schweinfurthia pterosperma A. Braun	L	–	–	–	–	–	SU+IN	Ann.	G		M, N	
36.Plumbaginaceae												
Limonium axillare (Forssk.) O. Kuntze.	1	2& 3	1	–	1	1	SU+SA	Per.	Th		G, M	
Limonium cylindrifolium (Forssk.) Verdc.	1	2& 3	–	–	–	1	SU	Per.	G		G, M	
Limonium lobatum	L	–	–	–	–	–	ME	Ann.	G		G, M	
37. Poaceae												
Aeluropus lagopoides (L.) Thwaites.	1	1	1	–	–	–	Plur.	Per.	G		K, M, N	
Aristida adscensionis L.	L	L	–	–	–	–	SU	Per.	G		K, M, N	
Aristida funiculata Trin. & Rupr.	L	L	–	–	–	–	SA	Ann.	G		K, M, N	
Brachiaria ovalis Stapf.	L	L	–	–	–	–	SU+IN	Ann.	G		K, M, N	
Brachiaria ramosa (L.) Stapf.	L	L	–	–	–	–	SA	Ann.	G		K, M, N	
Cenchrus ciliaris L.	1	1	–	–	–	–	Plur.	Per.	G		K, M, N	
Cenchrus setiger Vahl.	1	1	–	–	–	–	SU+SA	Per.	G		K, M, N	
Chrysopogon plumulosus Hochst.	L	L	–	–	–	–	SU	Per.	G		K, M, N	
Cynodon dactylon (L) pers	L	L	–	–	–	–	Plur.	Per.	G		K, M, N	
Dactyloctenium aegyptium (L.) Willd.	L	L	–	–	–	–	Plur.	Ann.	G		K, M, N	
Dactyloctenium aristatum Link.	L	L	–	–	–	–	IN	Ann.	G		K, M, N	
Dactytoctenium scindicum Boiss.	L	L	–	–	–	–	SU+IN	Per.	G		K, M, N	
Dichanthium foveolatum (Delile) Roberty	1	1	1	–	1	–	SU+SA	Per.	G		K, M, N	
Digitaria ciliaris (Retz.) Koeler	1	1	–	–	–	–	SU+IN	Ann.	G		K, M, N	
Dinebra retroflexa (Vahl) Panz.	L	L	–	–	–	–	SU+IN	Ann.	G		K, M, N	
Dinebra somalensis (Stapf) P.M.Peterson & N.Snow #	L	L	–	–	–	–	SU+IN	Ann.	G		K, M, N	
Elionurus royleanus Nees ex A.Rich.	L	L	–	–	–	–	SU+IN	Ann.	G		K, M, N	
Eragrostis ciliaris (L.) R.Br.	L	–	–	–	–	–	SU+SA	Ann.	G		K, M, N	

Eragrostis lepida (A.Rich.) Hochst. ex Steud.	L	–	–	–	–	–	IN+SA	Ann.	G		K, M, N	
Eragrostis minor Host	L	–	–	–	–	–	SU+TR	Ann.	G		K, M, N	
Eriochloa fatmensis (Hochst. & Steud.)	L	–	–	–	–	–	SU+IN	Ann.	G		K, M, N	
Halopyrum mucronatum (L.) Stapf.	L	–	–	–	–	–	IN+SA	Ann.	G		K, M, N	
Hyparrhenia hirta (L.) Stapf.	L	–	–	–	–	–	SA	Ann.	G		K, M, N	
Panicum coloratum L.	1	–	–	–	–	–	SU	Per.	G		K, M, N	
Panicum turgidum Forssk.	1	1	–	–	1	–	ME+SA+IT+SU	Per.	G		K, M, N	
Paspalidium desertorum (A.Rich.) Stapf.	L	–	–	–	–	–	SA+SU+IN	Ann.	G		K, M, N	
Setaria verticillata (L.) P.Beauv.	L	–	–	–	–	–	SU+SA+TR	Ann.	G		K, M, N	
Setaria viridis (L.) P.Beauv.	3	–	–	–	–	–	SA+TR	Ann.	G		K, M, N	
Sporobolus helvolus (Trin.) T.Durand & Schinz.	1	1	–	–	1	–	SU+IN	Per.	G		K, M, N	
Sporobolus ioclados (Nees ex Trin.) Nees.	1	1	–	–	1	–	SA+ME+IN	Per.	G		K, M, N	
Sporobolus spicatus (Vahl) Kunth.	L	L	–	–	–	–	SU+SA	Per.	G		K, M, N	
Stipagrostis ciliata (Desf.) De Winter.	L	–	–	–	–	–	SU+SA+IT+ME	Ann.	G		K, M, N	
Tetrapogon tenellus (Roxb.) Chiov.	L	–	–	–	–	–	SU+IN	Ann.	G		K, M, N	
Tricholaena teneriffae (L.f.) Link.	1	1	–	–	1	–	SU+IN+ME	Per.	G		K, M, N	
Urochondra setulosa (Trin.) C.E.Hubb.	1	1	–	–	–	–	SU+IN	Per.	G		K, M, N	
38. Polygalaceae												
Polygala erioptera DC.	1	–	–	1	–	–	SA+TR	Per.	Th		G, M	
39. Portulacaceae												
Portulaca oleracea L.	1	–	–	–	–	–	plur.	Ann.	Th		M, N	
40. Resedaceae												
Ochradenus baccatus Del.	1	–	–	–	–	–	SA	Per.	Ch		M, N	
41.Rhamnaceae												
Ziziphus spina-christi (L.) Desf.	1&2	1	–	–	1	–	plur.	Per.	Ph		M, N	
42.Rhizophoraceae												
Rhizophora mucronata Lam.	1&2	–	1	–	–	–	SU	Per.	Ph		G, M, N, I	

43. Rubiaceae												
Kohautia caespitosa Schnizl.	L	–	–	–	–	–	SU+TR	Per.	G		G, M	
Kohautia caespitosa subsp. *caespitosa* Schniz.	1	1	–	–	1	–	SU+TR	Per.	G		G, M	
Oldenlandia corymbosa L.	L	L	–	–	–	–	SA	Ann.	G		G, M	
44.Salvadoraceae												
Salvadora persica L.	1	1	–	–	–	–	SA+SU+ME	Per.	Ch		G, M, H	
45. Scrophulariaceae												
Anticharis glandulosa Aschers.	2	–	–	–	–	–	IN+TR	Ann.	G		G, M, H	
46.Solanaceae												
Solanum coagulans Forssk.	1	1	–	–	–	–	SU+TR+ME	Per.	Th		G, M, N	
Solanum forskalii Dun.	1	–	–	–	–	–	IN+ME	Per.	Th		G, M, N	
Solanum virginianum L.	L	–	–	–	–	–	SU	Per.	Th		G, M , N	
47.Tamaricaceae												
Tamarix aphylla (L.) Karst.	1&3	–	–	1	–	–	SA	Per.	Ph		G, M	
48. Urticaceae												
Forsskaolea viridis Ehrenb. ex Desf.	L	–	–	–	–	–	SU+TR	Ann.	G		G, M	
49.Vahliaceae												
Vahlia digyna (Retz.) O. Kuntze #	1	–	–	–	–	–	IN+TR	Ann.	G		G, M	
50. Verbenaceae												
Chascanum marrubiifolium Fenzl ex Walp.	L	–	–	–	–	–	SU+IN	Per.	Th		H, M	
Priva adhaerens (Forssk.) Chiov.	1	1	–	–	–	–	SU+IN	Per.	G		H, M	
Priva cordifolia (L.f.) Druce	1	–	–	–	–	–	SU+IN	Per.	G		H, M	
51. Vitaceae												
Cissus quadrangularis L.	1	1&2	–	–	–	–	SU+TR	Per.	Epiphytes		G, M, I	
Cissus rotundifolia (Forsk.) Vahl	1	1	–	–	–	–	SU+TR	Per.	Epiphytes		G, M ,I	
52.Zygophyllaceae												
Tetraena alba var. *alba* (L.f.) Beier & Thulin	1	–	–	–	–	1	SU+ME	Per.	Th		M, N, Q	

Tetraena propqinua ssp. *migahidii* (Hosny) M.Hall	2	–	–	–	–	–	SU+ME	Per.	Th		Q	
Tetraena coccinea (L.) Beier & Thulin	1&2	2	–	1	–	–	SA+SU+ME	Per.	Th		G, M, N, Q	
Tetraena simplex (L.) Beier & Thulin	1&2	2	–	–	1	–	SA+SU+ME+IT	Per.	G		G, M, N, Q	
Tribulus terrestris	3	–	–	–	–	–	Plur.	Ann.	G		J, M	

2.3.1 Farasan Alkabir Island (369 km²)

All habitat types were visited in Farasan Alkabir Island, across three trips, around 80% of the area of this island was covered. Some locations northwest and southeast Farasan Alkabir Island were not reachable due to the ravines, low ground ridges and the presence of earth cracks. Within the island, 60% of the surface is fossil limestone (**Figure 2.5)** and the remainder is divided among sand, and mangrove habitat. 144 were found in Farasan Alkabir Island from a total of 245 species previously reported in this island. Three of the species (*Ficus populifolia, Euphorbia collenetteae* and *Dinebra somalensis*), were found in Farasan Alkabir Island which is the only Saudi Arabian locality. Individuals of some of these species have been destroyed for construction, to set up farms, through infection of insect pests and some yellow and dying due to the severe drought.

2.3.2 Sajid Island (149 km²)

All habitat types were visited in Sajid Island across three trips. This island is largely flat with a higher western end and 20% of habitat has both rocky and sandy areas. Ninety-two species were found in Sajid Island from total of 140 previously reported in this island. The Four Small islands Zifaf, Qummah, Dawshak and Dumsok were visited in the first trip, however it was not possible to visit these islands in the second and third trips because the intensification of the war in Yemen (the Archipelago is located in the border area) and the lack of funds affecting the second and third trips duration and the number of visited islands.

2.3.3 Zifaf Island (33.2 km²)

The mainland side of this island is different than other islands in that the coastline is tilted upward approximately 50 m above sea level, with a broad wadi between the ridges. Thirteen species were confirmed in Sajid Island from a total of seventeen species previously reported in this island.

2.3.4 Qummah Island (15.2 km²)

The only small inhabited island. The principal occupation is fishing, though herds of goats and camels graze in the vicinity of the villages. About 50% of this small island is sandy; 50% has both rocky and sandy areas, and is surrounded by narrow bands of reef habitats, generally with water depths of less than 11 m. Twelve species were confirmed from total of fifteen species previously reported in this island. During the first field trip, only the sandy habitat was visited because there was no car making it difficult to cover the other part of Island.

2.3.5 Dushak Island (149 km²)

This is an uninhabited island. The mainland of the island has clumb of *Euphorbia fractiflexa*, and sandy beach habitat. There are a lot of small dead herbs which suggests there is no grazing in this island. Fourteen species were confirmed in Dawshak Island from total of eighteen species were previously reported.

2.3.6 Dumsuq Island (12 km²)

Dumsuq Island is the only locality in the Arabian region for *Commiphora erythraea*, which is distributed across north eastern Africa from Tanzania to Eritrea. It characterised as well as small islands by sandy beach. Twenty-six species were confirmed in Dumsuq Island from total of thirty-two species were previously reported. The three small islands Dumsuq, Dawshak and Qummah Islands are devoid of any favourable area to the growth of mangrove habitat.

The largest family was Poaceae with 35 species, representing 14.7% of the total flora. The other common families were Fabaceae (10.5%) and Amaranthaceae (6.7%). However, in the Field trips Fabaceae is the largest family with twenty species (**Table 2.3**). The geographical distribution of each species that have been recorded during the field trips shown in (**Figure 2.6)**. Asclepiadaceae, Tiliaceae, Periplocaceae, Chenopodiaceae, Hyacinthaceae, Liliaceae and Xanthorrhoeoidaceae, have become synonyms of other families following APG IV (APG, 2016), while four: Cleomaceae, Asphodelaceae, Loranthaceae and Asparagaceae, are newly applied. **Table 2.4** shows species that have been renamed to follow current taxonomic opinion. This project has published an updated online checklist and hard copy version.

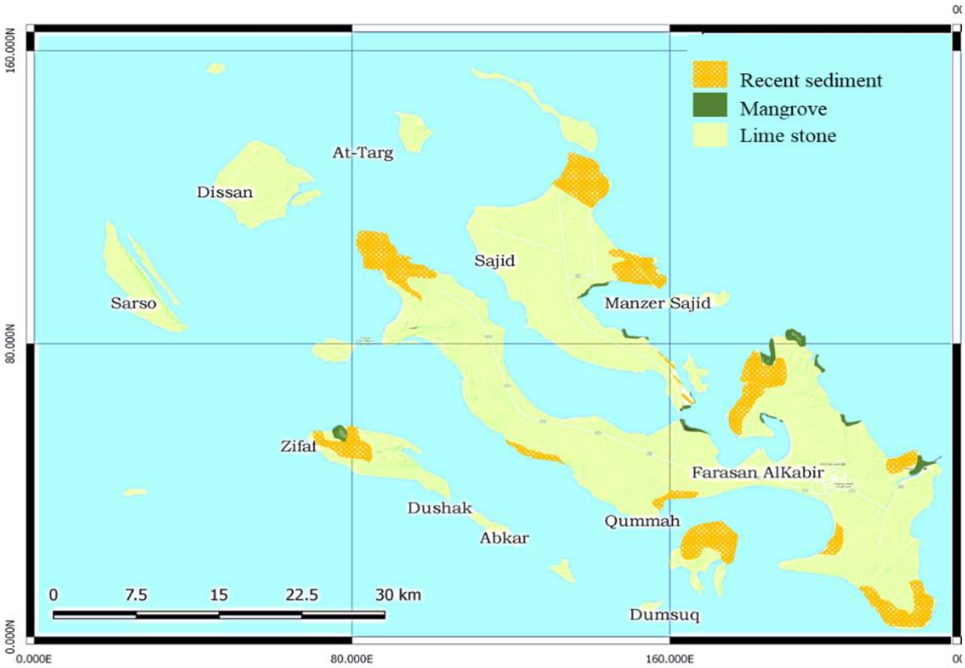

Figure 2.5. The major habitat in the Farasan Archipelago.

Table 2.3 The number of species and specimens per family which were collected during field trips.

Family	Species	Specimens	Family	Species	Specimens
Acanthaceae	4	8	Malvaceae	10	20
Aizoaceae	2	4	Moraceae	3	5
Amaranthaceae	9	29	Molluginaceae	2	4
Apocynaceae	5	12	Nyctaginaceae	1	2
Arecaceae	2	4	Plantaginaceae	3	6
Aristolochiaceae	1	1	Phyllanthaceae	1	2
Aspargaceae	1	1	Plumbaginaceae	2	8
Asphodelaceae	2	3	Poaceae	15	28
Asteraceae	2	2	Polygalaceae	1	2
Boraginaceae	3	6	Portulacaceae	1	1

Burseraceae	2	7	Resedaceae	1	1
Capparaceae	7	18	Rhamnaceae	1	3
Caryophyllaceae	1	3	Rhizophoraceae	1	2
Cleomaceae	1	1	Rubiaceae	1	3
Commelinaceae	1	2	Salvadoraceae	1	2
Convolvulaceae	5	10	Solanaceae	2	3
Cucurbitaceae	2	3	Scrophulariaceae	1	1
Cyperaceae	4	11	Tamaricaceae	1	2
Euphorbiaceae	7	11	Vahliaceae	1	1
Fabaceae	21	40	Vitaceae	2	4
Juncacea	1	1	Zygophyllaceae	5	10
Lamiaceae	2	4	Verbenaceae	2	2
Loranthaceae	1	2	**Total**	**144**	**295**

Figure 2.6 Distribution of the collecting sites of the 144 species.

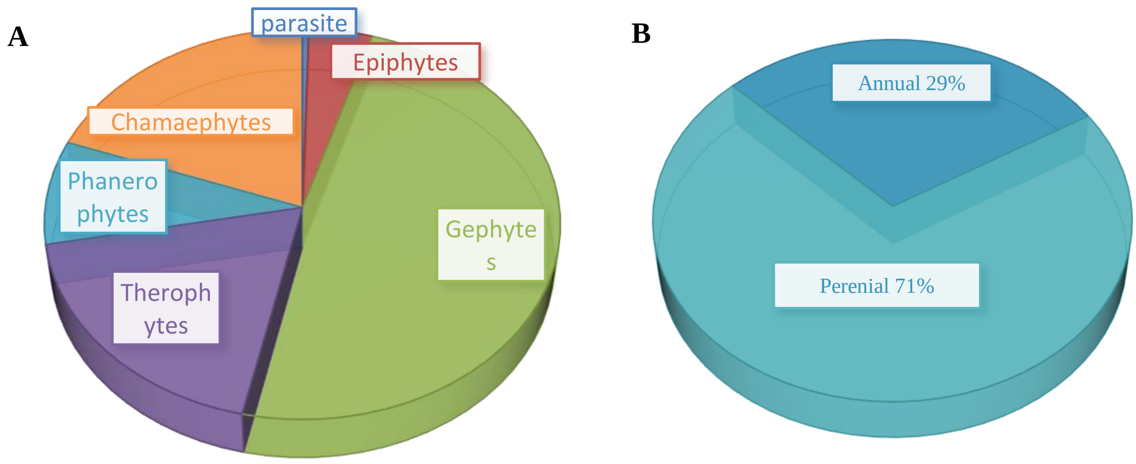

Figure 2.7 A. Life form spectra of the recorded species associated in the Farasan Archipelago, **B.** Percentage of habits of the recorded specie in the Farasan Archipelago.

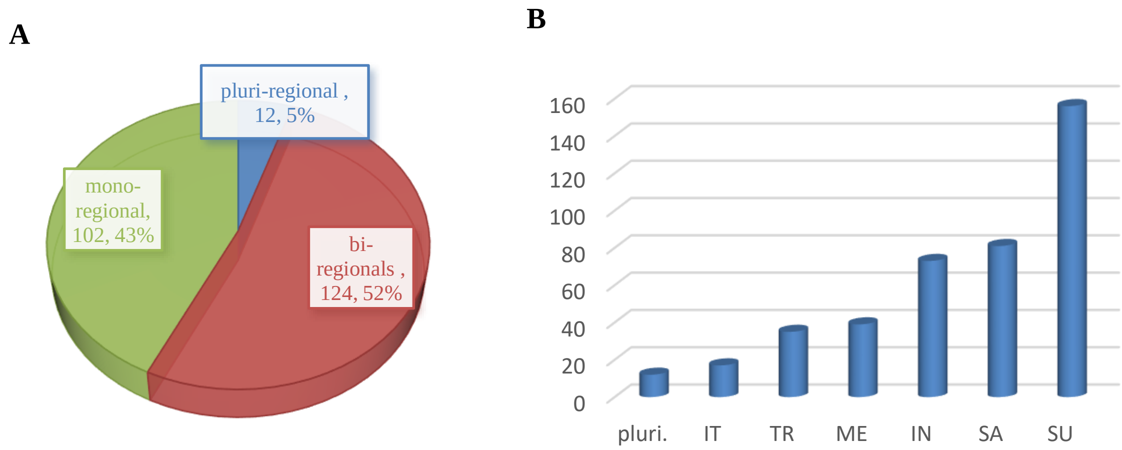

Figure 2.8 Chorotype spectra of the recorded species associated in the Farasan Archipelago.

2.4 Discussion

The previous Farasan Archipelago flora checklists vary with different authors possibly due to a species being mistakenly identified and/or in the time between different publications, populations may have gone extinct or be overlooked. The recent checklist (Hall *et al.*, 2010), lacks distribution data for many taxa and the nomenclature is now out of date. Hence, the study here used the Angiosperm Phylogeny group system for Plant Family classification followed by field surveys across the entire islands.

The update of the Farasan Archipelago checklist and record of the distribution of the remaining taxa is therefore an essential first step to create an online flora of the Farasan Archipelago that allows botanists to link their work in the area and enhances the ability to communicate internationally even further. According to size and the impact of human influence, it is obvious that the diversity of each islands different than others. The large islands have the high diversity than small islands, however the first one are facing the high anthropogenic influence as in Mandura and Khafaji (1993). This contribute to a greater focus on the large islands which are more threatened than small islands.

This study confirms that the biodiversity of the Farasan Archipelago tends to be somewhat different from the closet area on the mainland (Jizan region). Jizan region is located in the south-western tip of the country, and the rich and varied flora present in the mountains. Approximately 850 species in 434 genera of 98 families have been reported from the Jizan Region with 2.8 % endemic species(Alfarhan *et al.*, 2005). The Farasan Archipelago is in the same part of Saudi Arabia, includes 245 species (177 species are also found in Jizan region), under extreme, unrelenting environments with limited land area and thin soils, constant sea spray and the continuous exposure to strong winds.

The revision of the 16 taxa in the Farasan Archipelago which have not been reported in any other part of Saudi Arabia, with relevant literature (Chaudhary, 2001, Al-Zahrani and El-Karemy, 2007, Daur, 2012, Kasem and Marei, 2017), and herbarium specimens to be seen on the Royal Botanic Garden Edinburgh website (Collenette, I.S. No. 4017 RBGE) has shown that six of these species have since been recorded in other parts of Saudi Arabia. In addition, as a result of the change of the taxonomic status of *Commiphora erythraea* (Ehrenb.) to a synonym of widespread *C. kataf* (Forssk.) Engl (Roskov *et al.*, 2013), this taxon has been excluded from the group. Across the three field trips, only three *Ficus populifolia, Euphorbia collenetteae* and *Dinebra somalensis* from the remaining nine species were found in Farasan Alkabir Island. Five taxa *Basilicum polystachion, Ipomoea hochstetteri, Micrococca mercurialis, Nothosaerva brachiata* and *Vahlia digyna* were not found due to drought, off-road traffic, habitat loss and they are annuals and rare in small size population.

Around 60% of the Farasan Archipelago flora has been confirmed across field trips, the rest was not confirmed that due to the time of the visit did not match the growth seasons of some taxa, particularly the annual herbs and the time limitation. More surprising are the new records of as conspicuous taxa as *Digera muricata, Blepharis sp., Plicosepalus curviflorus, Ocimum basilicum, Sesbania leptocarpa, Aloe vera* and *Indigofera sp.* . Most of these records are based on only one or few individuals which were most probably overlooked, rather than established recently.

The Farasan Archipelago adhere to the species-habitat relationship. The vegetation in the small Islands, such as Dushak are dominant by halophyte plants due to the habitat type and the high soil salinity from the surrounded sea water. Larger islands often have a combination of shoreline types (salt marsh, sand formations) and their interiors are usually rocky leading to high percent of gephytes; and these islands have dominant with perennial shrubs and trees. Similarly, the succulents of saline habitats are lower than those of non-succulents, however, most succulent species were found across the field trips; because they have the ability to adapt in areas with high temperatures and low rainfall such as *Desmidorchis penicillata and Aloe officinalis.* Furthermore, some taxa which were reported across the three field trips are perennial herb, subshrub, and tree such as *Cyperus conglomeratus*, *Indigofera coerulea, Vachellia flava, Vachellia tortilis* and *Ziziphus spina-christi.* Some other taxa not found across field trips are annual herbs and suffer from the long period of drought such as *Brachiaria ovalis*. Surprising absence amongst root parasitic plants such as *Cistanche* ssp. is probably because these species occur in sand flat, where a layer of sand covers under lying rock. There is a dominance of members of the Fabaceae family, which are characteristic of desert and semi-desert regions with high temperature and low rainfall as well as Saudi Arabia (Chaudhary, 2001, Collenette, 1999). This family is the most common in the flora of Jizan (Alfarhan *et al.*, 2005) and flora of Yemen (Khulaidi, 2013), because the Farasan Archipelago belong to the bio-geographical region of the southwestern coastal regions of the Arabian Peninsula and the area lies within the Somalia-Masai regional region, the Farasan Archipelago has a high similarity with that of Jizan by 73%, other species may sharing with Yemen, Sudan, Somalia and Eritrea.

The Farasan Archipelago is inhabited particularly the large islands and visited frequently by tourists, throughout the district, coastal and marina resources are used intensively by people. These activities contribute to some taxa were reported by previous studies as dominant taxa, however across field trips, these species were found in small population size not more than 5 individuals. For example, *Tetranea alba* var. *alba.* was found only in two locations in Farasan Alkabir Island with three individuals that may be because the modifications of community structure partially to impacts of anthropogenic and zoogenic influences, such as heavy grazing, wood cutting and termites.

Farasan Alkabir Island supports relatively dense and diverse vegetation of certain valuable native plant species. Despite this, the island is highly threatened by anthropogenic activity. The development of the port on Farasan Al Kabir, and the increase in resident human population and tourists might have negative impacts particularly on the coastal zone. In addition, branches of mangroves especially *Avicennia marina* are commonly cut on uninhabited islands for the purpose of making traps for catching migratory birds (Tomas *et al.*, 2010), which damages the most significant vegetation elements in these islands.

There were some difficulties with studying the flora of the Farasan Archipelago particularly in the field trips. The field studies were made over three visits between 2015 and 2017. The large islands (Farasan Alkabir and Sajid) were extensively explored because they are connected by a bridge facilitating transport between them by car. The small inhabited islands were explored less due to limitations, mainly funding resources, the weather conditions and accessibility. Qummah, Zifaf, Dumsuq and Dushak Islands, which were reached by boat, were explored to a limited extent on foot. It was unsafe to camp on the islands due to the war in Yemen during the trips. In addition, during the second and third field trips, strong winds hampered sailing safely and the intensification of the war on the border with Yemen during the visit meant that it was unsafe to sail to the other islands. The inaccessibility of the small uninhabited islands was therefore of special conservation significance, as they are relatively undisturbed by human. More field work is needed to confirm the presence of taxa which are previously reported, but that were not been found during these field trips. In particular, we should focus on annual herbs because the local people have reported the archipelago has experienced a long period of drought from 2012 onward and these herbs may well be present only as dormant seeds.

Although Saudi wildlife authority protects some places, areas devoid of wild animals are poorly enforced. Having a current action plan in use by Saudi wildlife authority for the protection of the coastal zone and endangered flora of the archipelago, not only helps the sustainable development and protects the environment but also safeguards the future income, food and jobs of the local people. Therefore, the large two islands need more focus for improving training programmes and making better resources available to stakeholders and local people. In addition, Zifaf Island is one of the small islands in the Farasan Archipelago that remains undisturbed, reducing the number of invasive species that have threatened the biodiversity within the archipelago. Zifaf Island has a mangrove population, one of the habitats threatened the most by human activities on Farasan Alkabir Island. The population of mangrove in Zifaf shown a better population of mangrove species within the archipelago because of the absence of anthropogenic influence and development activities. Qummah, Dumsuq and Dawshuk are of no lesser significance and include a number of species which have not been reported previously in other parts of Saudi Arabia, such as *Ficus populifolia* on Qummah Island and *Commiphora erythraea* on Dumsuq Island. The islands have a particular set of habitats, with different variations between them. This leads to the possibility for the endangered species to be recorded on the Farasan islands and not in other parts of Saudi Arabia. They can be moved from the large islands to the smaller islands for conservation. So, the small islands will be engineered to be compatible for the species. This aspect makes the Farasan Archipelago flora valuable for biological research.

2.5 Conclusion

The updated checklist flora has provided the basis for review of the current state of vegetation and confirmation of previous species records; however the ongoing drought and limited field time mean that further work is required to check the status of the remaining 60% of the flora. The value of the new checklist is evidenced by the discovery of several previously unreported species, and it published online. The distinctive species list, with only 73% overlap with the adjacent mainland emphasises the need for a complete, readily available flora for the islands to support further field survey.

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CHAPTER 3

Progress towards an electronic flora of the Farasan Archipelago: The future prospects for the flora and its conservation

CHAPTER3

Progress towards an electronic flora of the Farasan Archipelago: future prospects for the flora and its conservation

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Abstract
The web infrastructure to record the diversity and structure of plant communities in the Farasan Archipelago, at 380 square kilometres, the second largest group of islands in the southern part of the Red Sea, is reported here ffa.myspecies.info/. Efforts to record knowledge of this flora began in the early 1990s and have resulted in several publications (books and papers). However, there has been a notable lack of use of appropriate new technology to make the flora adaptable and widely available. There is a need for accessible and free floras driven by government organisations aimed at specialist and non-specialist users and for research and teaching purposes. Moreover, e-publication of the Farasan Flora contributes to target 1 of the Global Strategy for Plant Conservation GSPC, to make information on the global flora available online for all. Data, covering 245 species and representing 52 families, were acquired from different organizations and used to create a database for a Scratchpad website. It will be translated into the Arabic language later.

Keywords Online flora- Floristic studies- Open access- The Farasan Archipelago.

3.1 Introduction

With the pressing issues of the effective conservation, naming and describing of plant species around the world, electronic floras provide easily updated, accessible and free tools to develop education and research. Moreover, the electronic flora at regional level contributes to the Global Strategy for Plant Conservation (GSPC), particularly the first target which aims to provide an online flora for all known plants of the world by 2020 (Miller *et al.*, 2014, Victor *et al.*, 2014).

The Guide to Standard Floras of the World by Frodin (2001) summaries much that is available in print up until the end of the 20th century. Within the Kingdom of Saudi Arabia, the morphological description of most of the Arabian species can be found in published floras, alongside illustrations and data regarding all the native names for plants as well as dichotomous identification keys (Migahid, 1978, Mandaville, 1990, Chaudhary, 1998, Chaudhary, 2000, Chaudhary and Al-Jowaid, 1999, Collenette, 1998, Collenette, 1999). There have been efforts by Jacob Thomas at the King Saud University herbarium in Riyadh to make information about the Saudi flora available electronically, to increase the usefulness of the data on Thomas (2011). This website provides an excellent checklist of species combined with notes of some plants groups such as aromatic, poisonous and medicinal plants and includes the topography and endemism in the Saudi Flora. However details of species descriptions, images, identification keys and geographic distributions are not provided.

The Red Sea (the western border of Saudi Arabia) has a unique environment with a wide range of habitats and outstanding biodiversity, which confers a great scientific and ecological importance (Gladstone, 2000; Le Houerou, 2003) to the area. It contains the coral-based Tiran Archipelago in the north and the Dahlakh and the Farasan Archipelagos in the south (Al Mutairi *et al.*, 2012). The Farasan Archipelago is the largest on the Saudi Arabian side, and has been managed by the Saudi Wildlife Commission (SWC) as a protected area since 1989 (Hall *et al.*, 2010) because of the presence of an endemic Gazelle known as *Gazella gazella farasani* and the endemic snake, the Sarso Island racer *Coluber insulanus* (Thouless, 1991; Masseti, 2014).

The Farasan Archipelago is home to 20,000 people for whom the biodiversity provides key aspects of their economic, environmental and cultural activities (Bruckner, 2011). Recently the Farasan Archipelago has been subject to intense pressure from climate change and the increase in anthropogenic pressures (overgrazing, cutting of trees, further expansion of farms, road construction, uncontrolled tourism, pollution and waste disposal and urban expansion). As a consequence of these threats, a great loss of the valued floristic biodiversity has occurred (Mandura, 1997, Gladstone *et al.*, 1999). Therefore, conservation of the Farasan Archipelago flora is essential for biodiversity conservation and to increase the awareness for tourists is a sustainable way.

Currently, the creation of an online Flora of all known plants is a major aim of the United Nations Convention on Biological Diversity (CBD) and Global Strategy for Plant Conservation (CBD, 2002). This is motivated by the need to document all plant species in the world to aid in the discovery of new species and for the conservation and sustainable use of others (Secretariat of the Convention on Biological Diversity, 2009). In 2005, the Arabian Plant Specialist Group (APSG) established the Important Plant Area (IPA) programme plan to achieve this target in Arabian Peninsula countries (Hall and Miller, 2013). By using this programme, many areas have been identified as an important site for plant conservation; the Farasan Archipelago is one of them (Hall *et al.*, 2010).

Many biologists have suggested that taxonomic studies should be published at least in part online (Bisby, 2000, Moretzsohn, 2000, Wheeler *et al.*, 2004, Knapp *et al.*, 2007). The massive development of E-flora components generated by technological advances has created an exciting spread of information over the world. The Flora of Gibraltar (Perez 2016), Flora of Thailand (Cámara-Leret, 2015), Flora of Nepal (Royal Botanic Garden Edinburgh (RBGE) with other international partners) and Flora of Australia (ABRS, 2017) provide examples of online floras that have been largely completed. The most common elements expected in any online flora are species descriptions identification keys, images, maps, references and specimens. Some online floras have included all of the elements and some not. **Table 3.1** compares the features of these example floras.

Electronic floras can easily and continuously be improved without incurring the same costs as paper-published floras. Additionally, they can be updated rapidly in comparison with the time it takes to publish in hardcopy format. E-Flora information can potentially be searched through multiple access points such as a tablet computer or mobile phone (Brach and Boufford, 2011) rather than carrying around numerous volumes of heavy weight Floras. An online flora however requires internet reception. Custom-designed smart phone applications could be particularly valuable for field use since once downloaded from the distribution platform to the device, they do not require mobile reception (Araya, 2013). However the storage needed for even a moderate flora is beyond the capacity of most current smartphones (Bewisey, 2018).

These approaches led this study to the use of community e-tools for taxonomy such as Scratchpads as an aid to the efficiency of the taxonomic work processes. Scratchpads (Smith *et al.*, 2012) is a social networking application that enables communities of researchers to manage, share and publish taxonomic data online. Architecture of Scratchpads is based on the Drupal content management system that facilitates the collaboration of distributed communities of taxonomists (Brake *et al.*, 2011). It provides the tools to enter, structure, curate, link and publish biodiversity data online (Baker *et al.*, 2014). These online floristic data can be included in active species distribution maps, images, sounds, videos, ecological interaction and data set description (Costello *et al.*, 2013). In Scratchpads the content can be accommodated in various ways, from highly unstructured 'pages' or nodes, through to highly structured normalised datasets (Blagoderov *et al.*, 2010). These characteristics provide the flexibility necessary to accommodate different use-cases and helps the content provider visualize how content will be presented to their audience. The unstructured pages are a free formatted, whereas, the structured pages pre-formatted and simply provide data to go in the field such as a table of species description page (Smith *et al.*, 2009). For online floras, the Creative Commons CC-BY 3.0 license is most commonly used (Hagedorn *et al.*, 2011, Escribano *et al.*, 2018).

Scratchpads help to increase visibility of ongoing projects, and create interaction and synergy between remote working groups (Costello, 2009). It supports a large number of users, editorial hierarchies serving individual and community needs, flexible data models that can be modified or added by contributors, content archiving and citation (Smith, 2009). Third party content such as the Encyclopedia of Life (EoL), the Global Biodiversity Information Facility (GBIF), the Biodiversity Heritage Library (BHL), the International Union for Conservation of Nature (IUCN), and National Center for Biotechnology Information (NCBI) can be automatically integrated into species descriptions using shared identifiers (Smith *et al.*, 2009). There are more than 4,500 active users for more than 900 sites (Scratchpad site 2018). Using such a widely used system is a logical state aim to initiate a single, comprehensive, electronic documentation source for the plants in the Farasan Archipelago.

Table 3.1 features present in several examples of online floras. S, Static map- I, Interactive map.

Features / Online floras	Species description	Keys	Images	Maps*	References	Specimens	Single website
Flora of Gibraltar	x	x	✓	S	✓	x	✓
Flora of Thailand	✓	✓	✓	S	✓	x	x
Flora of Nepal	✓	✓	✓	S	✓	✓	✓
Flora of Australia	✓	✓	✓	I	✓	✓	✓

3.2 Material and methods

The summary of the workflow for the compilation of the E flora of the Farasan Archipelago is shown in **Figure 3.1.**

3.2.1 Data collecting

1. Literature Review

The initial data were collected from literature review (**Table 3.2**), converted to a spreadsheet using Excel (2013). The name of plant species from previous literature was updated based on current taxonomic views following taxonomic databases such as The International Plant Names Index IPNI (2012) and The Plant List (2013). The plant families were updated following APG IV (2016). This process and the results found are detailed above (Chapter 2).

Table 3.2 The literature that was used in the E-Flora of the Farasan Archipelago.

Reference	**Title**
Alwelaie *et al.* (1993)	Vegetation of some Red Sea islands of the Kingdom of Saudi Arabia
Newton (1995)	Kingdom of Saudi Arabia.
Hassan and Al-Hemaid (1996)	Composition, origin and migration trends of perennial vegetation in the Farasan El-Kabir Island (Red Sea, Saudi Arabia)
Collenette (1999)	Wildflowers of Saudi Arabia.
Alfarhan *et al.* (2001)	Annotated list to the flora of Farasan Archipelago, Southern Red Sea, Saudi Arabia.
Chaudhary *et al.* (2000), Chaudhary (2001)	Flora of the Kingdom of Saudi Arabia illustrated
Rahman *et al.* (2002)	A check list of angiosperm flora of Farasan Islands, Kingdom of Saudi Arabia
Alfarhan *et al.* (2005)	Flora of Jizan Region
Al-Zahrani and El-Karemy (2007)	A new succulent Euphorbia (*Euphorbiaceae*) species from the Red Sea coast and islands
Aldhebiani (2010)	The Genus Euphorbia L. in Saudi Arabia
Hall *et al.* (2010)	Important Plant Areas in the Arabian Peninsula: 2. Farasan Archipelago
Tomas *et al.* (2010)	Floristic Composition of the Farasan Archipelago in Southern Red Sea and its Affinities to Phytogeographical Regions
Mutairi *et al.* (2012)	Floristic diversity, composition, and environmental correlates on the arid, coralline islands of the Farasan Archipelago, Red Sea, Saudi Arabia.
Al Mutairi *et al.* (2012)	Influences of island Characteristics on Plant Community Structure of Farasan Archipelago, Saudi Arabia: island Biogeography and Nested Pattern.

2. Field trip planning

The necessary permits and risk assessments were completed before the field trips to the Farasan Archipelago. Health and safety risk assessment was done by the University of Reading for the fieldwork. In addition, permits were obtained from Saudi Wildlife Authority (SWA) which controls The Farasan Archipelago protected area. Three field trips were carried out in 2016 and 2017.

The first field trip (April 2016) covered six islands: Farasan AlKabir, Sajid, Qummah, Zifaf, Dumsuq and Dawshuk. The second and third field trips (December 2016 and December 2017 respectively) covered two islands: Farasan Alkabir and Sajid. Locations with a high vegetation density and different habitats were visited during trips. Coordinates were recorded by GPS to fill the gaps in knowledge of the distribution of species. Specimen Identifications followed the previous references and were also confirmed by comparison with herbarium specimens at RNG and pictures of herbarium specimens provided by the Royal Botanic Garden Edinburgh website, the Royal Botanic Garden Kew website, and experts in Facebook groups such as Flora and Vegetation of Yemen Facebook group. These treatments can be used to extract valuable floristic information that can be consolidated to form the major part of the online Flora of the Farasan Archipelago.

The study has used the data from published hard copy literature reworked for web use. Data from field trips was recorded and all of these data were checked for typographic errors and unrecognised symbols when converting to digital format. Chapter 2 has the details of the last update of the Farasan Archipelago flora checklist. This step allows us to organize the full details of plant species and localities of the Farasan archipelago flora. After that, these data were digitalised in the relevant pages of the scratchpad.

3.2.2 Workflow of E-Flora of the Farasan Archipelago

1. Creating a project within scratchpads

The researcher received e-mail notification of their new work site, and was assigned the role of site maintainer, and granted administrative permission, which included the ability to assign new users.

2. The content type

This study has been used to make two unstructured pages for a brief summary of the history, climate, topography and blog. Structured pages used for species description, locations, bibliography, specimens, images and identification keys. **Table 3.2** shows the total content types created for the E-flora of the Farasan Archipelago. In both type of pages, the process started from hardcopy of the manuscript (book, journal article or field trip data) being converted to a word document. The data were then encoded to Text file and/or Excel file templates. After that, the data were imported into the specific page.

3. **Data analysis**

For the data analysis, Google analytics has been used to record information about the users, countries and sessions following Pakkala *et al.*, (2012). That may help to improve the site and marketing, by knowing what is working and what is not, understanding why or why not and how it should be optimized. Promotion of the site was not conducted during the PhD research as it was under constant development.

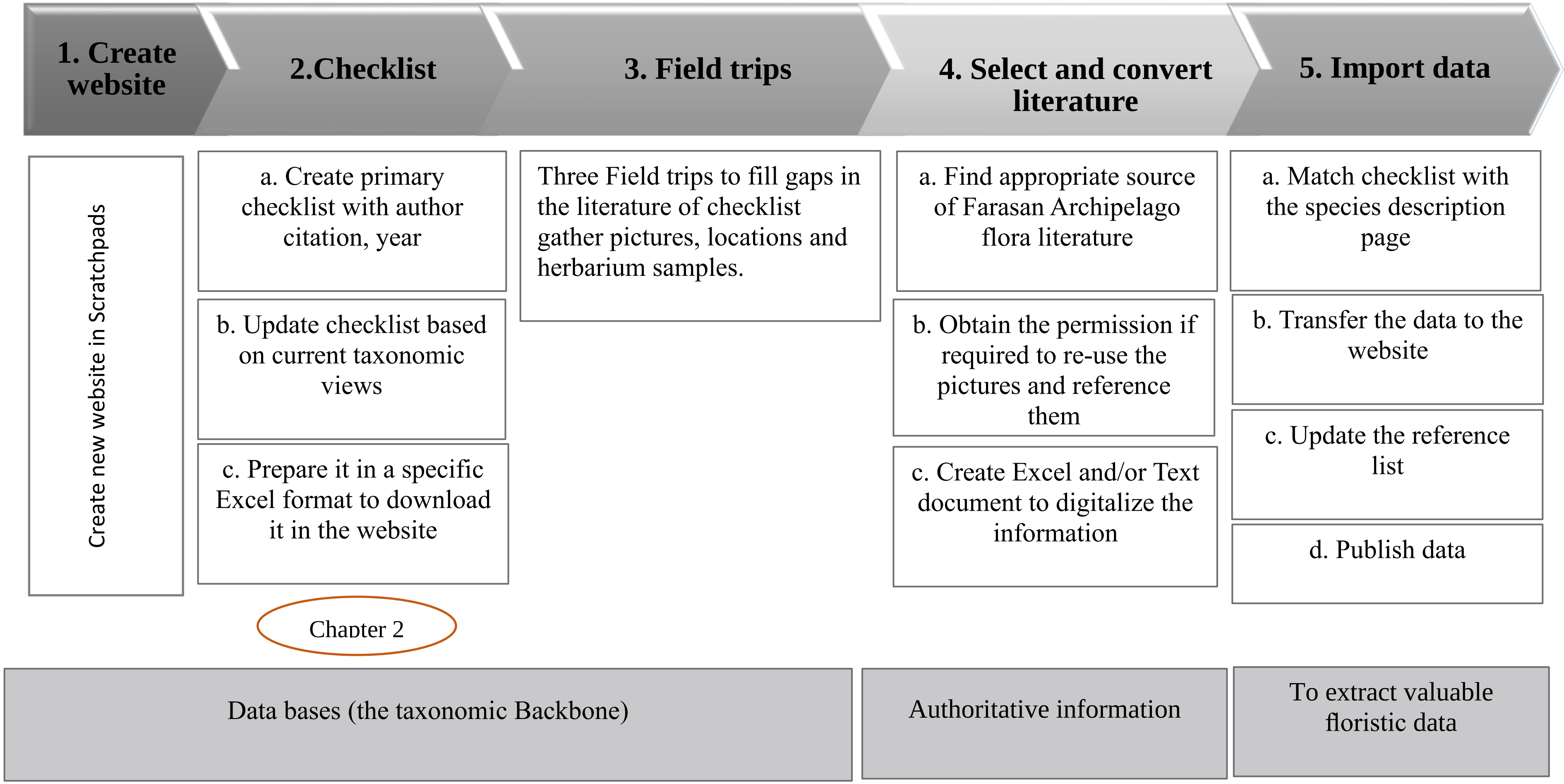

Figure 3.1 A summary for the workflows of the compilation of the E-Flora of the Farasan Archipelago.

Table 3.3 Total of 12 content types were created for the study at the first stage of E-flora of the Farasan Archipelago.

The content type	Page title		Page content
Unstructured	The Farasan Archipelago flora checklist attachment (PDF)		The last updated checklist (Chapter 2)
Unstructured	The climate and the Farasan Archipelago topography		A brief summary of the climate and the topography structure in the Farasan Archipelago.
Unstructured	The history of the Farasan Archipelago flora		A brief summary about the geological history of the Farasan Archipelago.
Unstructured	Blogs, forums and events		Various ways of communicating with site members and visitors
Structured	The plant checklist (including species description)		Building and managing a matrix of controlled text or numeric characters associated with selected species following Smith and Penve (2011).
Structured	Locations		Displaying the presence or absence of species from particular islands. The study used the TDWG geographic region ontology (levels 4) following Smith and Penev, (2011), and Erwin *et al.*, (2011).
Structured	Bibliography	Main literature	Two styles. First one, they are stand-alone in a separate content type as the whole list. The second, they are integrating into species description pages associated with taxonomic names and specimen records. The references were imported through EndNote by XML formats following King *et al.* (2011).
		ReFindit literature	The related literature from ReFindit, included The Encyclopedia of Life (EoL), The Global Biodiversity Information Facility (GBIF), The Biodiversity Heritage Library (BHL), The International Union for Conservation of Nature (IUCN), and National Center for Biotechnology Information (NCBI).

Continued Table 3.3 Total of 12 content types were created for the study at the first stage of E-flora of the Farasan Archipelago.

Structured	Specimens	Allows the recording of specimens which have been collected during field trips and can be connected different specimens at the same location following Smith (2009).
Structured	Media gallery	A display of images were uploaded associated with species description information and these images can be shown in a separate page not related to species description page. The study used a watermark on pictures by Photo marker program v.2.2.
Structured	Identification keys	Lucid Key as multi-access key for electronic plant identification (Zuquim *et al.*, 2017)
Structured	Licence	The licences of site has been applied from the Creative Commons module following Hagedorn *et al.*, (2011).

3.3 Results

3.3.1 Design of the website

The website was designed in Scratchpads, http://ffa.myspecies.info/ and offers a sound basis for the publication of an online manual of the Farasan Archipelago flora. **Figure 3.6** shows summary of Scratchpads workflow. A welcome message was then set as in **Figure 3.2**; including a short paragraph about the Farasan Archipelago flora. The main language of the E-Flora of the Farasan Archipelago is English.

Figure 3.2. Screenshot of the welcome page from the website of the Farasan Archipelago Flora.

3.3.2 The content type

1. The unstructured contents

Four main pages were created, **Figure 3.4A** shows an example of the unstructured content page. The climate and the Farasan archipelago topography page http://ffa.myspecies.info/node/8, and the history of the Farasan Archipelago flora page http://ffa.myspecies.info/node/9 have general information about the Farasan Archipelago. The Farasan Archipelago flora checklist attachment (PDF) page http://ffa.myspecies.info/node/3 has the updated checklist as a pdf format for those who do not prefer an online checklist.

The blog page has sole blog designed the logo of the Farasan Archipelago site http://ffa.myspecies.info/blog. The logo features have the most important elements that characterise the Farasan archipelago, which includes: a group of islands (The Farasan Archipelago), the head of the Arabian Gazelle which is an endemic species to the Farasan Archipelago and the main reason to register the Farasan Islands as a protected area since 1986. The waters surrounding the islands are equally important for marine life including dugongs and sea turtles, and the important element that makes the Farasan Archipelago unique is the presence of two important Mangrove species, *Avicennia marina* and *Rhizophora mucronata*. These species are ecologically important and highly productive littoral biotopes and are acting as a reservoir and refuge for many small animals, birds and fish (Khafaji *et al.*, 1991).

2. The structured contents

Six types of structured pages have been used in the E-flora of the Farasan Archipelago (the Farasan Archipelago checklist flora, locations, literature, specimens, media gallery and identification keys), **Figure 3.4B** shows an example of a structured content page.

The Farasan Archipelago flora checklist page has been reported 245 plant species http://ffa.myspecies.info/taxonomy/term/12. This online checklist provides an overview of all vascular plant species recorded in the Farasan Archipelago to date. Each plant species has seven tabs containing an overview and a description which has additional useful information (for instance geographical distribution and flowering time). All the 145 taxa descriptions have been completed. The measurement of these completed plant species was digitalised from published studies in the flora of Saudi Arabia and compare plant specimens by the herbarium specimens in available herbarium such as Royal Botanic Gardens, Kew and Royal botanic garden, Edinburgh. Zygophyllaceae family is the only family that direct measurement from the field trip in the Farasan Archipelago.

The checklist itself is kept up-to-date and new information (additional taxa, new information, name changes, etc.) is quite regularly added (monthly, sometimes weekly). The Excel (2013) format of species description did not work because the version of the template on scratchpads is out of date, so the descriptions of the taxa were imported one by one.

The locations of the six islands have been recorded on this site. This study has used an alternative method through multi process and the point locations which worked best in the identification of the islands is shown in **Figure 3.3**. This method was an effective way to use the map in the project, independently or in association with the species description. A tutorial video has been imported into the site to explain the method.

In the Bibliography page, thirty-eight references were imported from EndNote in this project. References were exported as a list to http://ffa.myspecies.info/biblio. In addition, there was a variable number of ReFindit literature. ReFindit literature provides a basic block on taxon pages that shows related literature from records.

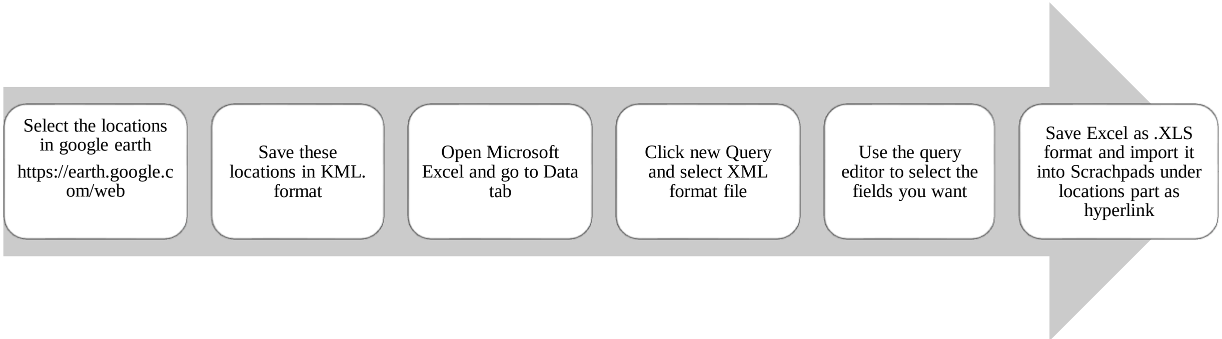

Figure 3.3. Flowchart for identifying the locations in Scratchpads.

Figure 3.4. A. An example of the unstructured page, E-Flora of the Farasan Archipelago, **B.** An example of the structured page, E-Flora of the Farasan Archipelago.

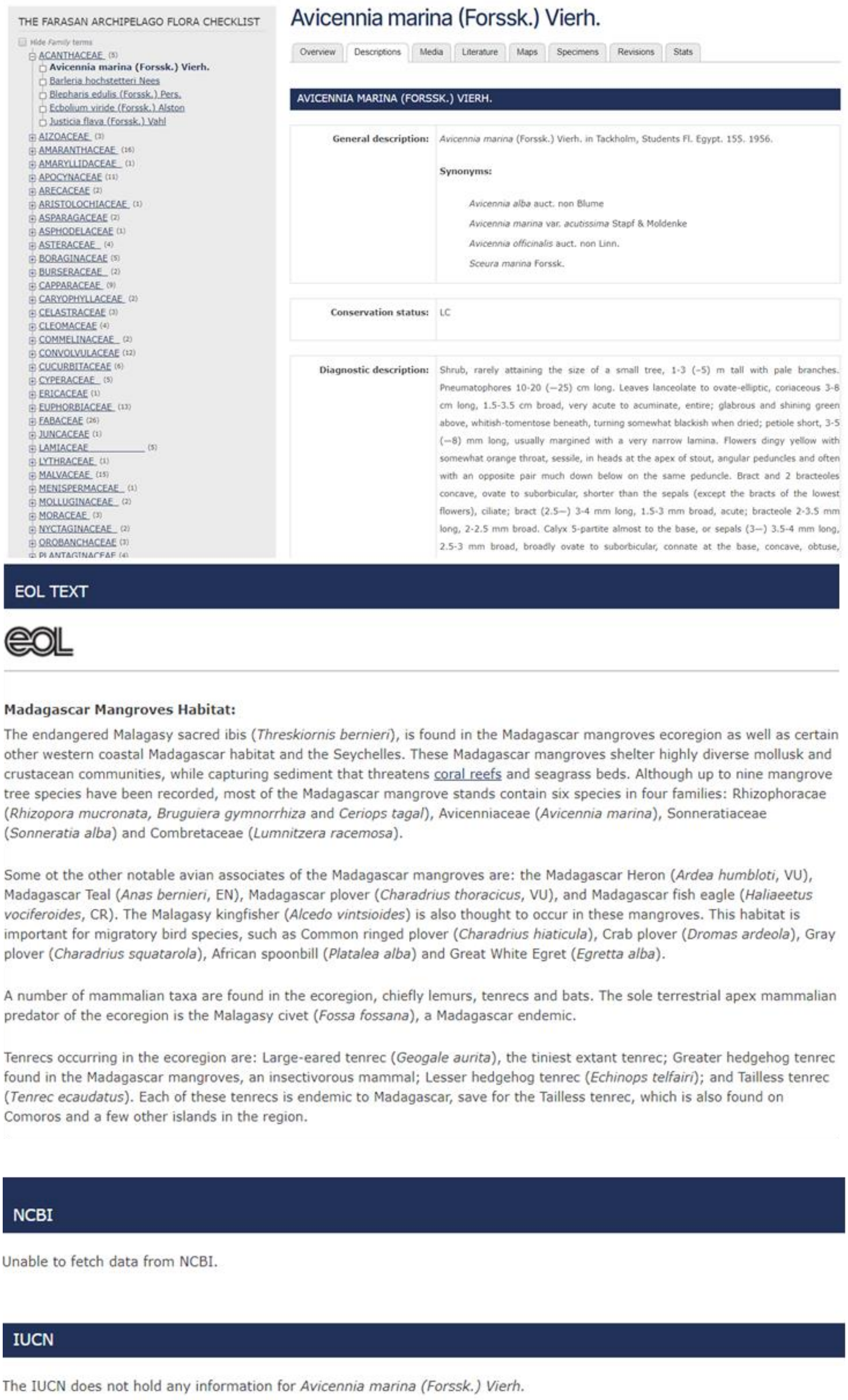

Figure 3.5. An example of third-party content linked with species description page.

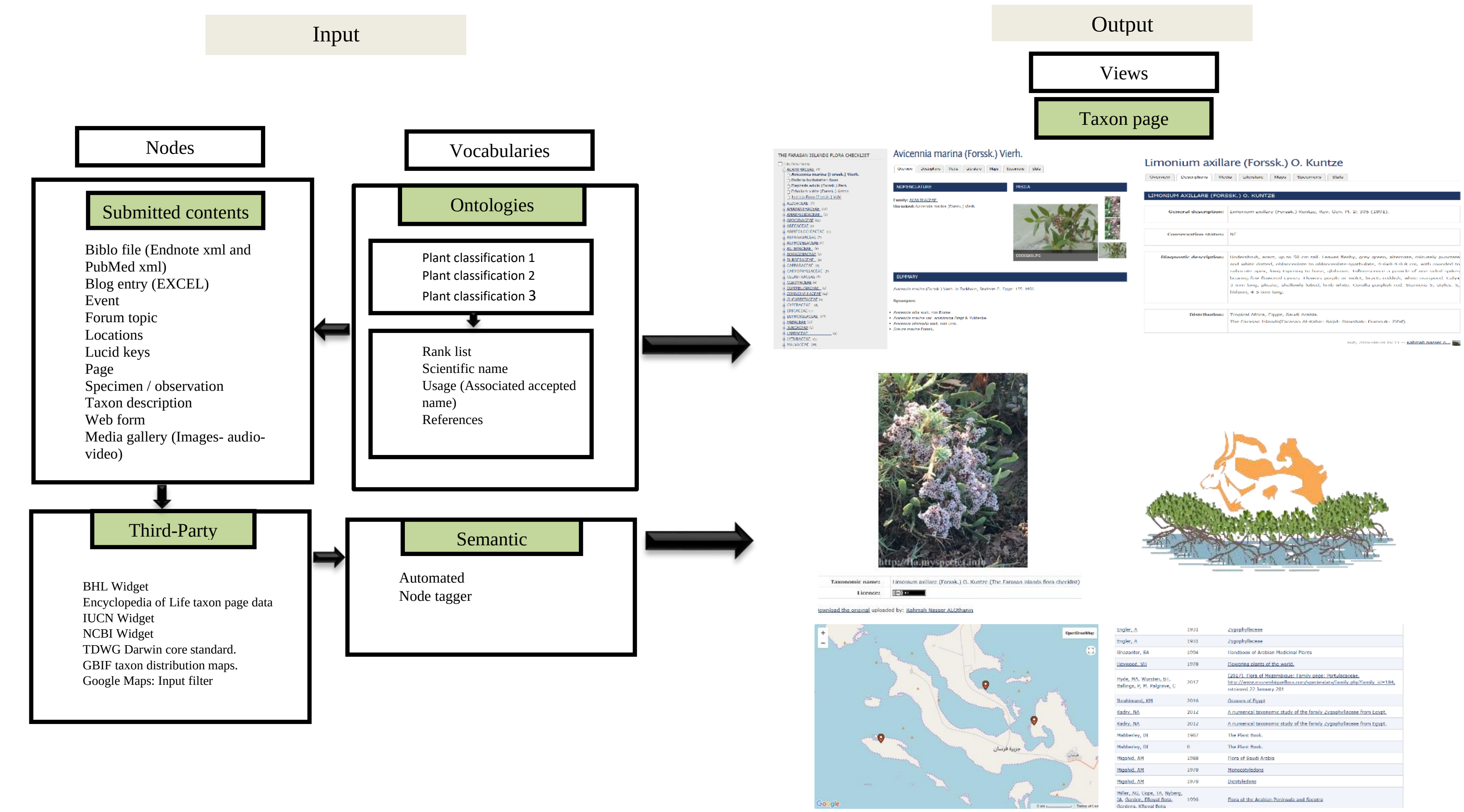

Figure 3.6. Summary of scratchpads workflow; this model provides groups of nodes and vocabularies as an importing type and page as exporting type. Smith *et al.* (2009) modified by Rahmah Al Qthanin (2016).

In the specimen page, 295 dried specimens were recorded for this project and serve as an electronic guide for herbarium samples. These specimens were collected from the six islands during the field trips.

In the media gallery page, Three-hundred and ninety images were uploaded to the site, http://ffa.myspecies.info/gallery. All of these images and information in the site were published under the CC BY 3.0 license, which include the NC condition that were freely available for non-commercial use and Non-Derivative Works (CC BY-NC-ND Licence).

The species description pages link through to external databases using the species name to retrieve additional data **Figure 3.5** shows an example of *Avicennia marina* species linked to the Encyclopaedia of life (EOL), International Union for Conservation of Nature (IUCN) and National Centre for Biotechnology Information (NCBI).

3.3.3 Website use state

Google Analytics indicated that 262 users visited the website during one year and nine months after the website launched, **Figure 3.7** shows the summary of the percent of users, the type of devices, the country and the percent of new and returned users overall the world and Saudi Arabia. The highest number of users was in January 2017. Worldwide, returning users around 71% were more common than new users around 28%. The United States of America was the highest percentage of users at 28%, with the lowest at Russia by 3%. In Saudi Arabia, the returning users around 53% were more than the new users around 46%. The users mostly used a desktop device by 97%, and the remaining 3% used a mobile phone or tablet.

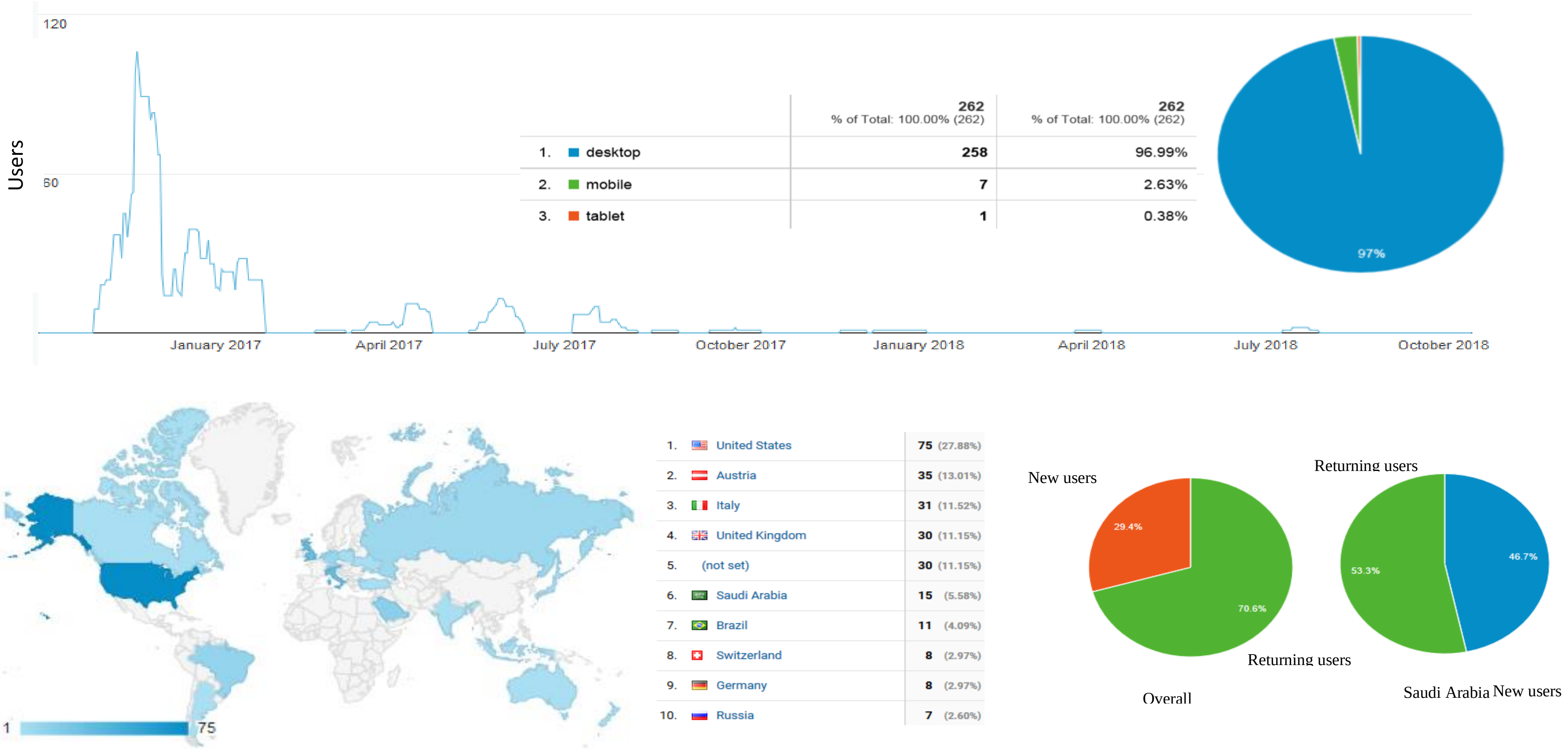

Figure 3.7. The summary of the percentage of users, the type of devices that they used to search, the country of users and the percent of new and returning users overall the world and Saudi Arabia.

3.4 Discussion

In comparison with previous paper-based flora of the Farasan Archipelago, an electronic flora of the Farasan Archipelago contributes to the first target of the GSPC (GSPC, 2002) which is that all known plant lists around the world must be online by 2020. It allows to support the plant diversity of the Farasan Archipelago flora.

The creation of E-flora of the Farasan Archipelago presents opportunities to provide free access link to taxonomic information of the Farasan Archipelago, such as images, maps, illustrations, and identification keys. It is the first time that electronic flora provides a tool for a continually updated information system in comparison with the time it takes to publish in hardcopy format that were out of date (Hall *et al.*, 2010, Alfarhan *et al.*, 2001); and without incurring the same costs as for paper-published Floras. Additionally, the electronic flora provides extensive access to specialist (researchers, students) and non-specialist users (the general public) who are interested about the flora (Brach and Boufford, 2011). The information in this online flora can potentially be searched through multiple access points on a tablet computer or mobile phone (Victor *et al.,* 2014).

The E- flora of the Farasan Archipelago permits botanists and users to browse treatments by family, genus and species; and to search by name, and free text entries. That is similar to some other online floras such as Flora of Gibraltar (Perez, 2016), Flora of Thailand (Cámara-Leret, 2015), Flora of Australia (ABRS, 2017) and Flora of Nepal (Royal Botanic Garden with other partners, 2014), These online floras have many common features, but differ in some features and overall organisation. Images are present on species description pages in all of these examples except the Flora of Nepal where they are on separate non-linked pages. The Farasan Archipelago flora, Flora of Australia and Flora of Nepal record specimens, but that feature is not present in the others. Dichotomous identification keys are used in the Flora of Australia and Flora of Nepal, whereas the Farasan Archipelago used multi-access key. The remainder do not have ID keys. Non interactive (static) maps have been used in Flora of Nepal and Flora of Gibraltar, however the Flora of Australia and the Farasan Archipelago use interactive maps that allow users to zoom in and out of the geographical distribution of species. All features from this comparison are found in the online flora of the Farasan Archipelagos

Delivery of an online flora does not guarantee ease of access or integration of information. One case is the online Flora of Thailand that uses different websites focused on individual plant families rather than the overall regional flora. For example, Euphorbiaceae by Peter and Savilia (2017) and Rubicaceae by Puff (2007) have entirely separate websites. However, many accounts for the Flora have their own Scratchpads (Cámara-Leret, 2015).

Despite these several key advantages in publishing electronic floras, an online Flora is not a one-off effort: it will require curation, such as following technology advances, the availability of broadly-based taxonomic expertise, and biodiversity informatics specialists who can develop and maintain a robust electronic(Victor *et al.*, 2014).

Scratchpads system has been used for producing electronic flora of Farasan Archipelago as well as many examples of online floras such as Flora of Gibraltar (Perez 2016), Flora of Thailand (Cámara-Leret, 2015) (both on scratchpad). Scratchpads are a free, quick, simple and effective way to present taxonomic data online.

Scratchpads provide the necessary tools to allow you to mobilise and link your biodiversity data (http://scratchpads.eu/ **).** All information relevant to the E-Flora will be exported from scratchpads onto the website using the scratchpads publishing function. Although Scrachpads is free to use, it is funded and supported by the Natural History Museum, London and has received funding from several European Union and UK funded projects such as eMonocot Project (Smith *et al.*, 2011).

The choice of the English language in E-Flora of the Farasan Archipelago was dictated by the wealth of botanical literature accumulated in the past, which is almost exclusively in English and the requirement of the PhD thesis to be in English. In addition, English might also be useful to promote foreign tourism to the islands. Future translations into the Arabic languages are planned to deliver the information to the general public in Middle Eastern countries.

E-flora of the Farasan Archipelago has data held from GBIF, BHL, and NCBI which will be particularly valuable to users seeking more precise distribution data, however, information data from EOL are not substantial in terms of the descriptive information provided. The percent ReFindit found was inconstant because open access sites in Scratchpads were gradually becoming part of the day-to-day activities of research communities around the world. The checklist of E-Flora has been provided in structured page type, one checklist is online (Structured page), whereas the second checklist are in pdf. (Unstructured page), because sometimes user prefer printed resource rather than computer.

The geographical distribution of various species was recorded by Chaudhary (2000; 2001) and Collenette (1999) as habitat details rather than decimal geographic distribution. These were not useful because of manmade changes which have happened over the previous 20 years. To overcome this, this study used modified point locations for all field trips specimens from the Farasan Archipelago. The mixed data from previous literature review and the field trips have created a basis on which to build a complete flora.

The highest percentage of visitors to the E-flora of the Farasan Archipelago website was in January 2017. This is probability because the study was presented in the young systematic forum in January 2017. This indicates that to increase the number of visitors to the E-flora of the Farasan Archipelago, there needs to be focus on marketing and content efforts on email and social media.

3.5 Conclusion

This web infrastructure publishing makes it easy for taxonomists to share the Farasan Archipelago botanical knowledge and contribute to support the GSPC Target one. It enables for effective identification, clear documentation geographic distributions of plant species. E-flora of the Farasan Archipelago needs concerted efforts from many contributors from the government and researchers to keep it updated in the future.

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CHAPTER 4

Re-evaluation of Zygophyllaceae species in the Farasan Archipelago

CHAPTER 4

Identification of Zygophyllaceae species in the Farasan Archipelago

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ABSTRACT

The identification of threatened plant species plays an integral part in conservation planning yet this is dependent on current and complete floristic treatments for correct identification of species. For most of the world there is limited coverage by floras and many of these are outdated. The replacement of traditional printed floras with online tools that are easily updated is part of target 1 of the Global Stratagy for Plant Conservatian (GSPC). In this study, we present an exemplar diagnostic multi-access key to the Zygophyllaceae of the Farasan Archpelago using Lucid, to distinguish these challenging taxa which are little studied despite being some of the most threatened species on the coast of the Archipelago. Morphometric analysis of 27 morphological characters allows recognition of five species in the Archipelago. This study presents the first multi-access key for the Zygophyllaceae for the area including synoptic illustrations to allow confident identification of these difficult species.

Keywords Identification, LUCID, Biodiversity conservation, The Farasan Islands, Morphometric analysis, Zygophyllaceae.

4.1 INTRODUCTION

The Farasan Archipelago has long been recognised as an Important Plant Area for conservation in the Red Sea (*Hall et al., 2010*), following the adapted Arabian criteria (*Al-Abbasi et al., 2010*). The seven main islands cover more than 380 km² (*Mutairi et al., 2012*). It has been managed by the Saudi Wildlife Commission (SWC) as a protected area since 1989 (*Hall et al., 2010*).

Many of researchers and non-specialist people who need to identify plants for different purpose such as ecological, medicinal and conservation aspects, have no training on the use of dichotomous keys, struggle to identify species and can misidentify material leading to incorrect records (*El-Demerdash et al.,* 1994, *Alfarhan et al.,* 2001), or under-recording (*Zuquim et al., 2017*).

Multi-access keys have proven value in the identification of plants, especially where the material is incomplete, such as lacking flowers or fruit, and the presence of a range of variation within a species; such as the challenging plant family (Caryophyllaceae) in Greece (*Gutiérrez et al., 2017, Trigas et al., 2018*). Multi-access keys are particularly suited to use in online floras, a key part of target 1 of the GSPC (*Moretzsohn, 2000*; *Knapp et al., 2007*) and these keys are becoming more popular (*Dallwitz, 1996*; *Dallwitz et al., 2000*; *, Farr, 2006*; *Walter and Winterton, 2007*; ; *Drinkwater, 2009*; *Bittrich et al., 2012*).

Taxonomically, Zygophyllaceae R. Br. are a heterogeneous family with disagreement about the systematic status of some groups within the taxon (*Shamso et al., 2013*). It consists of herbs, shrubs and trees with imparipinnate, usually opposite leaves, nectariferous, dichlamydeous flowers and usually 2(1, 3)-seriate stamens on filaments with basally glands or scale-like appendages, and a syncarpous gynoecium with 5(1, 4, 6) carpels resulting in a fruit that is usually a lobed capsule or schizocarp rarely a drupe or berry with oily or absent endospermic seeds (*Simpson, 2010*).

Worldwide, there are scattered accounts of Zygophyllaceae (e.g. *Barker, 1998, Beier et al., 2003, Khalik, 2012, Shamso et al., 2013*). In the Saudi Arabian mainland, Zygophyllaceae has been recorded as one of the important components of the desert vegetation (*Chaudhary and Al-Jowaid, 1999*) and approximately 28 Zygophyllaceae species are reported in eight genera: *Balanites, Fagonia, Nitraria, Peganum, Seetzenia, Tribulus, Zygophyllum* and *Tetraena* (*Migahid, 1978, Mandaville, 1990, Collenette, 1998, Collenette, 1999, Chaudhary, 2001, Tomas et al., 2010, Abdel-Kader et al., 2016*).

The few taxonomic studies that have focused on the genera *Tetraena* Maxim. and *Triblus* L. in Saudi Arabia distinguish them using characteristics such as growth habit, colour of plant, leaf structure, colour of flower, type of fruit, and fruit shape; Table 4.1 summaries these.

The two genera of Zygophyllaceae in the Farasan Archipelago grow in the low shoreline coast habitat under severe, dry climatic conditions (*Hammad and Qari, 2010*). The species under these genera are Perennial shrub except *Tetraena simplex* which is Annual herb (*AL Farhan et al., 2005, Alzahrani & Albokhari, 2018*). The *Tetraena* fruits are Mericarp (*Van Zyl, 2000*). The flowering time of these both genera are from February to June and the fruiting time from September to October (*, Alzahrani & Albokhari, 2018*). The Dispersal syndrome in *Tetraene* is Anemochory and Zoochorous (*Van Zyl, 2000, Sheahan, 2007*). The *Tribulus* spiny fruits are probably locally distributed after adhering to some wild animals (*Chandra, 1985*).

Many species of this family, especially the *Zygophyllum* species (=*Tetraena*) are under the threat of extinction owing to habitat loss due to land use changes (Gladstone, 2000). For example, the long sandy beaches where most Zygophyllaceae grow have been a primary destination for tourists with camping and expanding resorts and hotels (*Gladstone, 2000*).

This is one of the most challenging plant families to identify in the Farasan Archipelago due to the similarity of basic morphological traits among species, and the occurrence of several closely related species distinguished on microscopic characters, which makes this a particularly good example of the problems in identification of similar looking species. Only three species *Zygophyllum coccineum*, *Z. album* and *Z. simplex* of five reported in the Archipelago were examined by *AL Farhan et al.* (*2001*, *2005*). The studies lack morphometric analyses to assess the most important characters. The provided dichotomous keys follow a single pathway of character-state choices as the main identification tools which means the species cannot be identified at specific times of the year (particularly, out of flowering and fruiting time).

To engage non-specialists and facilitate the rapid and reliable identification of Zygophyllaceae there is a need for an accessible key with less complex terminology for a broad range of non-specialist users. This research aims to: 1) determine which species occur on the islands based on current published accounts for the family, 2) identify the most effective morphological characters to distinguish the species, 3) construct a key to identification based on morphology, 4) incorporate this into an E-flora of the Farasan Archipelago.

Table 4.1 Summary of the literature review of morphological characteristics used in studies on Zygophyllaceae species in Saudi Arabia in general and the Farasan Archipelago.

Region, Author	Species	Characters
Saudi Arabia, (Migahid, 1989)	*Zygophyllum album* L.*f*., *Z. simplex* L., *Z. decumbens* Del., *Z. coccineum* L., *Z. gaetulum* Emb. Et Maire, *Z. mandavillei* Hadidi, *Z. migahidii* Hadidi. and *Tribulus terrestris* L.	**Leaf:** leaf colour and leaf length **Flower:** flower colour, flower peduncle **Fruit:** fruit shape and fruit size.
Saudi Arabia, (Al-Hemaid and Thomas, 1996)	*Tribulus terrestris*	**Leaf:** leaf length and leaf size **Flower:** flower wide, sepal length, petal length, flower colour **Fruit:** Fruit size, spine numbers and spine shape.
Saudi Arabia, (Collenette, 1999)	*Zygophyllum album* L.F., *Z. coccineum* L., *Z. boulosii* Hadidi, *Z. decumbens* Delile, *Z. hamiense* Schweinf., *Z. mandavillei* Hadidi, *Z. migahidii* Hadidi, *Z. qatarense* Hadidi, *Z. simplex* L. and *Tribulus terrestris* L.	**Leaf:** leaf shape **Stem:** stem length **Flower:** flower colour, flower width **Fruit:** fruit shape
Saudi Arabia, (Chaudhary ,2001)	*Zygophyllum simplex* L., *Z. decumbens* Del., *Z. fabago* L., *Z. coccineum* L. var. *coccineum* L., *Z. coccineum* L. var. *berenicense* Schweinf. Muschl, *Z. album* L.F., *Z. propinquum* Decne., *Z. hamiense* schweinf. var. *hamiense* Schweinf, *Z. hamiense* Schweinf. var. *qatarense* Thomas & Chaudhary, *Z.*	**Leaf:** leaf arrangement, leaflet shape and leaflet length **Flower:** sepal number and shape, Petal number and shape and flower colour **Fruit:** fruit shape and fruit size.

	hamiense schweinf. var. *mandavillei* Thomas & Chaudhary and *Tribulus terrestris* L	
The Farasan Archipelago (Alfarhan *et al.*, 2001)	*Z. album, Z. coccineum, Z. simplex*	**Flower:** flower shape, flower length **Fruit:** fruit size, fruit shape.
Jizan and the Farasan Archipelago (Alfarhan *et al.* , 2005)	*Z. album, Z. coccineum, Z. simplex* and *Z. hamiense* var. *mandavillei* and *Tribulus terrestris* L.	**Leaf:** leaf length **Flower:** flower shape, flower length **Fruit:** fruit size, fruit shape.
Eastern Costal Of Saudi Arabia (Al-Fredan, 2008)	*Z. coccineum*, *Z. album* and *Z. qatarense* Hadidi.	-
Al Rass, (El-Ghazali *et al.*, 2010)	*Z. coccineum* and *Z. simplex.*	-
SW Asia (Ghazanfar and Osborne, 2015)	*T. coccinea* and *T. migahidii*	**Leaf:** leaf color and leaf size **Flower:** sepal length, petal length, flower colour, stamens and ovary. **Fruit:** fruit size, fruit shape.
Saudi Arabia (Alzahrani and Albokhari, 2018)	*T. alba, T. coccinea, T. decumbens, T. hamiensis, T. propinqua*, *T. simplex* and Z. *fabago*.	**Leaf:** leaf length and width **Flower:** flower color, arrangement and size **Fruit:** fruit size, fruit shape.
Saudi Arabia (Hosni and Hegazy, 1996)	*Tribulus terrestris*	-

4.2 MATERIALS AND METHODS

Four steps are required to build an identification key:

4.2.1 Plant material and data collection:

Field studies were conducted during 2015 and 2016. Samples of *Tetraena* were collected from three islands in the Farasan archipelago (53 accessions) and *Tribulus* from Farasan Alkabir Island (7 accessions). The accessions were identified by comparison with herbarium specimens (King Abdulallaziz University herbarium) and recorded using current taxa names following The Plant List (2010) (Table 4.2). Species name, locations and geographical coordinates are provided in Supplemental Information 1. An additional 15 herbarium specimens were examined from the Royal Botanic Gardens Edinburgh (**E**), (Supplemental Information 2).

Table 4.2 *Zygophyllaceae* species in the Farasan Archipelago and their current treatment.

Old species name and Authorities	New species name and Authorities	Authors
Zygophyllum simplex L.	*Tetraena simplex* (L.) Beier and Thulin	(Norton *et al.*, 2009, Mosti *et al.*, 2012, Sakkir *et al.*, 2012)
Zygophyllum album L.f.	*Tetraena alba var. alba* (L.f.) Beier and Thulin	(Louhaichi *et al.*, 2011, Mosti *et al.*, 2012)
Zygophyllum migahidii Hadidi	*Tetraena propinqua* ssp. *migahidii* (Hadidi) Beier and Thulin	(Ghazanfar and Osborne, 2015)
Zygophyllum coccineum L.	*Tetraena coccinea* (L.) Beier and Thulin	(Ghazanfar and Osborne, 2015)
Tribulus terrestris L.	*Tribulus terrestris* L.	No change, (Beier *et al.*, 2003)

4.2.2 The morphological characters were examined and recorded according to the availability of specimens:

The morphological characters were examined and recorded from at least three specimens of each species, according to the availability of specimens (22 of *T. simplex*, 23 of *T. coccinea*, 5 of *Tetraena propinqua* subsp. *migahidii,* 3 of *Tetraena alba* var. *alba* and 7 of *Tribulus terrestris*). Quantitative morphological characteristics were measured using a ruler (smallest measurement 1 mm). Initially 38 characters were recorded but 11 proved invariant leaving 27 (16 quantitative and 11 qualitative) for the analysis (Table 4.3). A minimum of five measurements was taken from an individual specimen for a character; the methods used to measure each feature were described in Figure 4.1**.** The data were entered into spreadsheet and were later transformed into a file format suitable for morphometric analysis. These morphological characteristics have been used as the basis for construction of the multi-access keys for the Zygophyllaceae species in the Farasan Archipelago. The features are richly illustrated, which allows visual comparison between the specimen and the candidate species.

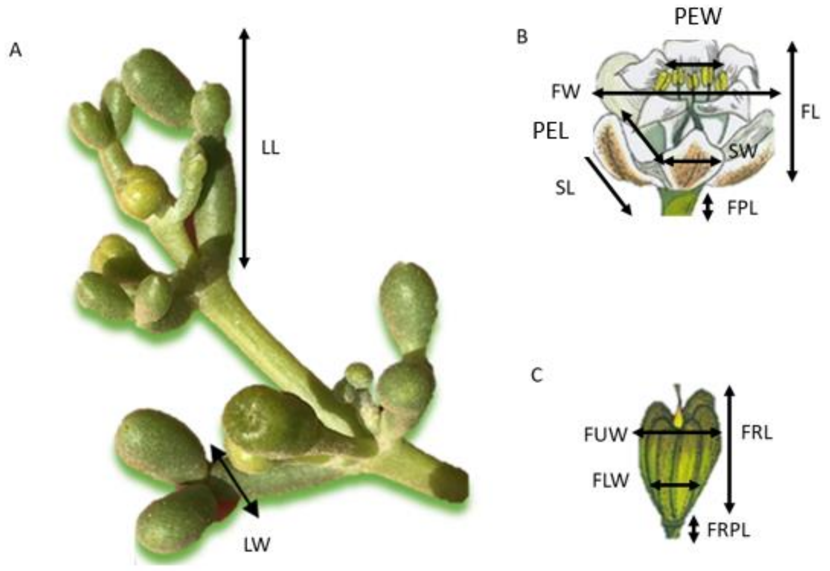

Figure 4.1 Morphological measurement of plant part used in this study (see Table 4.3 for character codes), A. Branch of plant B. Flower C. Fruit. **LL**- Leaf length **LW**- Leaf width **FPL**-Flower pedicel length **FL**- Flower length **FW**- Flower width **PEW**- Petal width **PEL**-Petal length **SW**-Sepal width **SL**-Sepal length **FRPL**-Fruit pedicel length **FRL**-Fruit length **FUW**-Fruit upper end width **FLW**-Fruit lower end width.

Table 4.3 Traits measured in Zygophyllaceae species in the Farasan Archipelago to build the LUCID identification key.

Number	Traits	Type of variable	Level code / Character states	Abbreviation
1	Habit of Plant	Categorical	1-Shrubs	HP
			2-Herbs	
2	Stem growth form	Categorical	1-Prostrate	SG
			2-Erect	
3	Plant Colour	Categorical	1-Green group (N137 A)	PC
			2-Greyed-green group (191 A)	
			3-Yellow-green group (144 A)	
4	Stem surface	Categorical	1-Pubescent	SS
			2-Glabrous	
5	Leaf type	Categorical	1-Simple	LT
			2-Bifoliolate leaflet	
			3- Pinnate leaflet	
6	Leaf arrangements	Categorical	1-Alternative	LA
			2-Oppisite	
7	Leaf Surface	Categorical	1-Pubescent	LS
			2-Glabrous	
8	Leaf length	Continuous	mm	LL

9	Leaf width	Continuous	mm	LW
10	Leaf apex	Categorical	1-Rounded 2-Acute	LAP
11	Flower pedicel length	Continuous	mm	FPL
12	Flower colour	Categorical	1-Yellow group (6 A) 2-White group (NN 155) 3-Yellow white group (158 C)	FC
13	Flower width	Continuous	mm	FW
14	Flower Length	Continuous	mm	FL
15	Petal Length	Continuous	mm	PEL
16	Petal Width	Continuous	mm	PEW
17	Sepal Length	Continuous	mm	SL
18	Sepal Width	Continuous	mm	SW
19	Style Length	Continuous	mm	STL
20	Long stamens Length	Continuous	mm	LSL
21	Short stamens Length	Continuous	mm	SSL
22	Fruit Shape	Categorical	1-Obconical-star 2-Obconical-angled 3-Obovoid-lobed 4- Nutlet 5-Cylindrical	FSH
23	Fruit Length	Continuous	mm	FRL
24	Fruit upper end width	Continuous	mm	FUW
25	Fruit lower end width	Continuous	mm	FLW
26	Fruit Surface	Categorical	1-Pubescent 2-Spiny mericarp 3-Glabrous	FS
27	Fruit pedicel length	Continuous	mm	FRPL

4.2.3 Data analysis

Qualitative characters were coded as multi-state, for example (Leaf type Simple (1), Bifoliolate leaflet (2), Pinnate leaflet (3). Quantitative variables were standardized using the R studio. Version (2017), *Scale balance* function to remove bias due to size alone, following *Katapally and Muhajarine (2014)*, (Supplemental Information 3 and Supplemental Information 4).

The standardized data were analysed with R studio package *Factor Analysis of Mixed Data (FAMD)* version 1.2.3, this method included principal component analysis (PCA), used here to extract relevant information from high dimensional data sets. In addition, Linear Discriminant Analysis (LDA) was performed using the *lda* function and using the predict function with *mass* (Venables and Ripley, 2002) in R studio.

Cluster analysis including Principle Coordinates Analysis (PCoA) and unweighted pairs group using mean average (UPGMA) were carried out using the statistical software Minitab ver.18.1.1.0 (Minitab, Inc., State College, PA).

4.2.4 Preparing the Key

The key was made in Lucid 3.3 www.lucidcentral.org, which contains two main elements: Lucid Builder and Lucid player (Figure 4.2). Characters were scored into a Lucid spreadsheet using the categories in Table 4.3. Illustrations were based on digital photographs made during the field trips to the flora of the Farasan Archipelago; further hand drawn illustrations were digitized and added to give more clarity to the characters as necessary.

4.2.5 Testing the Key

Initial testing of the key used available images of samples included a scale and samples. 10 PhD student Specialists (High-knowledge) and 10 non-specialists (Low-knowledge), tested the key following usability test methods. This test allows us to be understanding how real users experience the online key. Participants were provided with a set of numbered specimens, recording sheet, and were allowed 20 mins per specimen. The author monitored participants' progress and responded to any issues that arose.

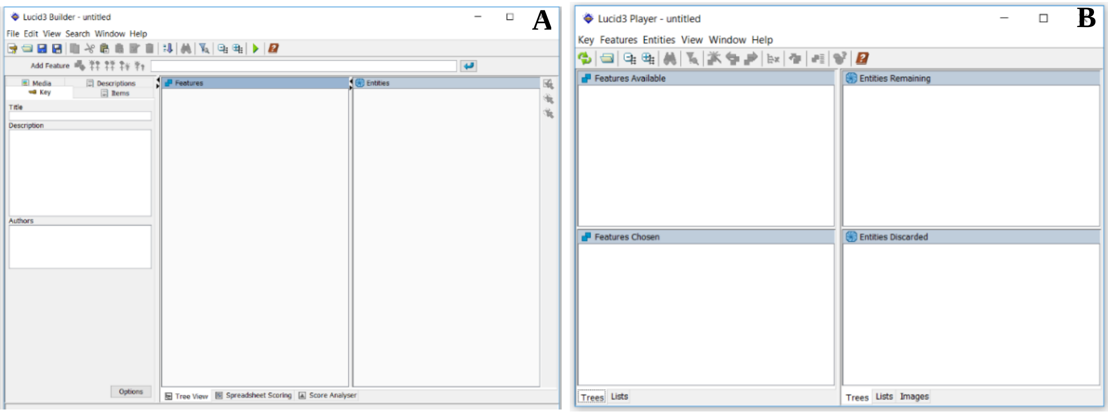

Figure 4.2 Screenshot from the Lucid key **A,** the builder window at lucid software, before building multi access key. **B,** the player window at Lucid software, where feature and species list available.

4.3 RESULTS

4.3.1 Morphometric analysis

The first two axes of PCA accounted for 74.7% of the overall variation **(**Figure 4.3**)**. The contribution of all morphological characters to the first and second axis are shown in Figure 4.4 and Figure 4.5 respectively **(**the red dashed line on the graph above indicates the expected average value if the contributions were uniform). The summary plot for investigating the influence of each morphological characteristic to each component is presented in Figure 4.6. The cluster analysis by PCoA and UPGMA of quantitative and qualitative data indicated the presence of five clearly distinguished functional groups (taxa): **group 1**, with *Tribulus terrestris* and it is the furthest distance from all other groups. **group 2**, containing *Tetraena simplex* and it is the largest distance within *Tetraena* species groups. **group 3** consist of *Tetraena alba* var. *alba*. **group 4,** with *Tetraena coccinea* and **group 5,** comprising *Tetraena propinqua* subsp. *migahidii* (Figure 4.7-4.8 and 4.9). The Figure 4.10-4.11-4.12-4.13-4.14 show the five taxa of Zygophyllaceae in the Farasan Archipelago.

The linear discriminant analysis found a linear combination of the explanatory variables that best discriminates between the groups. The characteristics in the first linear discriminant function that contributed to classifying the Zygophyllaceae into five groups depended on quantitative characteristics. The most important characters in the classification function were the size of petals in flowers, length of leaflet, fruit length, and fruit upper end width. In the second discriminant function, the characteristics were pedicel length, short stamen length, and flower pedicel length (Table 4.4). Selected characteristics from the first two discriminant functions are compared in the FAMD result, where it can be seen that petal length, petal width, fruit length, leaflet length, fruit upper end width, and style length are statistically different between Zygophyllaceae species and clearly distinguishing them. Table 4.5 records the prediction accuracy of the linear discriminant analysis of Zygophyllaceae taxa.

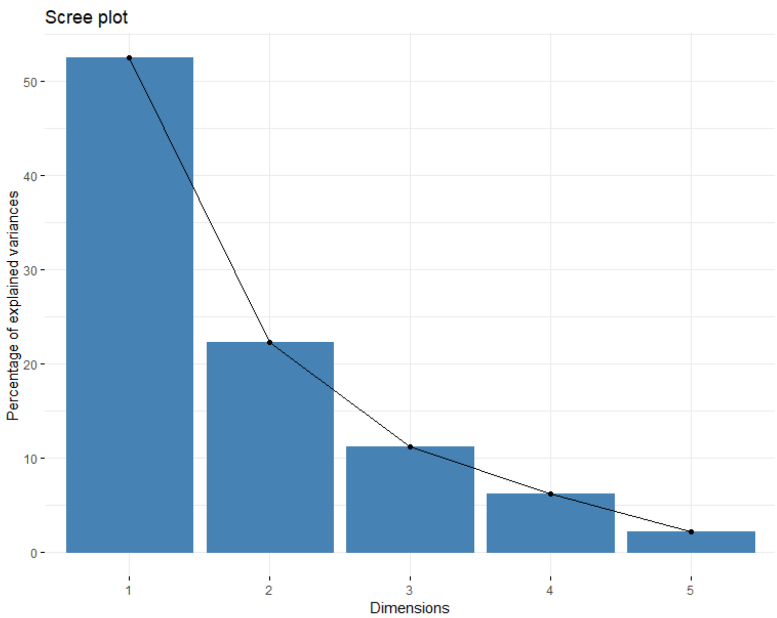

Figure 4.3 The proportion of variance retained by the different dimensions (axes), in PCA.

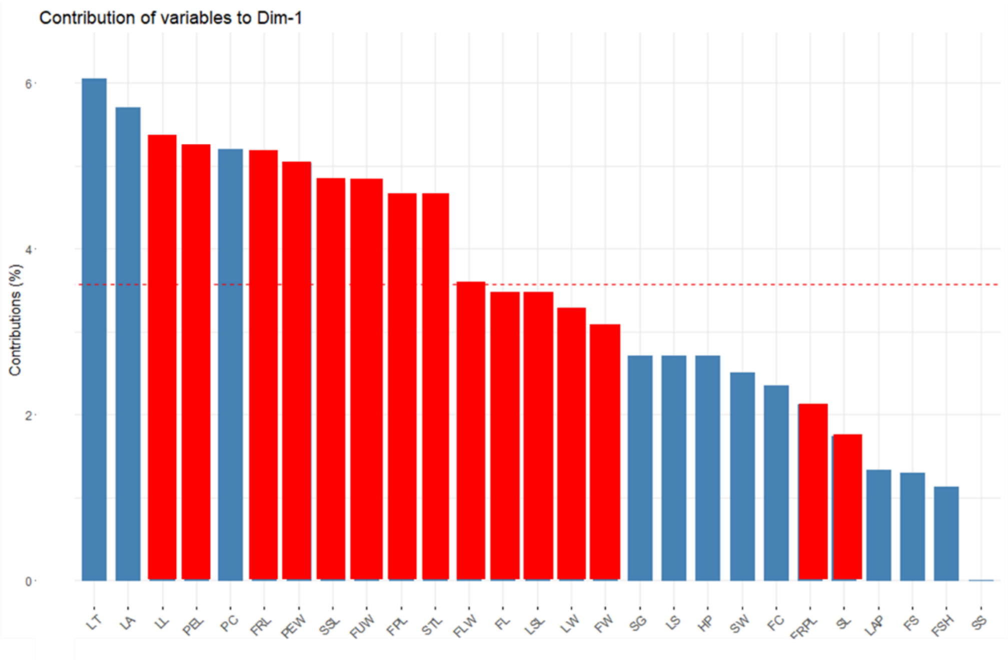

Figure 4.4 The contributions of 27 variables (morphological characters) to dimension 1. The red dashed line on the graph above indicates the expected average value, if the contributions were uniform. Blue colour- Quantitative character red colour- Qualitative character.

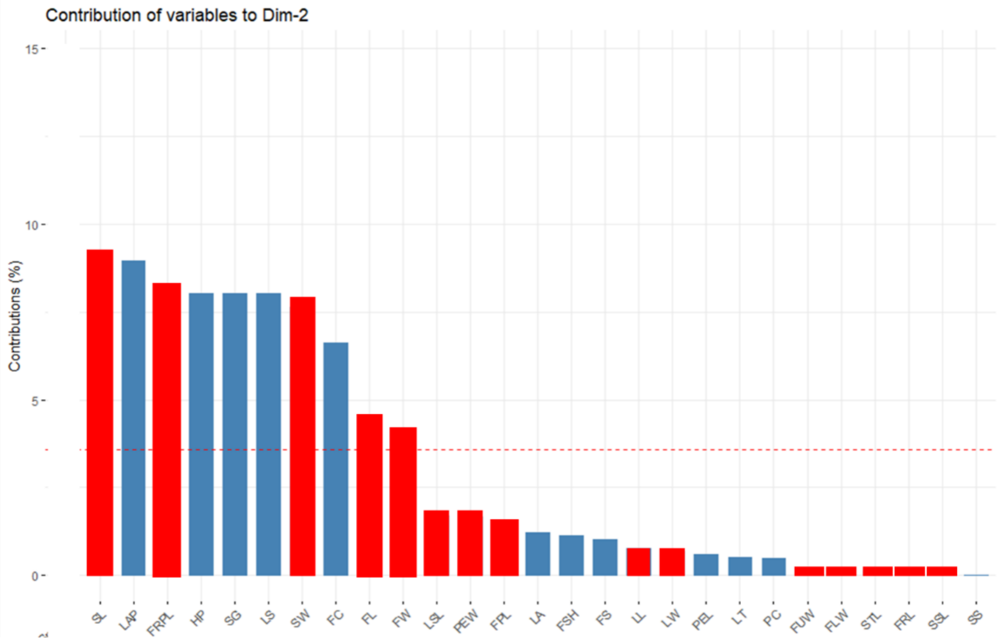

Figure 4.5 The contributions of 27 variables (morphological characters) to dimension 2. The red dashed line on the graph above indicates the expected average value, if the contributions were uniform. Blue colour- Quantitative character red colour- Qualitative character.

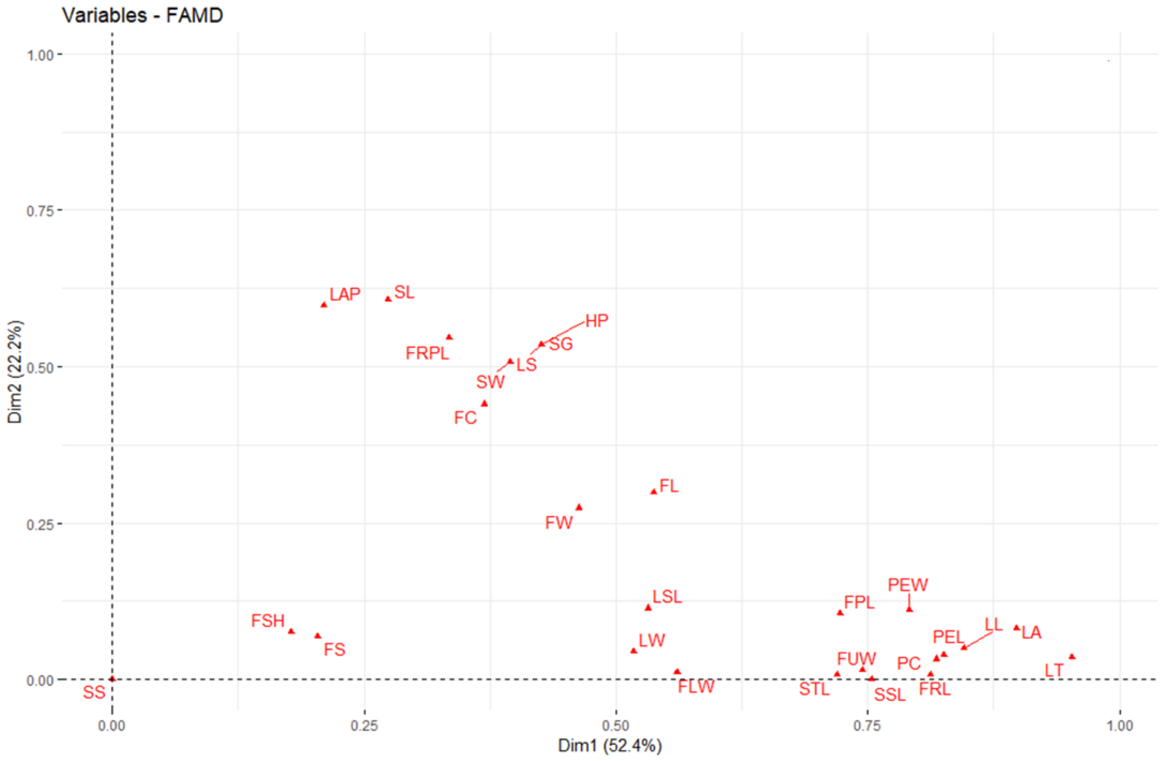

Figure 4.6 The PCA plot for investigating the influence of each variable to each component is presented from morphological characteristics of Zygophyllaceae species in the Farasan Archipelago.

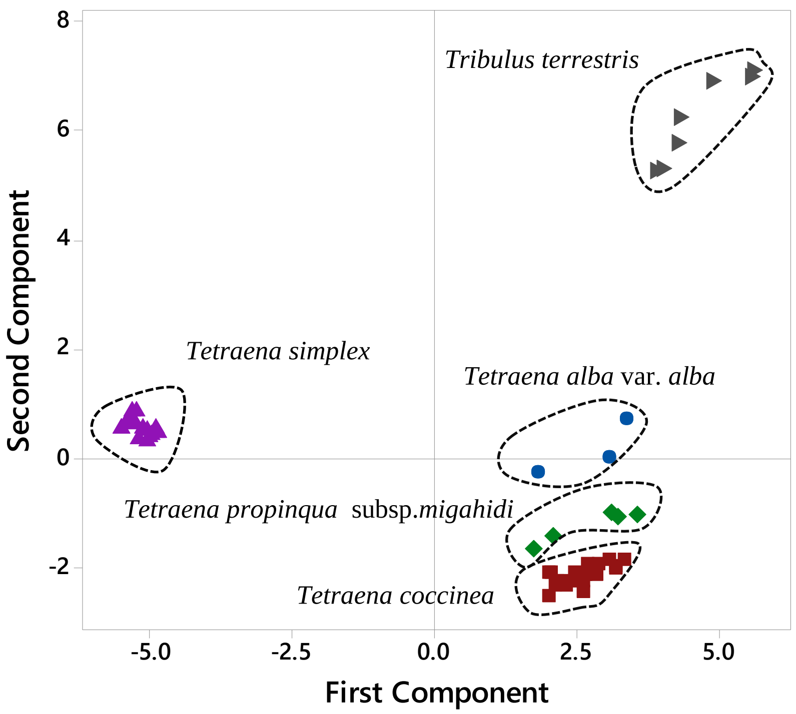

Figure 4.7 PCoA representation of morphological data of 60 accessions of the Farasan Archipelago *Tetraena* and *Triblus*, Principal Component axis 1 and 2.

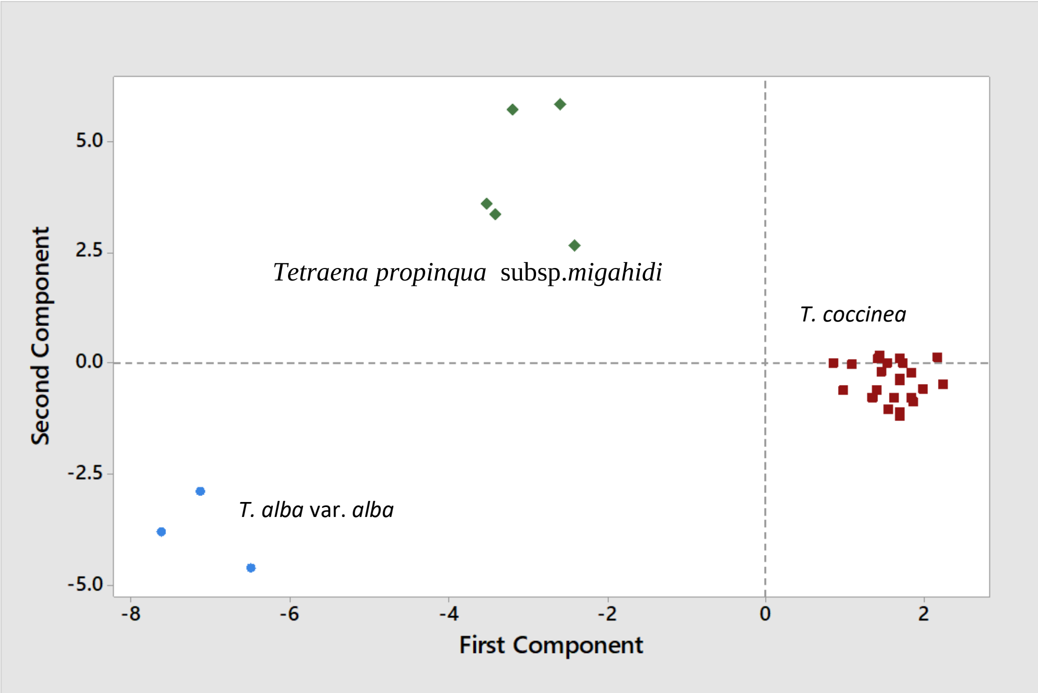

Figure4. 8 PCoA representation of morphological data of 31 accessions of the Farasan Archipelago *Tetraena alba* var. *alba*, *Tetraena coccinea and Tetraena propinqua* subsp. *migahidi*, Principal Component axis 1 and 2.

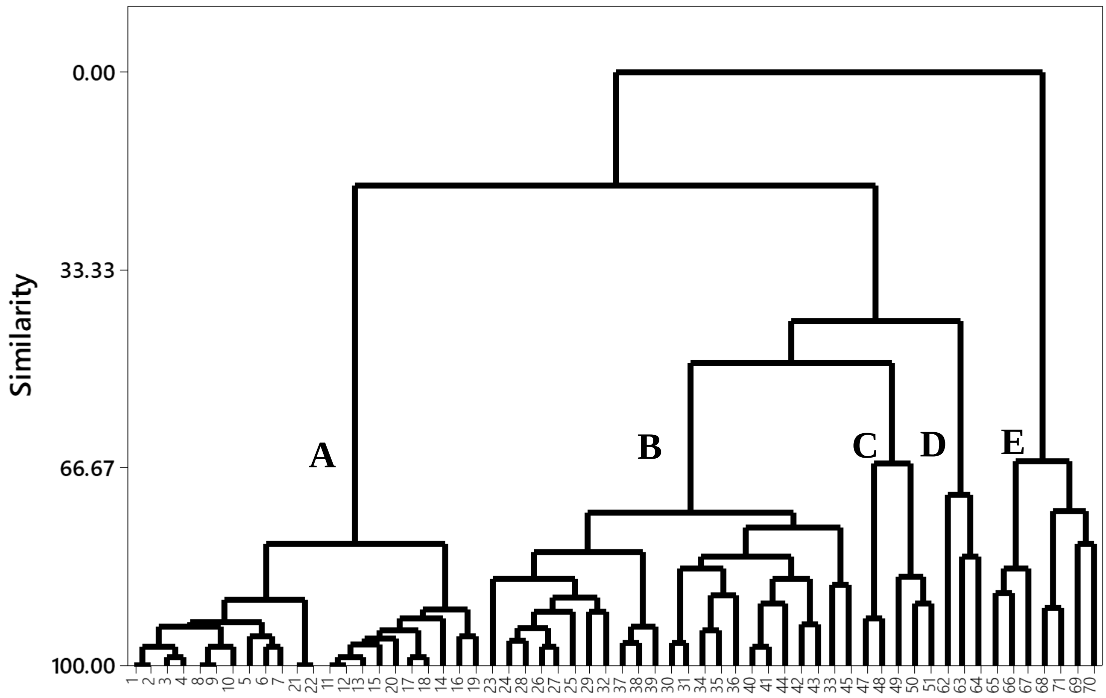

Figure 4.9 Dendrogram of morphologic relationships of all studied taxa of Zygophyllaceae in the Farasan Archipelago, developed using UPGMA method on standardized variables based on average linkage and Gower distances. A. *Tetraena simplex* B. *Tetraena coccinea C. Tetraena propinqua* subsp.*migahidi D. Tetraena alba* var. *alba E. Tribulus terrestris.*

Table 4.4 Linear discriminant analysis results on 17 characters of species and morph types of Zygophyllaceae Values expressed by standardized coefficients of the discriminant function.

Variable	**Code**	**LD1**	**LD2**	**LD3**	**LD4**
Leaf length	LL	-1.02943474	1.0036996	0.7138035	0.50818981
Leaf width	LW	-0.19807275	-0.9532458	0.7647112	0.72356398
Flower pedicel length	FPL	-0.41850525	2.6447020	0.7339165	2.81409465
Flower width	FW	3.46425713	-19.6978642	-7.7527115	2.12177322
Fruit length	FL	-3.28704287	18.2516226	7.3706971	-1.18788980
Petal length	PL__1	3.63881723	2.6837567	-2.0820654	-4.40232008
Petal width	PW	2.09050572	4.6708517	1.0021944	4.00014266
Sepal length	SL	0.66563861	1.8931989	-1.6428254	-0.61942867
Sepal width	SW	0.88832274	-0.6943648	-2.6372512	-2.74077935
Style length	STL	1.49613743	1.7523371	1.2129748	-0.13099855
Long stamen length	LSL	-0.06568015	0.8799832	0.4313786	0.09282289
short stamen length	SSL	0.15669727	-0.8525219	-0.4142576	-0.42739876
Fruit length	FRL	0.43882837	1.0290394	-0.5135204	1.76203807
Fruit upper end width	FUW	-1.79834287	3.1639310	2.3420541	0.38858672
Fruit lower end width	FLW	-0.27190954	-0.0379947	1.0681317	0.69110182
Fruit pedicel length	FRPL	1.96087694	-3.8221823	3.1899953	3.34345353
Proportion of trace		0.5429	0.3538	0.0839	0.0194

Table 4.5. LDA Predictions to evaluate the prediction accuracy of Zygophyllaceae taxa, the actual taxa as the row labels and the predicted taxa at the column labels.

	True Group				
Put into Group	*Tetraena simplex*	*Tetraena alba var. alba*	*Tetraena propinqua* subsp. *migahidii*	*Tetraena coccinea*	*Tribulus terrestris*
Tetraena simplex	0	0	0	0	7
Tetraena alba var. alba	22	0	0	0	0
Tetraena propinqua subsp. *migahidii*	0	23	0	0	0
Tetraena coccinea	0	0	5	0	0
Tribulus terrestris	0	0	0	3	0
Total N	22	23	5	3	7
N correct	22	23	5	3	7
Proportion	1.000	1.000	1.000	1.000	1.000

Figure 4.10 Morphological characteristics of *Tetraena simplex* species in the Farasan Archipelago in natural habitat and illustration by author. A. whole plant B. flower of taxa C. fruit of taxa.

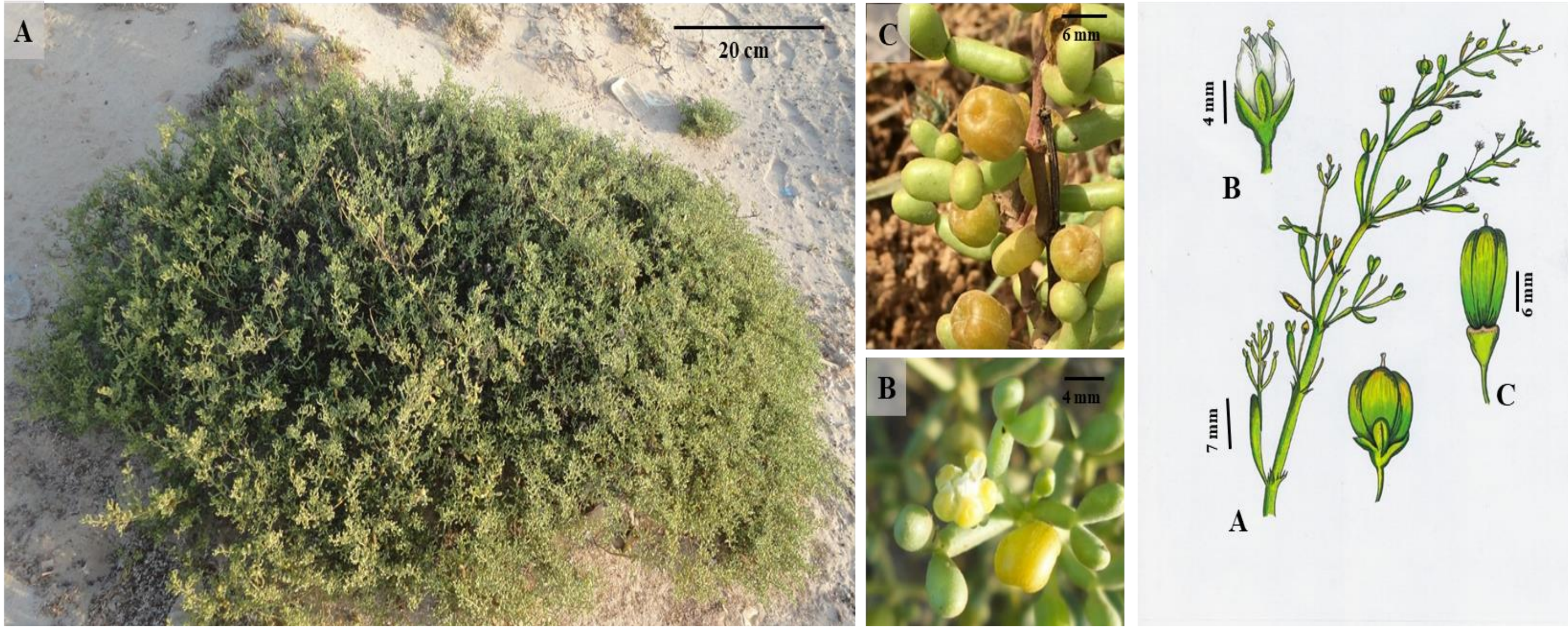

Figure 4.11 Morphological characteristics of *Tetraena coccinea* species in the Farasan Archipelago in natural habitat and illustration by author. A. whole plant B. flower of taxa C. fruit of taxa.

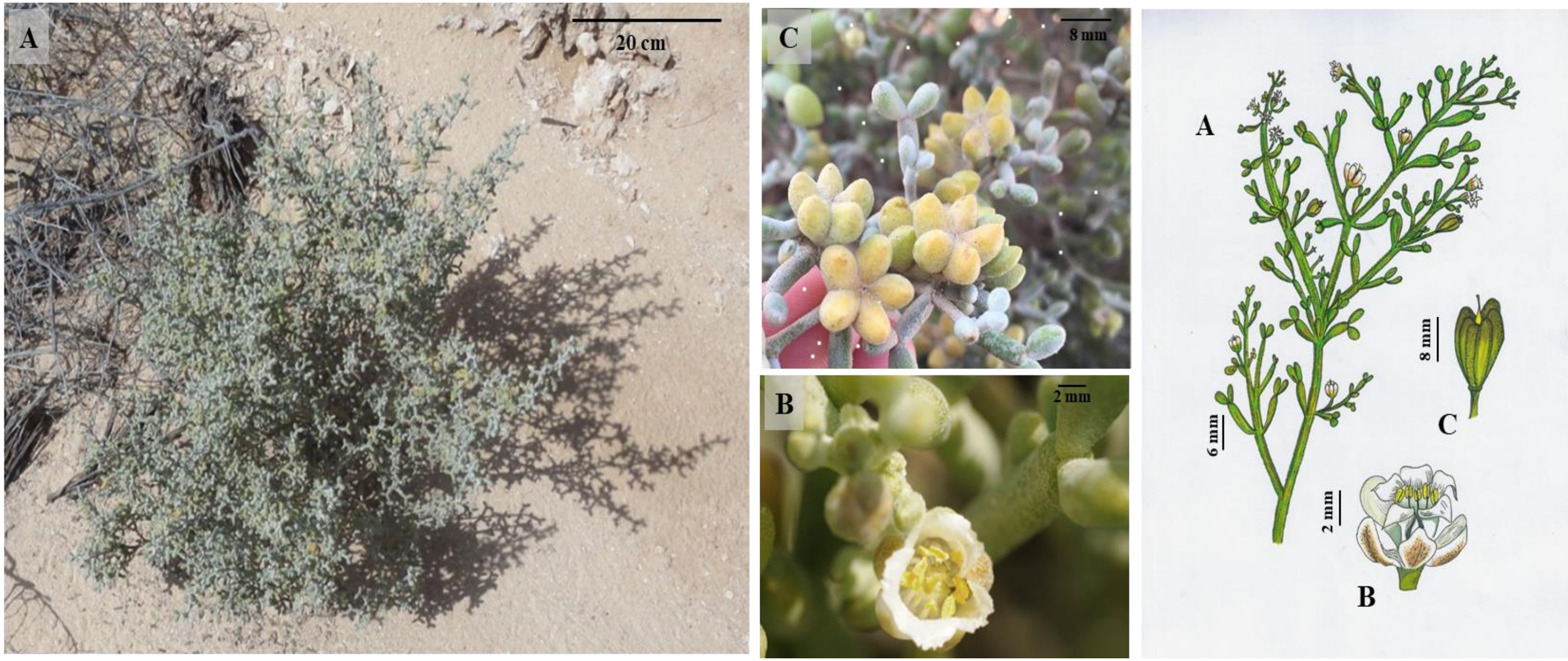

Figure 4.12 Morphological characteristics of *Tetraena alba* var. *alba* species in the Farasan Archipelago in natural habitat and illustration by author. A. whole plant B. flower of taxa C. fruit of taxa.

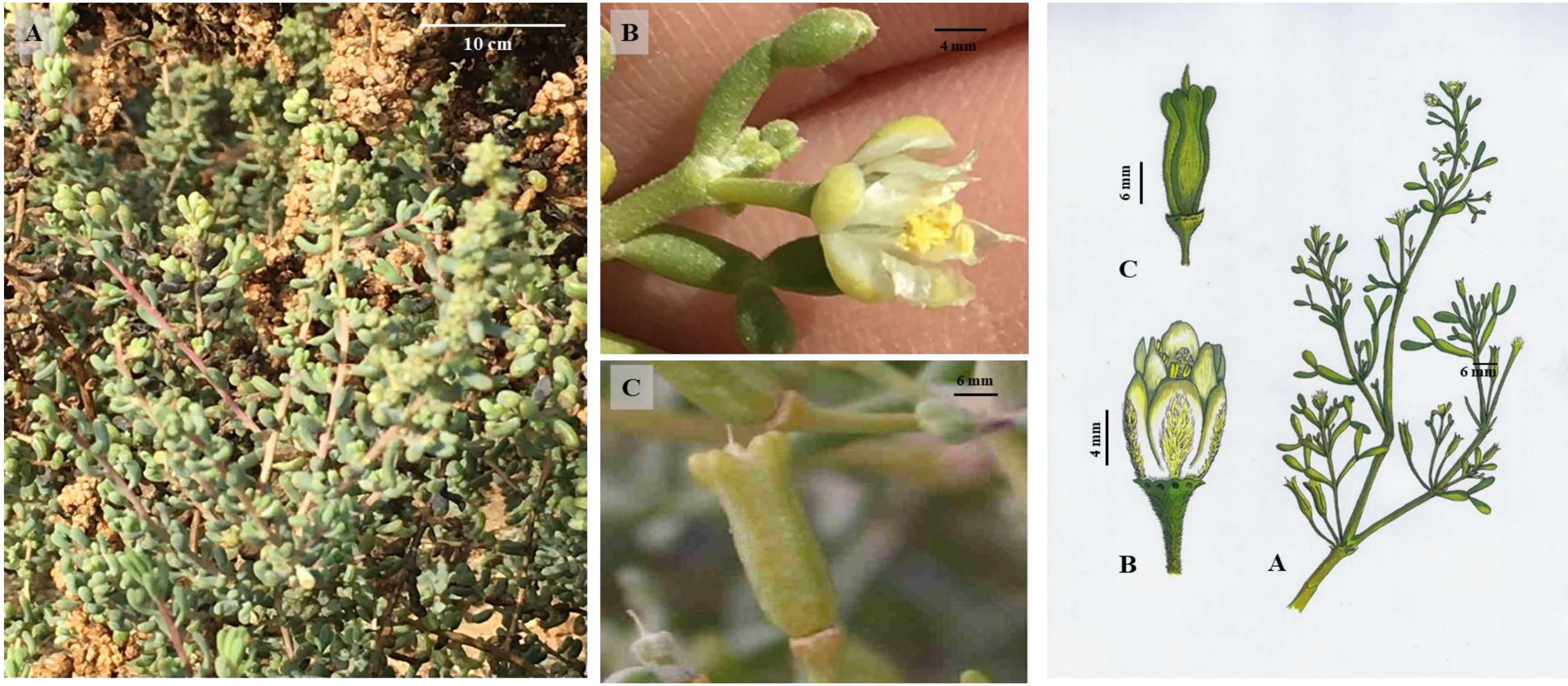

Figure 4.13 Morphological characteristics of *Tetraena propinqua* ssp. *migahidii* species in the Farasan Archipelago in natural habitat and illustration by author. A. whole plant B. flower of taxa C. fruit of taxa.

Figure 4.14 Morphological characteristics of *Tribulus terrestris* species in the Farasan Archipelago in natural habitat and illustration by author. A. whole plant B. flower of taxa C. fruit of taxa.

4.3.2 Multi-access Key to the Zygophyllaceae in the Farasan Archipelago

The study has developed a user-friendly free-access key that is available online https://keys.lucidcentral.org/keys/v3/zygophyllaceae, and summarizes some of the existing taxonomic information about Zygophyllaceae species in the Farasan Archipelago. This will contribute to the production of an easy guide for identification of these species and to conservation planning. Figure 4.15 and 4.16 show screenshots of an online key of Zygophyllaceae species in the Farasan Archipelago. Feedback on the multi-access key indicated that fruit features were easiest to use when identifying the Zygophyllaceae species.

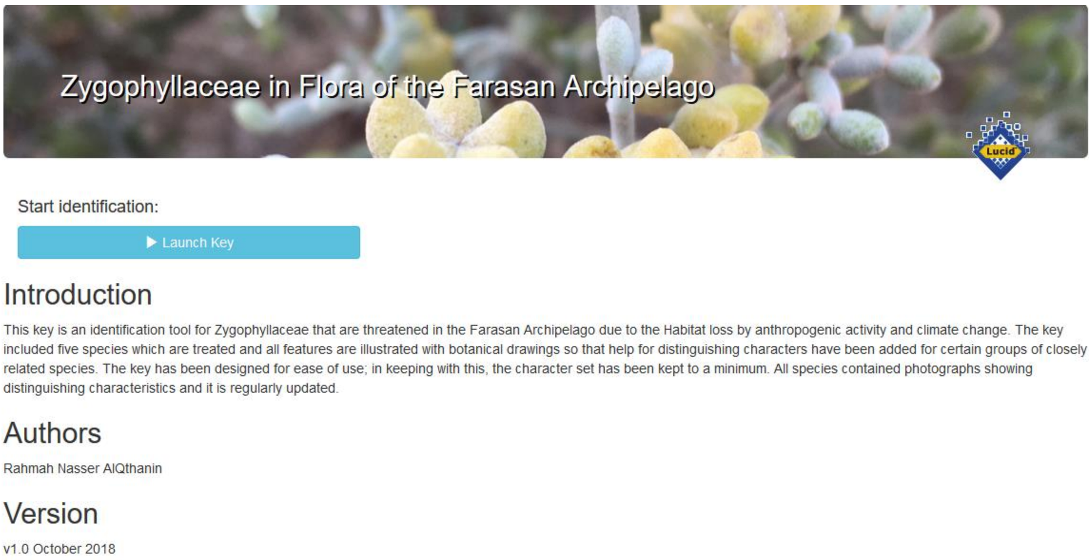

Figure 4.15 Screenshot of the welcome page of online key has been developed in Lucid Builder.

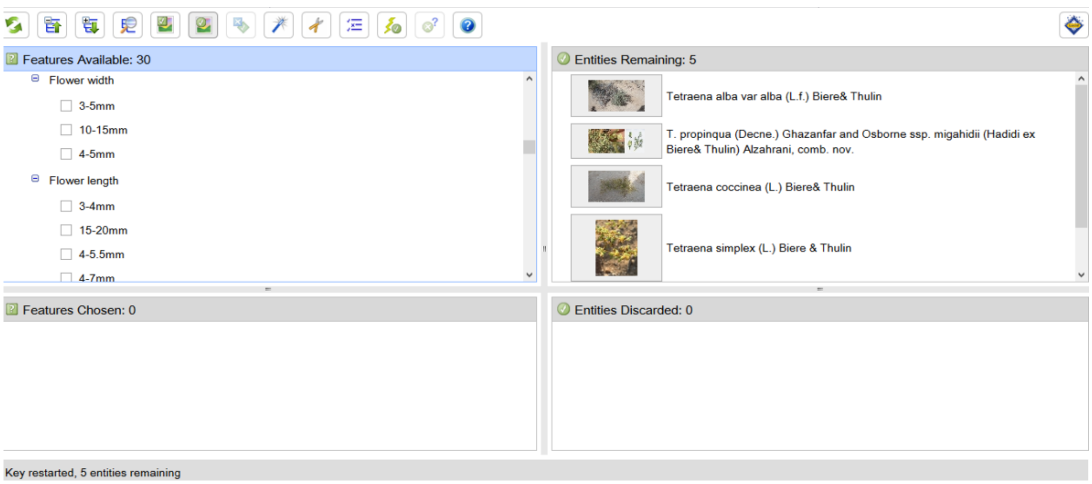

Figure 4.16 Screenshot of an online key for Zygophyllaceae species in the Farasan Archipelago has been published by Lucid Central Server.

4.3.3 Testing the key

Feedback on the multi-access key (Table 4.6) indicated that fruit features were easier to use when identification the Zygophyllaceae species. In additions, flowers and fruits characters shown that is possible to identify the Zygophyllaceae species using multi access key.

Table 4.6 Number of correct and incorrect identifications made by the "high-knowledge" and "low-knowledge" participants with the multi access key.

Participant category	**Identification**		**Time to reach identification**
	Correct	Incorrect	
High knowledge	8	2	5-15 mins
Low knowledge	7	3	11-20 mins

4.4 DISCUSSION

The initial issue was whether the five taxa can be distinguished consistently and reliably using morphology. In comparison with two previous studies of Zygophyllaceae in the Farasan Archipelago (*El-Demerdash, 1996*; *Alfarhan et al., 2005*), which were based on a small number of morphological characters or few taxa, the morphometric analysis in this research demonstrates clear morphometric differences among the five species of Zygophyllaceae in the Farasan Archipelago using 27 morphological characteristics.

The limited geographical distribution of some of these species has hindered the availability of more accessions of some Zygophyllaceae species in the Archipelago, such as *Tetraena alba* var. *alba* which is represented in this study by three accessions only.

Tribulus and *Tetraena* accessions are clearly separated to two main groups by several morphological characteristics such as size and shape of leaves, flowers and fruits. *Tribulus terrestris* L. characterized by pinnate leaf, opposite, glabrous, leaf apex acute and leaf 30-70mm long. Flowers yellow group 6A, 10-15mm across; pedicel up to 15mm long. Sepals 5-6 mm long, 3 mm broad. Petals obovate, 6-8 mm long, 3-4 mm broad. Filaments 3-5 mm long. Fruit 7-12mm broad, 8-13 mm long, spiny mericarps, which was partly agreed with *Al-Hemaid and Thomas* (*1996*).

Tetraena species are clearly distinguished from *Tribulus* by leaflet succulent, Within *Tetraena* species, *T. simplex* can be distinguished from the other *Tetranea* species by its simple leaves, yellow flowers, 2–4mm long and 3–5 mm wide, pedicel 1–2 mm long. Sepals 2mm long and 1 mm wide. Petals 2.5–3.0mm long and 1-1.5 mm wide. Stamens 2.5–3.0 mm. Fruit 5-lobed obovoid, peduncle 1–2 mm long.

Three taxa of *Tetraena* (*T.alba* var. *alba, T.coccinium, T.propqinum* subsp. *migahidii*) appeared in one large cluster or in closely related clusters. *T. alba* var. *alba* is characterized by the plant grey-green colour group 191 A, Leaves 2-foliolate, 7–12mm long and 3.0–5.5 mm wide, apex acute. Flowers white, 4-7 mm long and 6-8mm wide, pedicel 1–2 mm long. Sepals 3–4mm long and 2–3mm wide. Petals 3.5–6.0mm long and 1–2 mm wide. Stamens 3–4 mm long. Fruit obconical star-shaped, pedicel 1-2 mm long. After the reanalysis of that large group with excluded of other species, it can be cleary distinguished by different characteristics.

T. coccinium can be recognized the plant colour green group N137A. Leaves 2-foliolate, cylindrical, 14 mm long and 4.5 mm wide. Flowers white, 4–7mm long and 4–5 mm wide, pedicel up to 10 mm long. Sepals 4–6mm long and 2–3 mm wide. Petals 5–7mm long and 2.0–2.5 mm wide. Stamens 3.0–4.5 mm long. Cylindrical fruits, peduncle up to 11 mm long.

T. propqinum subsp. *migahidii* is recognized by the plant colour green group N137A. Leaves 2-foliolate, apex rounded, 14 mm long and 4.5 mm wide. Flowers Yellow white group 158C, 4-7mm long and 3.5–5.0 mm wide, pedicel 7–14 mm long. Sepals 3–5mm long and 2–3 mm wide. Petals 2.5 mm long and –7mm wide. Stamens 10, 3–5 mm long. Fruit obconical 5-angled, peduncle up to 11 mm long. This result is consistent with *Chauldhary* (*2001*), *Ghazanfar and Osborne* (*2015*) and *Alzahrani and Albokhari* (*2018*).

The discriminant analysis showed there are differences between the five taxa. With this knowledge, a key can be built with a confidence. The challenge then is to describe the key distinguishing characters in such a way that users will consistently reach the correct ID using the key.

This study has demonstrated that constructing a Lucid interactive key for the Zygophyllaceae as an example for Lucid key for identifying species in the Farasan Archipelago is useful. Furthermore, it has demonstrated that constructing a Lucid interactive key makes the identification easier and saves time and effort as discussed by *Walter and Winterton,* (*2007*) *and Farr* (*2006*). Feedback during testing the key suggested that flowers and fruit features were the easiest to examine.

5. CONCLUSIONS

This research has re-evaluated the Zygophyllaceae species using morphological characteristics as a model for the whole plant families in the Farasan Archipelago. The first identification key for Zygophyllaceae species in the Farasan Archipelago has been made available to a wide range of users on https://keys.lucidcentral.org/keys/v3/zygophyllaceae . The findings demonstrate that *Tetraene* and *Tribulus* genera, and *Tetraene* species of the Farasan archipelago can be distinguished by morphological characters and we have provided the means to do this. It confirms the importance of the morphological characteristics in the identification of Zygophyllaceae species in the Farasan Archipelago. It is/can be an important tool to identify species in the field before genetic research and IUCN Red listing. The next phases will be to expand the key to cover the Farasan Islands flora and develop more keys, however, this work needs collaboration by all concerned parties on this endeavour.

ACKNOWLEDGEMENTS

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APPENDIX:

Supplemental Information 1**:** List of samples collected from the Farasan Archipelago and used for morphometric analysis for this study, included sampling species name, locations and geographical coordinates.

Number	**Species**	**Species code**	**Location**	**Latitude**	**Longitude**
1	*Tetraena simplex*	T.S.1	Farasan Alkabir Island	16.679275	42.112569
2	*Tetraena simplex*	T.S.2	Farasan Alkabir Island	16.679375	42.112539
3	*Tetraena simplex*	T.S.3	Farasan Alkabir Island	16.680924	42.110151
4	*Tetraena simplex*	T.S.4	Farasan Alkabir Island	16.681787	42.109267
5	*Tetraena simplex*	T.S.5	Farasan Alkabir Island	16.682053	42.108905
6	*Tetraena simplex*	T.S.6	Farasan Alkabir Island	16.745928	41.995321
7	*Tetraena simplex*	T.S.7	Farasan Alkabir Island	16.745545	41.994299
8	*Tetraena simplex*	T.S.8	Farasan Alkabir Island	16.737805	41.980959
9	*Tetraena simplex*	T.S.9	Farasan Alkabir Island	16.748628	41.906056
10	*Tetraena simplex*	T.S.10	Farasan Alkabir Island	16.748765	41.905856
11	*Tetraena simplex*	T.S.11	Farasan Alkabir Island	16.748818	41.905713
12	*Tetraena simplex*	T.S.12	Farasan Alkabir Island	16.706461	42.182737
13	*Tetraena simplex*	T.S.13	Sajid Island	16.77185	41.99961
14	*Tetraena simplex*	T.S.14	Sajid Island	16.771552	41.99984
15	*Tetraena simplex*	T.S.15	Sajid Island	16.773295	41.999709
16	*Tetraena simplex*	T.S.16	Sajid Island	16.774995	42.000127
17	*Tetraena simplex*	T.S.17	Sajid Island	16.77185	41.99961
18	*Tetraena simplex*	T.S.18	Sajid Island	16.770121	41.990463
19	*Tetraena simplex*	T.S.19	Sajid Island	16.781907	41.987793
20	*Tetraena simplex*	T.S.20	Sajid Island	16.780461	41.988315
21	*Tetraena simplex*	T.S.21	Sajid Island	16.760346	42.002523
22	*Tetraena simplex*	T.S.22	Sajid Island	16.761014	42.00372
23	*Tetraena coccinea*	T.C.-1	Farasan Alkabir Island	16.745625	41.996646
24	*Tetraena coccinea*	T.C.-2	Farasan Alkabir Island	16.745269	41.996341
25	*Tetraena coccinea*	T.C.-3	Farasan Alkabir Island	16.744978	41.995869
26	*Tetraena coccinea*	T.C.-4	Farasan Alkabir Island	16.739193	41.994484
27	*Tetraena coccinea*	T.C.-5	Farasan Alkabir Island	16.738999	41.994012
28	*Tetraena coccinea*	T.C.-6	Farasan Alkabir Island	16.741424	41.99064
29	*Tetraena coccinea*	T.C.-7	Farasan Alkabir Island	16.741521	41.989188
30	*Tetraena coccinea*	T.C.-8	Farasan Alkabir Island	16.740327	41.988109
31	*Tetraena coccinea*	T.C.-9	Farasan Alkabir Island	16.669108	42.11662
32	*Tetraena coccinea*	T.C.-10	Farasan Alkabir Island	16.66877	42.116784
33	*Tetraena coccinea*	T.C.-11	Farasan Alkabir Island	16.668501	42.117089
34	*Tetraena coccinea*	T.C.-12	Farasan Alkabir Island	16.670323	42.116291
35	*Tetraena coccinea*	T.C.-13	Sajid Island	16.851652	41.931441
36	*Tetraena coccinea*	T.C.-14	Sajid Island	16.851225	41.931193
37	*Tetraena coccinea*	T.C.-15	Sajid Island	16.759688	41.999365
38	*Tetraena coccinea*	T.C.-16	Sajid Island	16.75894	41.999485

39	*Tetraena coccinea*	T.C.-17	Sajid Island	16.882244	41.904316
40	*Tetraena coccinea*	T.C.-18	Sajid Island	16.881747	41.905579
41	*Tetraena coccinea*	T.C.-19	Sajid Island	16.779946	41.988817
42	*Tetraena coccinea*	T.C.-20	Sajid Island	16.779865	41.989089
43	*Tetraena coccinea*	T.C.-21	Sajid Island	16.779775	41.98925
44	*Tetraena coccinea*	T.C.-22	Sajid Island	16.883308	41.903426
45	*Tetraena coccinea*	T.C.-23	Sajid Island	16.851902	41.930331
47	*Tetraena propinqua* ssp. *migahidii*	T.P.-1	Farasan Alkabir Island	16.832801	41.787239
48	*Tetraena propinqua* ssp. *migahidii*	T.P.-2	Farasan Alkabir Island	16.832015	41.787396
49	*Tetraena propinqua* ssp. *migahidii*	T.P.-3	Farasan Alkabir Island	16.831091	41.787324
50	*Tetraena propinqua* ssp. *migahidii*	T.P.-4	Farasan Alkabir Island	16.830597	41.786798
51	*Tetraena propinqua* ssp. *migahidii*	T.P.-5	Farasan Alkabir Island	16.829463	41.785976
52	*Tetraena alba* var. *alba*	T.A.-1	Farasan Alkabir Island	16.849832	41.816443
63	*Tetraena alba* var. *alba*	T.A.-2	Farasan Alkabir Island	16.849815	41.816411
64	*Tetraena alba* var. *alba*	T.A.-3	Dushak Island	16.645956	41.87377
65	*Tribulus terrestris*	T.T. -1	Farasan Alkabir Island	16.709988	42.11359
66	*Tribulus terrestris*	T.T. -2	Farasan Alkabir Island	16.710039	42.113416
67	*Tribulus terrestris*	T.T. -3	Farasan Alkabir Island	16.710423	42.11381
68	*Tribulus terrestris*	T.T. -4	Farasan Alkabir Island	16.70972	42.113516
69	*Tribulus terrestris*	T.T. -5	Farasan Alkabir Island	16.710447	42.11387
70	*Tribulus terrestris*	T.T. -6	Farasan Alkabir Island	16.706592	42.117622
71	*Tribulus terrestris*	T.T. -7	Farasan Alkabir Island	16.706552	42.117625

Supplemental Information 2**:** List of herbarium samples used for the morphometric analysis

Species name	**Country of origin**	**Barcode**	**Collection date**	**Collector**
Zygophyllum propinquum Decne.	Arabian Peninsula	E00333782	07 February 1982	Naylor, K.
Zygophyllum migahidii Hadidi	Saudi Arabia	E00333779	27 April 1988	Collenette, Iris Sheila (Mrs).
Zygophyllum migahidii Hadidi	Saudi Arabia	E00333778	16 March 1986	Collenette, Iris Sheila (Mrs).
Zygophyllum migahidii Hadidi	Saudi Arabia	E00333777	08 September 1983	Collenette, Iris Sheila (Mrs).
Zygophyllum migahidii Hadidi	Saudi Arabia	E00333776	12 March 1983	Collenette, Iris Sheila (Mrs).
Zygophyllum mandavillei Hadidi	Saudi Arabia	E00333774	03 February 1979	Mandaville, James P. Jr.
Zygophyllum coccineum L.	Saudi Arabia	E00338701	04 October 1983	Collenette, Iris Sheila (Mrs).
Zygophyllum coccineum L.	Saudi Arabia	E00338702	01 April 1989	Collenette, Iris Sheila (Mrs).
Zygophyllum boulosii Hadidi	Saudi Arabia	E00338703	11 February 1986	Collenette, Iris Sheila (Mrs).
Zygophyllum boulosii Hadidi	Saudi Arabia	E00338704	17 April 1987	Collenette, Iris Sheila (Mrs).
Zygophyllum boulosii Hadidi	Saudi Arabia	E00333789	10 November 1987	Collenette, Iris Sheila (Mrs).
Tribulus terrestris L. var. *terrestris*	Saudi Arabia	E00333574	03 March 1986	Fayed, A.A.
Tribulus terrestris L. var. *terrestris*	Saudi Arabia	E00333573	27 December 1979	Chaudhary, S.A.
Tribulus terrestris L. var. *terrestris*	Saudi Arabia	E00333572	27 December 1979	Chaudhary, S.A.
Tribulus terrestris L. var. *terrestris*	Saudi Arabia	E00333569	07 July 1976	Dwyer, J.D.

Supplemental Information 3**:** Qualitative data of the Zygophyllaceae species in the Farasan Archipelago.

Number	**Species**	**code**	**HP**	**SG**	**SC**	**SS**	**LT**	**LC**	**LA**	**LS**	**LP**	**LA**	**FP**	**FC**	**FSH**	**FS**	**HP**
1	*Tetraena simplex*	T.S.1	1	1	3	1	1	3	1	2	1	1	1	1	3	3	1
2	*Tetraena simplex*	T.S.2	1	1	3	1	1	3	1	2	1	1	1	1	3	3	1
3	*Tetraena simplex*	T.S.3	1	1	3	1	1	3	1	2	1	1	2	1	3	3	1
4	*Tetraena simplex*	T.S.4	1	1	3	1	1	3	1	2	1	1	2	1	3	3	1
5	*Tetraena simplex*	T.S.5	1	1	3	1	1	3	1	2	1	1	2	1	3	3	1
6	*Tetraena simplex*	T.S.6	1	1	3	1	1	3	1	2	1	1	2	1	3	3	1
7	*Tetraena simplex*	T.S.7	1	1	3	1	1	3	1	2	1	1	2	1	3	3	1
8	*Tetraena simplex*	T.S.8	1	1	3	1	1	3	1	2	1	1	2	1	3	3	1
9	*Tetraena simplex*	T.S.9	1	1	3	1	1	3	1	2	1	1	2	1	3	3	1
10	*Tetraena simplex*	T.S.10	1	1	3	1	1	3	1	2	1	1	2	1	3	3	1
11	*Tetraena simplex*	T.S.11	1	1	3	1	1	3	1	2	1	1	2	1	3	3	1
12	*Tetraena simplex*	T.S.12	1	1	3	1	1	3	1	2	1	1	2	1	3	3	1
13	*Tetraena simplex*	T.S.13	1	1	3	1	1	3	1	2	1	1	2	1	3	3	1
14	*Tetraena simplex*	T.S.14	1	1	3	1	1	3	1	2	1	1	2	1	3	3	1
15	*Tetraena simplex*	T.S.15	1	1	3	1	1	3	1	2	1	1	1	1	3	3	1
16	*Tetraena simplex*	T.S.16	1	1	3	1	1	3	1	2	1	1	2	1	3	3	1
17	*Tetraena simplex*	T.S.17	1	1	3	1	1	3	1	2	1	1	2	1	3	3	1
18	*Tetraena simplex*	T.S.18	1	1	3	1	1	3	1	2	1	1	2	1	3	3	1
19	*Tetraena simplex*	T.S.19	1	1	3	1	1	3	1	2	1	1	1	1	3	3	1
20	*Tetraena simplex*	T.S.20	1	1	3	1	1	3	1	2	1	1	2	1	3	3	1
21	*Tetraena simplex*	T.S.21	1	1	3	1	1	3	1	2	1	1	2	1	3	3	1
22	*Tetraena simplex*	T.S.22	1	1	3	1	1	3	1	2	1	1	2	1	3	3	1
23	*Tetraena coccinea*	T.C.-1	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2

24	*Tetraena coccinea*	T.C.-2	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
25	*Tetraena coccinea*	T.C.-3	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
26	*Tetraena coccinea*	T.C.-4	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
27	*Tetraena coccinea*	T.C.-5	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
28	*Tetraena coccinea*	T.C.-6	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
29	*Tetraena coccinea*	T.C.-7	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
30	*Tetraena coccinea*	T.C.-8	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
31	*Tetraena coccinea*	T.C.-9	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
32	*Tetraena coccinea*	T.C.-10	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
33	*Tetraena coccinea*	T.C.-11	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
34	*Tetraena coccinea*	T.C.-12	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
35	*Tetraena coccinea*	T.C.-13	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
36	*Tetraena coccinea*	T.C.-14	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
37	*Tetraena coccinea*	T.C.-15	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
38	*Tetraena coccinea*	T.C.-16	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
39	*Tetraena coccinea*	T.C.-17	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
40	*Tetraena coccinea*	T.C.-18	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
41	*Tetraena coccinea*	T.C.-19	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
42	*Tetraena coccinea*	T.C.-20	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
43	*Tetraena coccinea*	T.C.-21	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
44	*Tetraena coccinea*	T.C.-22	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
45	*Tetraena coccinea*	T.C.-23	2	2	2	1	2	2	2	1	2	1	2	2	5	3	2
46	*Tetraena propinqua* ssp. *migahidii*	T.P.-1	2	2	1	1	2	1	2	1	2	1	2	3	2	1	2
47	*Tetraena propinqua* ssp. *migahidii*	T.P.-2	2	2	1	1	2	1	2	1	2	1	2	3	2	1	2
48	*Tetraena propinqua* ssp. *migahidii*	T.P.-3	2	2	1	1	2	1	2	1	2	1	2	3	2	1	2
49	*Tetraena propinqua* ssp. *migahidii*	T.P.-4	2	2	1	1	2	1	2	1	2	1	2	3	2	1	2
50	*Tetraena propinqua* ssp. *migahidii*	T.P.-5	2	2	1	1	2	1	2	1	2	1	2	3	2	1	2
51	*Tetraena alba* var. *alba*	T.A.-1	2	2	1	1	2	1	2	1	2	2	2	2	1	1	2

52	*Tetraena alba* var. *alba*	T.A.-2	2	2	1	1	2	1	2	1	2	2	2	2	1	1	2
53	*Tetraena alba* var. *alba*	T.A.-3	2	2	1	1	2	1	2	1	2	2	2	2	1	1	2
54	*Tribulus terrestris L.*	T.T. -1	1	1	1	1	2	1	3	2	1	2	2	1	4	2	1
55	*Tribulus terrestris L.*	T.T. -2	1	1	1	1	2	1	3	2	1	2	2	1	4	2	1
56	*Tribulus terrestris L.*	T.T. -3	1	1	1	1	2	1	3	2	1	2	2	1	4	2	1
57	*Tribulus terrestris L.*	T.T. -4	1	1	1	1	2	1	3	2	1	2	2	1	4	2	1
58	*Tribulus terrestris L.*	T.T. -5	1	1	1	1	2	1	3	2	1	2	2	1	4	2	1
59	*Tribulus terrestris L.*	T.T. -6	1	1	1	1	2	1	3	2	1	2	2	1	4	2	1
60	*Tribulus terrestris L.*	T.T. -7	1	1	1	1	2	1	3	2	1	2	2	1	4	2	1

Supplemental Information 4**:** Quantitative data of the Zygophyllaceae species in the Farasan Archipelago.

Number	code	LL	LW	PL	FPL	FW	FL	PL	PW	SL	SW	STL	LSL	SSL	FRL	FUW	FLW	FRPL
1	T.S.1	0.712	-1.553	-0.997	-1.251	-0.581	-0.771	-1.047	-1.091	-0.826	-0.749	-1.066	-0.038	-1.101	-1.147	1.704	-0.935	-0.899
2	T.S.2	0.712	-1.553	-0.997	-1.251	-0.581	-0.771	-1.047	-1.091	-0.826	-0.749	-1.066	-0.038	-1.101	-1.147	1.704	-0.935	-0.899
3	T.S.3	1.130	-1.553	-0.997	-0.915	-0.581	-0.771	-1.047	-1.091	-0.826	-0.749	-1.066	-0.038	-1.101	-1.147	1.704	-0.935	-0.899
4	T.S.4	0.921	-1.553	-0.997	-0.915	-0.581	-0.771	-1.047	-1.091	-0.826	-0.563	-1.066	-0.038	-1.101	-1.147	1.704	-0.935	-0.899
5	T.S.5	1.340	-1.553	-0.997	-0.915	-0.581	-0.771	-1.047	-1.091	-0.506	-0.563	-1.066	-0.038	-1.101	-1.147	1.704	-0.935	-0.899
6	T.S.6	1.340	-1.553	-0.997	-0.915	-0.581	-0.771	-1.047	-1.091	-0.187	-0.563	-1.066	-0.038	-1.101	-1.147	1.704	-0.935	-0.899
7	T.S.7	0.921	-1.553	-0.997	-0.915	-0.581	-0.771	-1.047	-1.091	-0.187	-0.749	-1.066	-0.038	-1.101	-1.147	1.704	-0.935	-0.899
8	T.S.8	1.340	-1.553	-0.997	-0.915	-0.581	-0.771	-1.047	-1.091	-0.826	-0.749	-1.066	-1.171	-1.101	-1.147	1.704	-0.935	-0.899
9	T.S.9	1.340	-1.553	-0.997	-0.915	-0.581	-0.771	-1.047	-1.091	-0.826	-0.749	-1.066	-1.171	-1.101	-1.147	1.704	-0.935	-0.899
10	T.S.10	0.921	-1.553	-0.997	-0.915	-0.581	-0.771	-1.047	-1.091	-0.506	-0.563	-1.066	-1.171	-1.101	-1.147	1.704	-0.935	-0.899
11	T.S.11	0.921	-0.038	-0.997	-0.915	-0.930	-0.771	-1.301	-1.288	-0.187	-0.563	-1.066	-1.171	-1.101	-1.147	0.457	-0.935	-0.899
12	T.S.12	0.921	-0.038	-0.997	-0.915	-0.930	-0.771	-1.301	-1.288	-0.187	-0.563	-1.066	-1.171	-1.101	-1.147	0.457	-0.935	-0.899
13	T.S.13	1.130	-0.038	-0.997	-0.915	-0.930	-0.771	-1.301	-1.288	-0.187	-0.563	-1.066	-1.171	-1.101	-1.147	0.457	-0.935	-0.899
14	T.S.14	1.340	-0.038	-0.997	-0.915	-0.930	-0.771	-1.301	-1.288	-0.187	-0.563	-1.066	-1.171	-1.101	-1.147	0.457	-0.935	-0.899

15	T.S.15	1.340	-0.038	-0.997	-1.251	-0.930	-0.771	-1.301	-1.288	-0.187	-0.563	-1.066	-1.171	-1.101	-1.147	0.457	-0.935	-0.899
16	T.S.16	1.340	-0.795	-0.997	-0.915	-0.930	-0.771	-1.301	-1.288	-0.826	-0.563	-1.066	-1.171	-1.101	-1.147	0.457	-0.935	-0.899
17	T.S.17	1.130	-0.795	-0.997	-0.915	-0.930	-0.771	-1.301	-1.288	-0.826	-0.563	-1.066	-1.171	-1.101	-1.147	0.457	-0.935	-0.899
18	T.S.18	1.130	-0.795	-0.997	-0.915	-0.930	-0.771	-1.301	-1.288	-0.506	-0.563	-1.066	-1.171	-1.101	-1.147	0.457	-0.935	-0.899
19	T.S.19	1.340	-0.795	-0.997	-1.251	-0.930	-0.771	-1.301	-1.288	-0.187	-0.563	-1.066	-1.171	-1.101	-1.147	0.457	-0.935	-0.899
20	T.S.20	0.921	-0.795	-0.997	-0.915	-0.930	-0.771	-1.301	-1.288	-0.187	-0.563	-1.066	-1.171	-1.101	-1.147	0.457	-0.935	-0.899
21	T.S.21	1.340	-0.795	-0.997	-0.915	-0.581	-0.771	-1.301	-1.288	-0.187	-0.563	-1.066	-1.171	-1.101	-1.147	1.704	-0.935	-0.899
22	T.S.22	1.340	-0.795	-0.997	-0.915	-0.581	-0.771	-1.301	-1.288	-0.187	-0.563	-1.066	-1.171	-1.101	-1.147	1.704	-0.935	-0.899
23	T.C.-1	-0.335	0.720	1.199	0.428	0.465	0.721	1.233	0.673	-0.187	-0.192	0.066	1.096	0.194	1.226	-0.790	1.355	1.553
24	T.C.-2	-0.335	0.720	0.979	0.428	0.465	0.721	1.233	0.673	-0.187	-0.377	0.632	1.096	0.194	0.040	-0.790	1.355	0.940
25	T.C.-3	-0.754	0.720	0.650	0.260	0.465	0.721	1.233	0.673	-0.187	-0.192	0.066	-0.038	0.194	0.040	-0.790	1.355	0.940
26	T.C.-4	0.084	0.720	1.199	0.428	0.465	0.721	1.233	0.673	-0.187	-0.192	0.066	-0.038	0.194	0.040	-0.790	1.355	0.940
27	T.C.-5	-0.335	0.720	1.199	0.428	0.465	0.721	1.233	0.673	-0.187	-0.377	0.066	-0.038	0.194	0.040	-0.790	1.355	0.940
28	T.C.-6	0.084	0.720	1.199	0.428	0.465	0.721	1.233	0.673	-0.187	-0.192	0.066	1.096	0.194	0.040	-0.790	1.355	0.940
29	T.C.-7	-0.754	0.720	1.199	0.428	-0.232	-0.025	0.980	1.065	-0.506	-0.192	0.066	1.096	0.194	0.040	-0.790	1.355	0.940
30	T.C.-8	-0.335	-0.038	1.199	0.428	-0.232	-0.025	0.980	1.065	-0.187	-0.192	0.066	-0.038	1.490	0.040	-0.790	1.355	0.940
31	T.C.-9	-0.754	-0.038	0.979	0.428	-0.232	-0.025	0.980	1.065	-0.187	-0.377	0.066	-0.038	1.490	0.040	-0.790	1.355	0.940
32	T.C.-10	0.084	0.720	0.979	0.092	-0.232	-0.025	0.980	1.065	-0.187	-0.192	0.066	-0.038	0.194	0.040	-0.790	1.355	0.940
33	T.C.-11	-0.754	0.720	1.199	0.092	-0.581	-0.398	0.473	1.065	-0.187	-0.006	0.632	1.096	0.194	0.040	-0.790	-0.935	0.940
34	T.C.-12	0.084	0.720	1.199	0.092	-0.581	-0.398	0.473	1.065	-0.506	-0.192	0.632	-0.038	0.194	0.040	-0.790	0.210	0.940
35	T.C.-13	-0.335	1.477	1.199	0.428	-0.581	-0.398	0.473	1.065	-0.187	-0.006	0.632	-0.038	0.194	0.040	-0.790	0.210	0.940
36	T.C.-14	0.084	1.477	1.199	0.428	-0.581	-0.398	0.473	1.065	-0.187	-0.006	1.198	-0.038	1.490	0.040	-0.790	0.210	0.940
37	T.C.-15	-0.754	1.477	0.979	0.428	0.465	0.721	1.233	1.065	-0.187	-0.006	1.198	-0.038	1.490	0.040	-0.790	0.210	0.940
38	T.C.-16	-0.335	1.477	0.979	0.428	0.465	0.721	1.233	1.065	-0.506	-0.006	1.198	-0.038	1.490	0.040	-0.790	0.210	0.940
39	T.C.-17	0.084	1.477	0.650	0.428	0.465	0.721	1.233	0.281	-0.187	-0.006	1.198	-0.038	1.490	0.040	-0.790	0.210	0.940
40	T.C.-18	-0.754	-0.038	1.199	0.428	-0.581	-0.398	0.473	0.281	-0.187	-0.192	1.198	-0.038	0.194	0.040	-0.790	0.210	0.940
41	T.C.-19	-0.335	-0.038	1.199	0.428	-0.581	-0.398	0.473	0.673	-0.187	-0.006	1.198	-0.038	0.194	0.040	-0.790	0.210	0.940

42	T.C.-20	-0.754	-0.038	1.199	0.428	-0.581	-0.398	0.473	0.673	-0.187	-0.006	1.198	-0.038	1.490	1.226	-0.790	0.210	0.940
43	T.C.-21	0.084	-0.038	1.199	0.260	-0.581	-0.398	0.473	0.673	-0.187	-0.006	1.198	-0.038	1.490	1.226	-0.790	0.210	0.940
44	T.C.-22	-0.754	-0.038	0.979	0.092	-0.581	-0.398	0.473	0.673	-0.187	-0.006	1.198	-0.038	0.194	1.226	-0.790	0.210	0.940
45	T.C.-23	0.084	-0.038	0.979	0.092	-0.581	-0.398	0.473	0.673	-0.187	-0.006	1.198	-0.038	0.194	1.226	-0.790	-0.935	0.940
47	T.P.-1	-0.754	-0.795	0.540	1.100	-0.581	-0.771	0.473	1.261	-0.187	-0.006	-1.066	-1.171	0.842	1.226	0.457	-0.935	2.166
48	T.P.-2	-0.754	-0.795	0.320	-0.076	-0.581	-0.771	0.473	1.261	-0.187	-0.192	-1.066	1.096	0.842	1.226	0.457	-0.935	2.166
49	T.P.-3	-0.754	0.720	0.540	0.764	0.465	-0.025	0.473	1.261	-0.506	-0.192	-0.500	1.096	0.842	1.226	0.457	1.355	0.327
50	T.P.-4	-0.335	0.720	0.320	-0.076	0.814	0.348	0.473	1.261	-0.187	-0.006	0.632	1.096	-0.453	1.226	0.457	1.355	0.940
51	T.P.-5	-0.335	0.720	0.540	0.764	0.814	0.348	0.473	1.261	-0.187	-0.006	0.632	1.096	-0.453	1.226	-0.790	1.355	0.940
62	T.A.-1	-0.963	0.720	0.650	-0.915	0.814	-0.771	-1.047	-0.699	-0.826	-0.563	0.632	-1.171	-0.453	1.226	-0.790	-0.935	-0.899
63	T.A.-2	-0.335	2.234	0.979	-0.915	2.208	0.721	-0.541	-0.699	-0.506	-0.192	0.632	-1.171	0.194	1.226	-0.790	0.210	-0.899
64	T.A.-3	-1.382	2.234	0.101	-0.915	2.557	0.721	-0.034	-0.307	-0.187	-0.192	-0.500	-0.038	0.194	1.226	-0.790	0.210	-0.899
65	T.T. -1	-1.800	-0.038	-0.997	1.268	0.814	1.095	1.233	0.673	2.372	1.479	0.632	1.096	1.490	1.226	-0.790	1.355	-0.899
66	T.T. -2	-1.382	-0.038	-0.997	2.107	0.814	1.095	1.233	0.673	1.413	2.407	0.632	1.096	1.490	1.226	-0.790	1.355	-0.899
67	T.T. -3	-2.010	0.720	-0.997	2.107	0.814	1.095	1.233	0.673	3.012	2.407	0.632	1.096	0.194	1.226	-0.790	1.355	-0.899
68	T.T. -4	-2.010	-0.038	-0.997	2.947	2.557	2.960	0.473	0.281	3.012	3.335	1.764	2.229	1.490	1.226	-0.790	1.355	-0.899
69	T.T. -5	-1.591	-0.038	-0.997	1.268	2.208	2.587	0.473	0.281	3.012	1.479	1.764	2.229	1.490	1.226	-0.790	-0.935	-0.899
70	T.T. -6	-1.382	0.720	-0.997	2.107	2.557	2.960	0.473	0.281	2.372	3.335	1.764	2.229	0.194	1.226	-0.790	-0.935	-0.899
71	T.T. -7	-1.382	-0.038	-0.997	2.107	2.557	2.960	0.473	0.281	3.012	3.335	1.764	2.229	1.490	1.226	-0.790	1.355	-0.899

CHAPTER 5

Spatial structure and genetic variation of a mangrove species (*Avicennia marina* (Forssk.) Vierh) in the Farasan archipelago

CHAPTER 5

Spatial structure and genetic variation of a mangrove species (*Avicennia marina* (Forssk.) Vierh) in the Farasan archipelago

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Abstract

***Avicennia marina* is distributed in patches along the Farasan archipelago coast and is the commonest mangrove species in the Red Sea. However, to date, no studies have been directed towards the understanding of their genetic variation in the Farasan Archipelago. Genetic variations within and among *Avicennia marina* natural populations in the Farasan Archipelago were studied using fifteen microsatellite markers. The study found 142 alleles on 15 loci in 9 populations. The observed (H_o) and expected (H_e) heterozygosity values are 0.351 and 0.391 respectively, which is much lower compared to the earlier studies on *A. marina* in the Arabian Gulf. Inbreeding effect from self-pollination might explain its heterozygote deficiency. Population genetic differentiation (F_{ST} = 0.301) was similar to other mangrove species. Our findings suggest that the sea current direction and coastal geomorphology might affect genetic dispersal in *A. marina*. The more isolated populations with fewer connections by sea currents show the lower genetic variation and genetic differentiation observed between populations. The genetic clustering of populations fell into three main groups, Group 1(populations of Farasan Alkabir Island), Group 2 (populations of Sajid Island) and Group3 (mixed between one population of Farasan Alkabir Island and population of Zifaf Island). Higher genetic variation, and less genetic differentiation occurred when population was not isolated and had direct connection with sea currents. Both these factors contributed to limited propagule dispersal and produced significant structure among the population. It is expected that the results of this research will be useful in determining policy and species conservation strategies and for the rehabilitation of A. marina mangrove stands in the Farasan Islands towards saving this significant natural resource.**

Key words: *Avicennia marina*, genetic variation, conservation, the Farasan Archipelago, genetic structure.

5.1 Introduction

Mangroves are trees or shrubs found in coastal areas, lagoons, estuaries and deltas and form the main vegetation in tidal and saline wetlands, in turn providing habitat for many other species (Duke, 1992). They are present in the tropics (Chen and Twilley, 1999), and grow in mud with a flow of freshwater bringing nutrients (Kathiresan and Bingham, 2001). The most extensive mangrove areas are in Asia 42%, Africa 20%, North and Central America 15%, Oceania 12% and finally South America 11% (Giri *et* *al.*, 2011). They play a vital role in marine life and fisheries by providing food and shelter for a large and varied group of marine organisms including fish and shellfish (Bosire *et al.*, 2004), and protect coastal areas from storms and sea level rises (Barbier *et al.*, 2011). Globally, many mangrove forests have been converted to productive lands for agriculture and aquaculture (Mastaller, 1997). Estimates of loss range from 35 to 86 % (Duke *et al.*, 2007, Giri *et al.*, 2011) in the last two decades. Approximately only 6.9% of the world's mangroves areas are protected under the IUCN program (Giri *et al.*, 2011). These mangrove communities are vulnerable to threat mainly due to human impact through coastal construction, industrial pollution, littering, loss of water quality and fisheries development (Tawfiq and Olsen, 1993, Macintosh and Ashton, 2002, Persga, 2004, Kotb *et al.*, 2004). In addition, natural disasters in some areas, such as earthquakes, tsunamis, coastal erosion (Kumar *et al.*, 2010, Kumar, 2009) and climate change (Ellison and Stoddart, 1991, Spalding *et al.*, 1997) threaten mangroves.

The first record of mangroves in the Red Sea dates to 323 BC (Flenley, 1998, Schneider, 2011). Mangroves are not continuously distributed in the Red Sea and show evidence of being at the edge of their environmental range, being stunted in comparison to other deltaic and estuary areas in the world (Mandura *et al.*, 1987), mainly due to high salinity reaching around 40‰, poor soil textures and very high seawater temperatures (32°C) (Mandura *et al.*, 1987, Saifullah, 1997). A study conducted by Saifullah (1997) revealed that the conditions in the southern part of the Red Sea are more favorable for mangroves than the northern parts because of higher nutrient concentrations, more rainfall, many runnels and less salinity due to the connection to the Indian ocean and the water flow from the Gulf of Aden into the Red Sea (Bailey, 2010). Although large stands of mangroves are found along the Red Sea mainland coast, the Farasan Archipelago which is an uplifted fossil coral reef in the southern part of the Arabian coast of the Red Sea (Rohling, 1994, Khan *et al.*, 2010, Bailey *et al.*, 2017), has only around 36.15 km² of mangroves (Almahasheer *et al.*, 2016). The Farasan Archipelago is characterized by high humidity, high mean annual temperatures and low rainfall (Hall *et al.*, 2010). Two species of mangroves occur in these islands, *Avicennia marina* and the less common, *Rhizophora mucronata* (El-Demerdash, 1996, Farooqui *et al.*, 2015).

This paper focuses on *Avicennia marina* (Avicenniaceae) in the Farasan archipelago because it is the dominant mangrove species and because it can reproduce and thrive across a wide range of climatic, saline and tidal conditions (Migahid, 1978, Mandura *et al.*, 1987, Khafaji *et al.*, 1991). It has several mechanisms leading to high tolerance of high salinity levels, reaching 70‰ for populations of *Avicennia marina* in the Arabian Gulf (Dodd *et al.*, 1999). The scientific literature on *A. marina* in the Farasan Islands is limited in coverage of distribution and coastal ecology. The distribution size of *A. marina* in the archipelago ranges from stunted bushes, usually growing on the inner fringes of the stand, to well-developed trees reaching up to 4 m in height. This species is reported for three major islands, Farasan Al-Kabir, Sajid and Zifaf **(Figure 5.1)**; the largest stands occur within the Port of Farasan Alkabir Island (Mutairi *et al.*, 2012, Rasul and Stewart, 2015).

A. marina is important for the people of the islands and there is a strategy for its conservation in the natural environment (Persga, 2004). However, the loss and fragmentation of *A. marina* is enormous at regional level. Camel grazing has been reported to be a major problem causing degradation of *A. marina*, excluding only a few stands growing on Zifaf Island (Kotb *et al.*, 2004). Cutting has led to a reduction in the number of trees (Mandura and Khafaji, 1993). Mass mortality of *A. marina* trees has been caused by construction of a new soil dam, leading to dry-up, particularly of one stand of *A. marina* on Farasan Alkabir Island. This modification in the topography of the coastal area diverts tidal water away from *A. marina*, reducing the area of this species inundated by tidal water in the upper reaches of the stands (Kotb *et al.*, 2004).

Pollution of *A. marina* areas is largely confined to domestic solid wastes such as polythene bags and bottles, plastic and metal cans, which are disposed of in large quantities by tourists visiting near *A. marina* populations (Hariri *et al.*, 2014). This practice may have a serious impact by covering the young seedlings and pneumatophores, and blocking tidal channels (Al-Wetaid and Khalil, 2003). The industrial/commercial and artisanal fisheries sectors and coastal urbanization are likely to increase (Gladstone, 2000). Many changes are expected on land, a large part of southeast Farasan Alkabir has been earmarked for a naval base. That development could affect terrestrial and marine wildlife in the area (Al-Wetaid and Khalil, 2003).

To provide an integrated management plan for the species, the use of genetic based methods to measure diversity and structure among and within populations is fundamental (Allendorf and Luikart, 2009). For *A. marina* worldwide, genetic variation has been reported using allozymes (Duke *et al.*, 1998), random amplified polymorphic DNA (RAPD) (Parani *et al.*, 1997, Parida *et al.*, 1998, Hazarika *et al.*, 2013), amplified fragment length polymorphism (AFLPs) (Maguire *et al.*, 2002, Le *et al.*, 2003) and microsatellites (SSRs). These several types of molecular marker techniques currently available, and the most suitable technique to assess genetic variation depends upon both the question addressed and the type of genetic information available for the species (Allendorf and Luikart, 2013). Since theory predicts that intraspecific genetic variation is pivotal for the persistence of species (Ouborg *et al.*, 2006), SSRs can proved suitable for conservation studies interested in estimating population sizes, population structure, genetic variation, genetic drift and inbreeding (Allendorf and Luikart, 2013). SSRs have been widely used to study population level variation of *A. marina* in South Africa and Oceania (Maguire *et al.*, 2000a, Zolgharnien *et al.*, 2010, Yoshimori *et al.*, 2015, Manurung *et al.*, 2017,). In addition, the population structure of *A. marina* has been studied by many researchers and two scenarios have been found. First, some researchers suggested no discrete boundaries between different parts of the range with allele frequencies changing gradually without any discontinuities, and with little genetic structure, (Duke *et al.*, 1998, De Ryck *et al.*, 2016). This scenario is a rare case in mangroves forest. However it is common in major forest trees (Leonardi and Menozzi, 1996, Rossetto *et al.*, 1999). Others reported propagule dispersal limited by barriers of sea movement, and /or isolation by distance causing high genetic structured between populations (Maguire *et al.*, 2000b, Arnaud-Haond *et al.*, 2006). **Table 5.1** show the summaries of the finding of these studies for *A. marina.*

Only one study has focused on *A. marina* in the Red Sea (Yoshimori *et al.*, 2015), which concluded that the loss of genetic diversity in the Northern Red Sea populations was attributed to limited gene flow and increased genetic drift arising from a patchy distribution. That study suggested that the Red Sea plants have a distinct genetic composition compared with other regions of the Indo Pacific Ocean (Yoshimori *et al.*, 2015). To date, the extent and patterns of genetic diversity in natural *A. marina* populations in the Farasan archipelago are unknown.

Flies and bees are usually play an important role in the success of sexual reproduction in *Avicennia marina*. The production of one-seeded fruits may be due to maternal resource constraint or maternal regulation of seed set. Fruits grow and mature within 4 weeks (Raju et al., 2012). Each fruit contains one seed and the single seed is not dormant and germinates immediately to produce achlorophyllous seedling which remains within the fruit, while still on the maternal parent. This is a specific characteristic of "crypto-viviparous" mangroves (Duke, 1998). In all these species, fruit is the propagule; the seedling occupies the fruit cavity, the propagules are ellipsoidal to flattened ovoid, small and light, floating on the surface of the water, and the entire embryo is buoyant after detachment from the maternal parent. When the seedlings settle, radicle penetrates the sediment before the cotyledons unfold. The first formal leaves appear one month after germination and the second pair one to two months (Wium-Andersen & Christensen 1978).

Propagule dispersal is an important ecological factor in understanding the distribution of mangrove populations and patterns of genetic diversity. The high density of the propagules of *A. marina*, is not found in other mangrove species. Due to their high density they are not affected by wind action (Van Der Stocken *et al.*, 2015). Knowledge of dispersal distances and direction is essential as it allows the assessment and prediction of the chance of propagules to reach and colonize remote habitat fragments. Flowers appear all year round but propagule maturation occurs during July–August in the northern hemisphere (Duke, 2006, Giesen *et al.*, 2007). It has been suggested that dispersal of *A. marina* is strongly affected by sea currents (Duke, 2006). In addition to the effect of sea currents in the genetic structure of *A. marina*, some barriers exist, such as land barriers in fragmented habitats, the distance between populations (Melville and Burchett, 2002, Le *et al.*, 2003), the geomorphological coast line of the islands (Pavlopoulos *et al.*, 2018) and sea level change. Although there are limited studies on the impacts of climate change on mangroves within the Middle East, a recent study by Alothman *et al.* (2014) estimated recent relative sea level rise (SLR) to be 3.3 mm/yr in the Gulf of Aden and the Red Sea. This may threaten the mangroves as

Blankespoor *et al.* (2014) have suggested that up to 96% of coastal wetlands including mangroves are likely to be lost from the region because of sea level rise.

Here, microsatellite markers, which have been developed for *A. marina* by (Maguire *et al.*, 2000a) were used to, (1) assess the genetic diversity of the mangrove species *A. marina* in the densest area of the Farasan archipelago (2) identify levels of inbreeding in populations of *A. marina* found on the Farasan Islands and (3) investigate the genetic structure of populations of *A. marina* found on the Farasan Islands.

5.2 Material and methods

5.2.1 Study area

A. marina leaves were collected from nine populations across the Farasan Archipelago, during three field studies, between 2015 and 2016 **(Table 5.2).** Populations were sampled based on the accessibility of different habitats **(Figure 5.2)** and ensuring 5 meters between samples to prevent sampling ramets. Number of individuals which collected ranged from 6 to 33 per population, in order to ensure that sufficient samples were collected without endangering small populations.

Avicennia marina populations in the Farasan Islands occur in discontinuous stretches along the coast in suitable environments interspersed by unsuitable habitats such as long sandy beaches and rocky shores. The island's name and sizes, sampling locations and coordinates were recorded using a Global Positioning System (GPS) and are given in **(Table 5.2)**. Permission for sampling from the Saudi wildlife authority in the Kingdom of Saudi Arabia was obtained because these islands are registered as protected areas due to the presence of endemic Arabian gazelle.

5.2.2 DNA extraction

Leaves were dried in silica gel prior to extraction. Total genome of DNA was extracted from each individual of *A. marina* using a modified CTAB protocol, following the method of Maguire *et al.*, (1994). The final DNA was suspended in 50 µl of TE buffer. DNA extractions were visualized on 0.7% agarose gels in 1× TAE buffer, to confirm the size and concentration of the extracted DNA, using Hyper Ladder™ 1kb (Bioline Reagents Ltd., London, UK) as a marker and gels were illuminated by T: Genius. Concentration and quality were determined with NanoDrop Lite (Thermo Fisher Scientific Inc., Waltham, MA, USA). DNA was diluted to 5 ng/µl for polymerase chain reaction (PCR) amplification. After dilution, the stock DNA solutions were stored in the freezer at -20 ^{o}C.

5.2.3 DNA amplification by PCR

Microsatellite primer sequences (16 pairs) published by Maguire *et al.*, (2000a) were applied to *A. marina* samples. Initial primer optimization and screening resulted in the selection of 15 of the original 16 published primer sets for this study. Primer M76 was discarded due to its failure to prime to the samples. The 193 *A. marina* individuals were genotyped by PCR with fifteen polymorphic microsatellite markers as described in Maguire *et al.*, (2000b) and Zolgharnien *et al.*, (2010). Primers were labelled with fluorescent dyes (6FAM, VIC, PET, NED) for suspend amplification. The 1xPCR buffer contained 6 µl BioMix™, 2.6

µl water, 0.2 µl of each primer and 10–50 ng genomic DNA and yielded a total volume of 10 µl.

The conditions for amplifying the loci (M3, M32, M34, M40, M47, M62, M64, M73, M75, M81, M98, M85) were one activation cycle at 94 ^{o}C for 3 min, and then samples were incubated for 30 cycles of 94 ^{o}C for 30 s, 60 ^{o}C for 35 s, and 72 ^{o}C for 1 min. Reactions were completed by incubating at 72 ◦C for 5 min and held at 4 ^{o}C. For loci (M13, M27 and M49), the conditions were one activation cycle at 94 ^{o}C for 3 min, and

Table 5.1. Summarizes the findings from the genetic variation and genetic structure studies on *A. marina*.

Study area	No. of pop	Marker	No. loci	No. Alleles	Genetic diversity	Fst	Genetic structure	Data analysis	Study source
Pichavaram, Bhitarkanika Goa, Calicut	10	RAPD	14	132	27.47%	26.5%	Discrete subpopulations, 77% differential among population.	Multivariate Statistics Package	(Parani *et al.*, 1997)
Worldwide	18	Allozymes	8	26	High level 0-0.217	Low level 0.384	Discrete subpopulations, gene flow among populations was relatively low, except where populations were geographically continuous.	Biosys-l	(Duke *et al.*, 1998)
India	10	RAPD	14	172	76.7%	-	-	Nei's index- UPGMA tree	(Parida *et al.*, 1998)
Worldwide closet site =500 km	14	SSRs	3	70	0.407	0.384	Discrete sub-populations with inbreeding at the edge.	AMOVA- Mantel tests- Genepop	(Maguire *et al.*, 2000b)
Australia	6	SSRS AFLPs	3 3	52 918 b	0.78 0.193	-		GeeneAlEX (AMOVA- Mantel test)	(Maguire *et al.*, 2002)
Local scale- Sydney	9	Isozyme	22	83	-	-	Isolation by distance with inbreeding in each estuary.	ANOVAs- TWINSPAN	(Melville and Burchett, 2002)
Vietnam	6	AFLAP SSRS	3 5	232 21	0.086 0.210	0.262 0.338	Discrete sub-populations with inbreeding at all sites.	Popgene 3.2- PHYLP	(Le *et al.*, 2003)
Southeast Asian	12	SSRs	7	118	0.15-0.79	0.01-0.67	Discrete sub-populations with reduced diversity at range edges.	Bottleneck 1.2.02 - Genetix.	(Arnaud-Haond *et al.*, 2006)
Iran	3	SSRs	3	14	0.451 to 0.667	0.03-0.05	Reduced level of genetic variation was found in the central population indicating strong genetic structure among the other population with large area and less exploitation.	Popgene 3.2- UPGMA tree	(Kahrood *et al.*, 2008)
Arabian gulf	4	SSRs	5	4 to 4.6	0.782 to 0.960	0.044	low genetic differentiation among the populations.	FSTAT- UPGMA tree by TFPGA Ver. 1.3	(Zolgharnien *et al.*, 2010)
East coast of India	3	RAPD	10	388	0.2274 ± 0.1122	-	-	PopGene	(Hazarika *et al.*, 2013)
North Red Sea Coast	3	Est SSRs SSRs	5	3-6	0.5-0.7	-	-	GeeneAlEX Version 6.4	(Yoshimori *et al.*, 2015)
Indonesia	3	SSRs	4	14	0.54-0.6	0.002-0.09	low level of genetic variation in heavily polluted area.	PopGene - AMOVA by GeneAlEX Ver. 6.4- UPGMA tree by NTSys	(Manurung *et al.*, 2017)

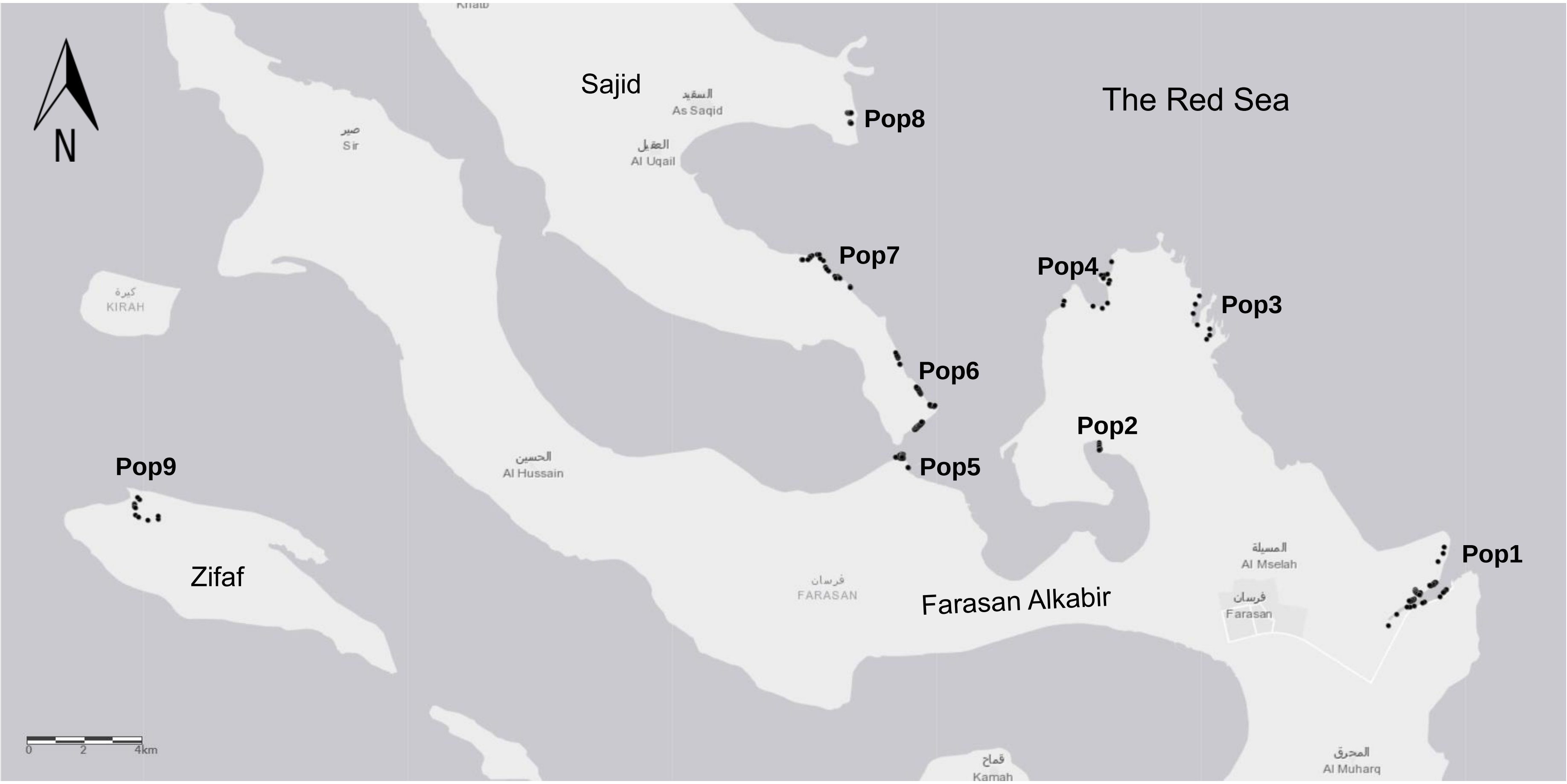

Figure 5.1. Geographical locations of the nine natural populations of *Avicennia marina* in the Farasan Archipelago.

Table 5.2 *A. marina* populations tested (name and code), latitude and longitude of the location, Island area, Island habitat and inhabited status.

Island's populations	Habitat	Inhabited area	Code	Latitude	Longitude
Farasan Al-Kabir	Sand	Yes	Pop1	16.708608	42.177948
Farasan Al-Kabir	Sand	Yes	Pop2	16.752721	42.065627
Farasan Al-Kabir	Rocky	Yes	Pop3	16.704969	42.172678
Farasan Al-Kabir	Rocky	Yes	Pop4	16.804166	42.069108
Farasan Al-Kabir	Sand	Yes	Pop5	16.747602	42.000543
Sajid	Sand	Yes	Pop6	16.756755	42.00426
Sajid	Sand	Yes	Pop7	16.856417	41.968098
Sajid	Sand	Yes	Pop8	16.857648	41.981981
Zifaf	Rocky	No	Pop9	16.733156	41.745078

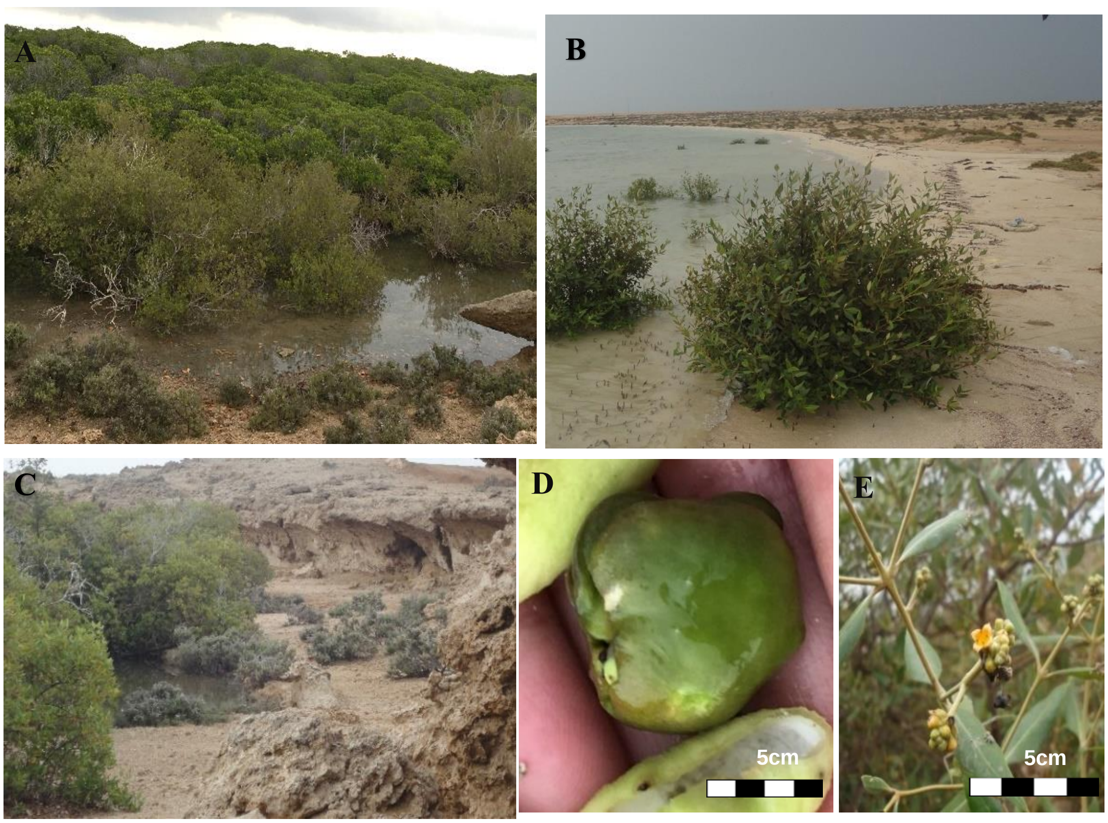

Figure 5.2 Different habitats of *A. marina* in the Farasan Archipelago (A) Coral sand in Farasan Alkabir Island, (B) Sand in Sajid Island, (C) Rocky habitat in Farasan Alkabir Island, (D) propagule of *A. marina*, (E) The flower of *A. marina* .

then 35 amplification cycles as follows: 94 °C for 40 s, 56 °C for 40 s, and 72 °C for 30s, ending with one extension cycle at 72 °C for 4 min. The microsatellite fragments were separated on 2% agarose gels in 1×TAE buffer. Allele size was estimated using Hyper Ladder™ 100bp (100bp to 1000bp; Bioline Reagents Ltd., London, UK) as a marker. Amplified products were run on an ABI 3031xl automated sequencer with the GeneScan-600 LIZ size standard. Visualization and scoring were carried out using Geneious R11(Kearse *et al.*, 2012).

5.2.4 Basic genetic parameters: diversity and differentiation

After scoring, the Hardy–Weinberg equilibrium (HWE) following (Goss *et al.*, 2014) and Linkage disequilibrium (LD) were tested between all microsatellite loci pairs for all accessions using package *poppr* in Rstudio (Kamvar *et al.*, 2014). The number of permutations performed for the LD analysis was 999.

GenAlEx v6.5 software (Peakall and Smouse, 2006), was used to determine the observed heterozygosity (H_O), expected heterozygosity (H_E), the number of alleles for each population, allelic richness (AR), and the average of inbreeding coefficient (F_{IS}) and (F_{ST}) across all loci (Weir and Cockerham, 1984) to assess the population differentiation.

Population differentiation was measured between population pairs across all loci using *Arlequin* 3.5 (Excoffier and Lischer, 2010)

5.2.5 Genetic structure across the Farasan Islands

A simple Mantel test was carried out to determine the relationship between the geographic distance and genetic distance of populations with 10,000 permutations. The genetic differentiation between population pairs was calculated as an F_{ST} computed with GenAlEx v6.5 (Peakall and Smouse, 2006).

AMOVA was carried out to examine the hierarchical partitioning of genetic variance, AMOVA was performed with GenAlEx v6.5. with 10,000 permutations. As a complementary visualization of the genetic structure, PCoA was presented for *A. marina* accessions using GenAlEx v6.5 software. The analysis computed a matrix of mean genotypic distance values between all pairs of individuals. A scatter diagram was plotted according to the Eigenvalues along the first two principal coordinate axes, which accounted for most of the variation. PCA was used to infer the population structure of the all accessions in *A. marina* using the function *prcomp* in Rstudio (Venables and Ripley, 2002). The ΔK method was used with the Structure harvester v.0.6.93 to identify the optimal K value following (Earl, 2012) . UPGMA phylogram was clustered with function *hclust.* (Murtagh and Legendre, 2014) in Rstudio to estimate the genetic distance among accessions. NJ tree was based on the genetic distance among populations by Ppotree2 software.

5.2.6 The Red Sea movement

To generate the sea surface circulation, the data were collected from Sofiaos (2002; 2003), Saad (2010), Yao et al., (2014a; 2014b) and (the Earth observatory EOS at NASA Goddard Space Flight Center), Circulation patterns were compared to the genetic clusters and clustered identified by STRUCTURE on the map bb QGIS

12.18.16 (Neteler and Mitasova, 2013).

5.3 Results

5.3.1 Basic genetic parameters: diversity and differentiation

PCR optimization and screening resulted in the selection of 15 from the original 16 Simple Sequence Repeat (SSR) published primers; primer M76 was discarded due to the visualization function for PCA by *ggbiplot* (Wickham, 2016). Observed heterozygosity was slightly lower than the expected heterozygosity in all the loci and populations, indicating a departure from Hardy–Weinberg equilibrium (HWE) and possibility of inbreeding. Significant deviation from HWE was observed in 10 out of 15 loci for populations at $P < 0.05$. All the markers were polymorphic and a total of 142 alleles were detected across the 15 loci (**Table 5.4)**. Allelic richness per locus varied among markers, ranging from 2 (M62) to 16 (M3, M47, M81). Major allele frequencies per locus ranged from 1.043(M62) to 4.153 (M40) (**Table 5.4).** Primers M13, M27 and M62, could not be amplified in several individuals, which were subsequently treated as missing data. Missing data comprised 0.06% of the entire data set for *A. marina*. Alleles are linked across loci with $P<0.001$ overall PIC percent from 93.33% (pop1 and pop3) - 73.33% (pop8 and pop9). Five loci were monomorphic in some populations (M 62 in all populations except Pop 2, M98 in Pop4 and Pop9, M27 in Pop2, M64 in Pop7, M85 in Pop2 and Pop9). Genetic diversity index values ranged from 1.040 (pop1) - 0.422 (pop8), indicating low genetic diversity in Sajid and Zifaf Islands populations whereas Farasan Alkabir Island population indicated moderate genetic diversity (**Table 5.3**). Expected heterozygosity (H_E) ranged from 0.500 (pop1) to 0.252 (pop8), based on populations analysis. The average number of alleles was from 5.733 (pop1) to 2.067 (pop8), indicating populations with a mean of 2.136 effected alleles. The number of alleles detected across the 9 populations ranging from 86 (pop1) to 31(pop8) (**Table 5.3)**. The value of F (inbreeding coefficient) is negative in the pop3 from Farasan Alkabir Island and pop9 from Zifaf Island, implying a considerable degree of outbreeding, whereas positive F in the other populations showed considerable degree of inbreeding. Pairwise F_{ST} values showed significant differentiation between the two populations and among the pairs of all subpopulations ranging from 0.886 to 0.004 **(Figure 5.3)**, which indicated that the populations and the subpopulations were significantly different. Pop3 and Pop8 were more differentiated from each other according to the F_{ST} value (0.886), followed by Pop3 and Pop6 (F_{ST} = 0.866). The AMOVA for the nine populations revealed that 55% ($P < 0.001$) of the genetic variation is found within populations, whereas 45% ($P < 0.001$) of the genetic variation is found among populations.

5.3.2 Population structure and cluster analysis across the Farasan Islands

Significant genetic divergence between populations from different islands was detected in *A. marina* populations with the exception of pop2 in Farasan Alkabir Island that was most closely linked to the population of Zifaf Island. Six different genetic analyses detected *A. marina* populations in the Farasan archipelago: Mantel tests revealed a weak positive correlation between the genetic distance matrix and the geographic distance matrix among the islands **(Figure 5.5)**, (R^2= 0.0778;

Table 5.3 Descriptive statistics overall loci for each population of *A. marina*: number of individuals(N), number of alleles(A), Percentage of Polymorphic Loci(Pic,%), number of Effective Alleles(Ne), Observed Heterozygosity(H_o), Expected Heterozygosity(H_E), Shannon's Information Index(I) and Fixation Index(F).

Population	N	A	Na	Pic	Ne	H_0	H_E	I	F
Pop1	33	86	5.733	93.33%	2.759	0.434	0.500	1.040	0.114
Pop2	6	48	3.200	86.67%	2.236	0.356	0.421	0.791	0.190
Pop3	11	55	3.667	93.33%	2.412	0.461	0.459	0.878	-0.047
Pop4	19	58	3.867	86.67%	2.398	0.344	0.437	0.841	0.169
Pop5	32	61	4.067	93.33%	2.402	0.404	0.462	0.888	0.084
Pop6	50	54	3.600	86.67%	2.045	0.320	0.389	0.740	0.098
Pop7	20	40	2.667	80.00%	1.679	0.273	0.292	0.535	0.028
Pop8	10	31	2.067	73.33%	1.470	0.253	0.252	0.422	0.005
Pop9	12	35	2.333	73.33%	1.820	0.317	0.325	0.557	-0.041
Total/Mean	193	52	3.467	85.19%	2.136	0.351	0.393	0.743	0.070

	Pop1	Pop2	Pop3	Pop4	Pop5	Pop6	Pop7	Pop8
Pop1								
Pop2	0.574							
Pop3	0.061	0.546						
Pop4	0.038	0.588	0.061					
Pop5	0.016	0.547	0.078	0.04				
Pop6	0.771	0.34	0.866	0.774	0.728			
Pop7	0.773	0.362	0.835	0.796	0.739	0.088		
Pop8	0.802	0.332	0.886	0.823	0.755	0.039	0.121	
Pop9	0.742	0.004	0.69	0.753	0.691	0.339	0.355	0.315

Figure 5.3 Heatmap of pairwise F_{ST} values estimated from microsatellite data between all populations. All values are significant at P<0.001 level, dark colour indicated the minimum value of genetic variation and the light colour indicated the maximum value of genetic variation between populations- for abbreviations of localities see **Table 1**.

P < 0.054).

The PCoA **(Figure 5.6)**, DAPC **(Figure 5.7)** and Structure analysis showed distinct clustering of individuals based on the origin of island, the first two principal component axes cumulatively accounted for 90% of the total variance in *A. marina* accessions on the different islands. **Group 1** *A. marina* on Farasan Alkabir Island (Pop1, Pop3, Pop4, pop5). **Group 2** *A. marina* on Sajid Island (pop6, pop7, pop8) and **Group 3** accessions from Farasan Alkabir Island (Pop2) and *A. marina* from Zifaf Island (pop9) from Zifaf Island.

The results from the Structure harvester analysis indicated that high peak of the number of clusters when the K value was 2.5~3. This meant the optimal value of K should be K= 3. An UPGMA (**Figure 5.8B**) tree of all 193 accessions was constructed based on Nei's genetic distance and all the accessions were assigned to the three main clusters. The clustering of accessions in the UPGMA tree (**Figure 5.8A**) was generally in agreement with the population structure identified by the Structure analyses.

5.3.3 Red sea current surface simulation

The Red Sea current flows in a southeast direction from the Indian Ocean to the northwest direction (January) and a strong north-west and east-west current drifts during the maturation period of *A. marina* in winter season. Whereas, during the summer season (June) the maps of surface circulation climatology indicate that the current direction from the north to south direction and the flow through the north part is stronger than south part of the islands. The genetic link detected between pop9 from Zifaf Island and pop2 of the Farasan Alkabir Island was congruent with Red sea current patterns at the northern side of the islands **(Figure 5.4)**.

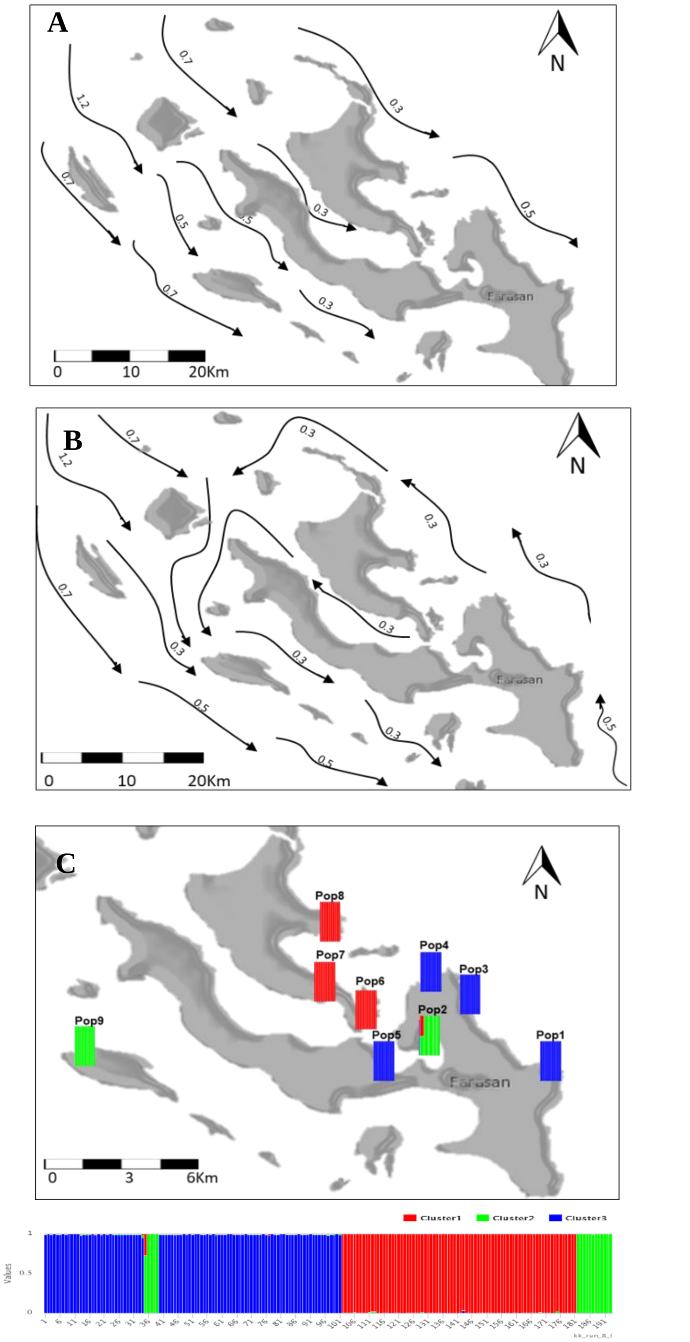

Figure 5.4 Maps depicting the genetic structure among Populations of *Avicennia marina* and the sea surface circulations in the Farasan Archipelago (A and B) Surface current climatology from the model is shown For (A)Summer season (B)Winter season, the number indicates the current speed in m/s. (C) structure bar plots showing the assignment of individuals into three distinct genetic clusters (K = 3).

Table 5.4 SSR primers screened for SSR-PCR in *A. marina:* Primer sequence, Repetitive sequence, Range size (bp), Total number of Alleles per primer over all localities (A), Observed Heterozygosity(Ho), Expected Heterozygosity(He) , Gene flow(Nm) and F-statistic (Fis, Fit, Fst).

Locus	Primer's sequence	Tm (°C)	Repetitive sequence	Range size (bp)	A	Ho	He	Nm	Fis	Fit	Fst
M13	F:CAATGGTGATTCTCCAAAATTGCTTTG R:TGGTGAATAGATGACAGTAAGGATCAGCC	56	(AT)10(GT)12	175-205	12	0.777	0.627	0.889	-0.238	0.033	0.219
M3	F:GGTTCCTGCAAGTATGTCAACACCCTC R:ACCTCGATTCCTCCCCGAATGC	60	(TG)15	183-200	16	0.694	0.709	0.965	0.021	0.222	0.206
M27	F:GGTGGAGTTTCAGTTCATCGTTCG R:CCGCAGTGGGGTTCATCAAAC	56	(CCG)8	103-108	5	0.383	0.280	1.666	-0.370	-0.191	0.131
M32	F:TGTGAACTTTGCTTCAGAGTCTCGAAGATG R:AGTCAAATGGAGCCTCATTCCTCCG	60	(AC)14	156-177	11	0.417	0.370	2.252	-0.126	-0.014	0.100
M34	F:TCTGCTGTTGCTGTTGTTGTTGATGC R:TGGTGTTGAAGACTAATCATGTGTTTCGC	60	(GCT)14	189-194	4	0.262	0.215	0.147	-0.218	0.550	0.630
M40	F:CCCATAGATGACGGCAATCTTATGATCC R:ACCATCCAAAATAAAATAAATCTCCCTCCC	60	(AG)32	140-168	14	0.609	0.682	1.284	0.106	0.252	0.163
M47	F:TGACACCAAGGGAAATCAACATGCC R:GAACCTAGCGACCAATAGATCATCCTGG	60	(CA)13	180-210	16	0.333	0.665	0.813	0.499	0.617	0.235
M49	F:TTTCCTCACGACAGACTAGAAACCACC R:CAATAAACTTGGATAAAGGCAACTCCGAC	56	(TG)16	176-180	5	0.098	0.297	0.572	0.671	0.771	0.304
M62	F:TTGAGGAAAACATGGGACTTTCACTCG R:GTGGGAGTAGCCGCATAGAGTCACG	60	(CGC)8	227-229	2	0.000	0.031	0.017	1.000	1.000	0.938
M64	F:CAAACCCTACCAATCAGAACACTTCAAGC R:CGATATTTGGCTAATCCACTCTGCTGACTG	60	(CAG)8	148-158	7	0.395	0.330	0.192	-0.199	0.479	0.565
M73	F:TTCCACAATCACTTGACCCTCGTCC R:TCTTCACAGGTCCTCTCCTGCCCTG	60	(TG)15	167-172	12	0.184	0.276	0.180	0.334	0.721	0.582
M75	F:TCCATAATCAAACAACTCGACAACGAAATC R:TCTTCTCTCCCTATTCCAAACTGGCTTG	60	(TG)14	208-210	9	0.412	0.574	1.688	0.281	0.374	0.129
M81	F:GAATGATGATCGGATGTTGCTACTCCTG R:CAATCCCAAAGCCCCAAAAATAATCC	60	(CA)9(CT)1	154-167	16	0.292	0.429	0.351	0.318	0.602	0.416
M85	F:TGACAGAGGTTTAGAGACATGGAGGGTGAG R:TGCCTCCCACATTCACCACACTGC	60	(GGC)8	105-118	9	0.201	0.224	2.251	0.104	0.193	0.100
M98	F:CCCAAACTCGTTACGATGGATGACTTC R:CTTACAGTTGCGGTAAAATGAGACGTGC	60	(CGG)8	211-220	4	0.212	0.186	2.077	-0.139	-0.017	0.107

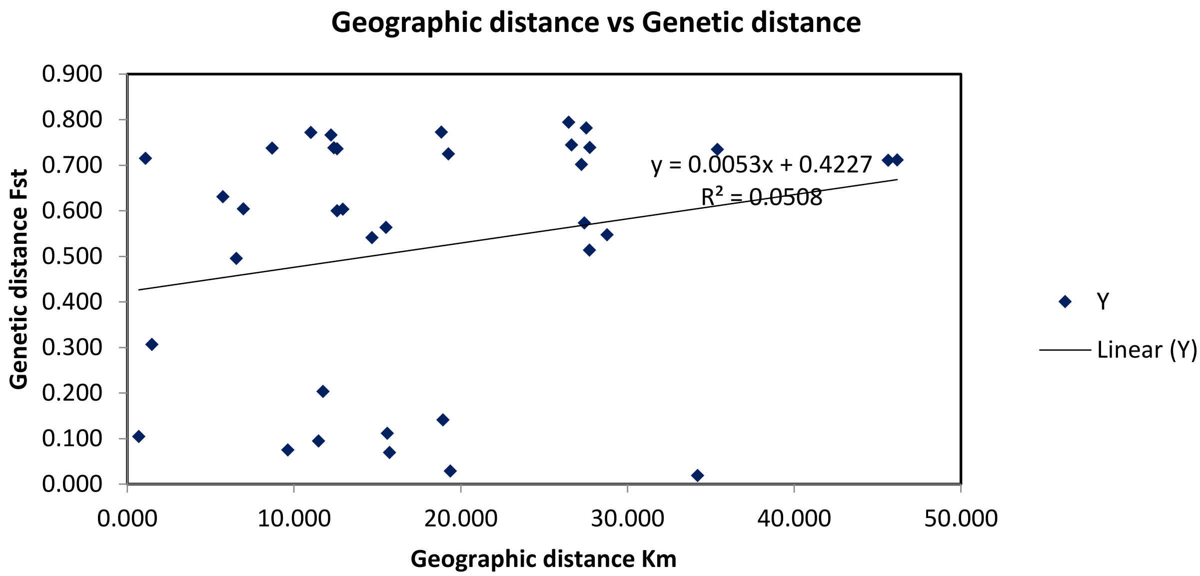

Figure 5.5 Mantel's test for correlation between Fst genetic distance and geographic distance (km), (R^2 =0.0508; P<0.05).

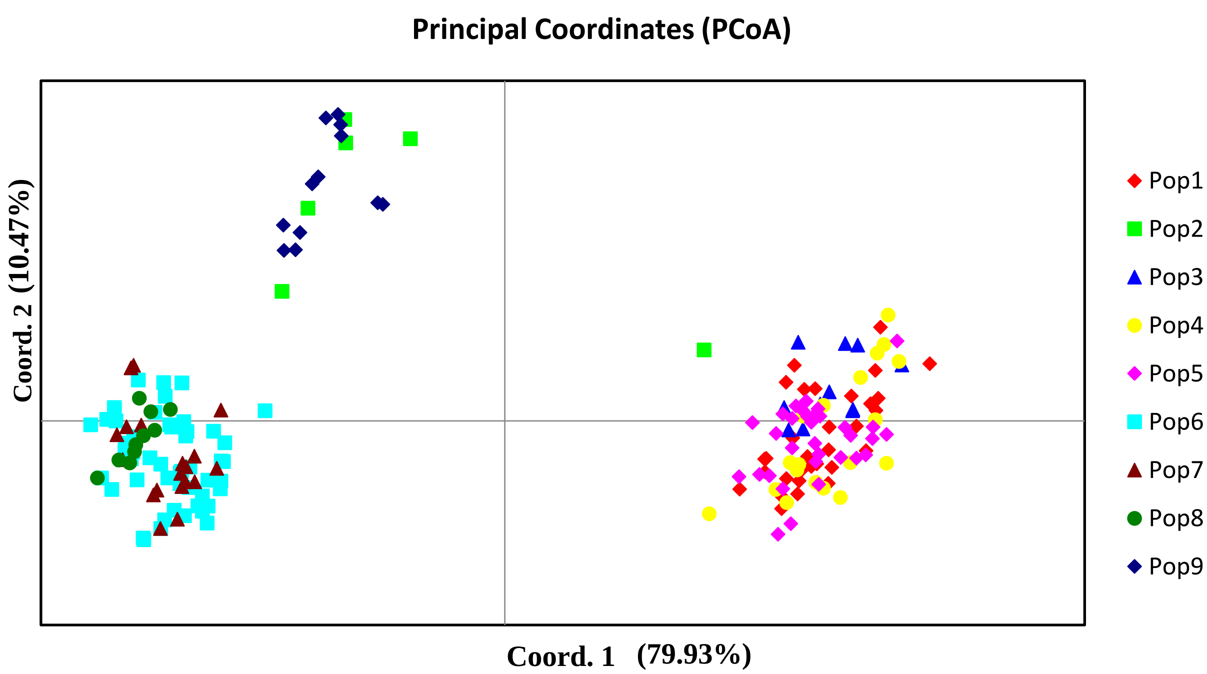

Figure 5.6 Principal coordinate analysis (PCoA) of microsatellite diversity among the 193 Accessions of *A. marina*, the samples are color coded according to their membership in the nine populations

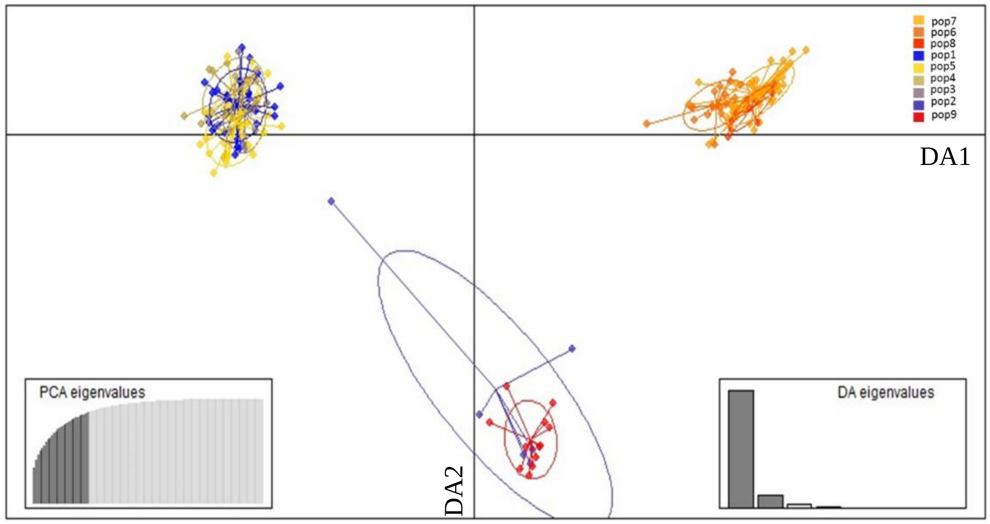

Figure 5.7 Discriminant analysis of principal components (DAPC) among nine natural populations of *A. marina* across the Farasan Archipelago, eigenvalues are presented here.

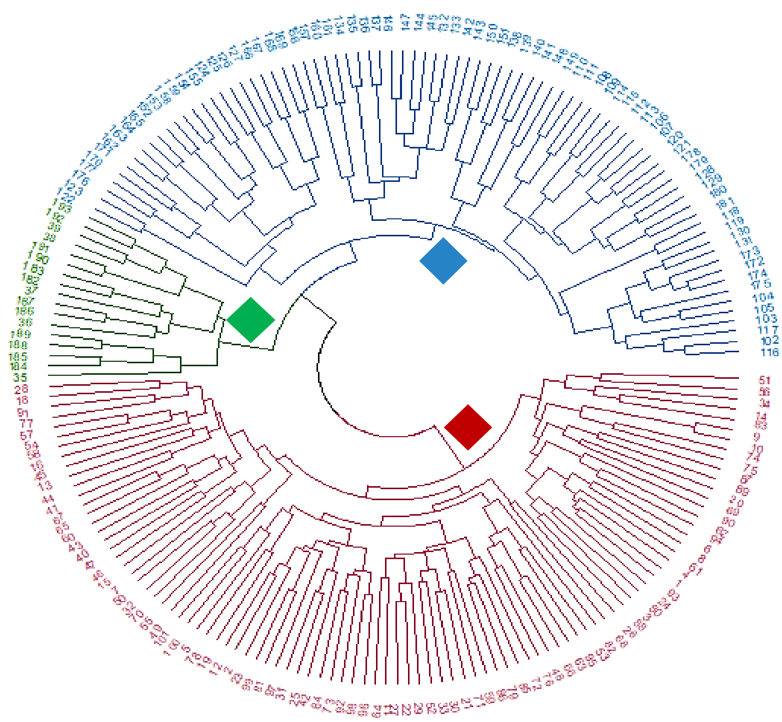

Figure 5.8 UPGMA tree of *A. marina* from nine natural populations along the Farasan Archipelago, red colour includes individuals from Farasan Alkabir Island (Pop1, Pop3, Pop4), blue colour includes individuals from Sajid Island (Pop5, Pop6, Pop7), and green colour includes individuals from Zifaf Island and Farasan Alkabir Island (Pop2 and Pop9).

5.4 Discussion

In this paper, *A. marina* from the Farasan Archipelago was studied to understand the genetic variation and the pattern of population structure of this ecologically and economically dominant mangrove tree species. This study included 193 individuals and 15 SSRs loci, more comprehensive and representative in comparison with previous microsatellite studies of *A. marina* because the number of samples and SSRs loci have been low (Maguire *et al.*, 2000b, Le *et al.*, 2003, Zolgharnien *et al.*, 2010, Kahrood *et al.*, 2008, Yoshimori *et al.*, 2015). Primer M76 was discarded for failing to prime and demonstrate polymorphism across all populations, this is in agreement with (Maguire *et al.*, 2002). This study showed the lack of polymorphism of some loci could be associated with shorter repeats (GGC) 8 and (Tri or combined repeats type), which were more frequently monomorphic than long repeats, and dinucleotide repeats (TG) 15 (Biswas *et al.*, 2014). Departures from HWE of the similar magnitude were also reported in *A. marina* in Vietnam (Le *et al.*, 2003) and *Avicennia germinans*, *Rhizophora mangle* in Caribbean and Pacific estuaries of Panama (Cerón-Souza *et al.*, 2012).

In the analyses of allelic diversity per locus, the average of alleles diversity found here was 9.4, showing a slightly high level of allelic diversity compared to the values detected previously for *A. marina* samples from the Australia's Northern Territory was (6.7) (Maguire *et al.*, 2000b, Maguire *et al.*, 2002, Zolgharnien *et al.*, 2010). Perhaps because these previous studies used less than half of the SSRs loci and small sized populations. The allelic diversity in this study showed a lower level of allelic diversity than Maguire, *et al.*, (2001) in six different Australian states and territories (17.3).

The SSRs are more informative for understanding population genetic diversity when the studies used a greater number of loci and increased the number of samples. Comparative analysis of allelic diversity across the populations, observed and expected heterozygosity revealed *A. marina* populations have a moderate genetic variation in Farasan Alkabir Island which is consistent with study of *Avicennia marina* worldwide (H_e 0.494; Maguire *et al.* 2000), the north of the Red Sea (Yoshimori *et al.*, 2015). Low genetic variation in Zifaf and Sajid Islands, as revealed *A. marina* in Vietnam (He 0:322; Le *et al.* 2003), Australia especially the north population (Maguire *et al.*, 2002) and East-coast of India (Hazarika *et al.*, 2013). In comparison with *A. marina* populations in the Arabian gulf (Zolgharnien *et al.*, 2010), the Red Sea populations show lower genetic diversity, because the harsh environment condition in the Red Sea. Authors of previous studies suggested that reduction in the heterozygosity level may be due to repeated bottlenecks and founder effects (Islam *et al.*, 2013, Yang *et al.*, 2017), that are associated with geoclimatic history in the Red Sea and genetic drift in the small isolated populations. This could explain the pattern of *A. marina* populations in the Farasan Archipelago. The historical Red Sea level fluctuations due to past climate changes (Saad, 2010), would further reduce the long-term effective population size. In addition to distinct genetic compositions which it lead to low genetic diversity within populations. Beside the sea level fluctuation factor, the patchy distribution of *A. marina* populations along the coast of the Farasan Archipelago, with complicated geomorphological coastline (Pavlopoulos *et al.*, 2018) prevents genetic exchanges among sampled populations as the study shown in the north Red Sea by Yoshimori *et al.* (2015). The pattern of the isolated populations increases the inbreeding coefficient which is the most reasonable explanation for heterozygote deficiency. Moreover, strong inbreeding and high self-fertilization have been reported as common characters among mangrove species *Avicennia germinans*, *Rhizophora mangle* (Cerón-Souza *et al.*, 2012).

The estimation of F_{ST} showed high genetic differentiation among populations (0.322). The value was similar with those in populations' *A. marina* worldwide (Maguire *et al.*, 2000, Duke *et al.*, 1998) and in Vietnam populations (le, 2003). This indicates that the gene flow is limited between populations within Archipelago. As the *A. marina* pollen dispersal can only occur within populations or nearby populations, the propagule dispersal is the main factor in the genetic connectivity in *A. marina* populations. In this study, dispersal of *A. marina* propagule is limited by sea currents and the gene flow has shown the populations which are separated by a few tens of kilometers (Maguire 2000b, dodd *et al.*, 2002). So, it is clear *A. marina* in the Farasan Archipelago show significant genetic differentiation among populations. Hierarchical analysis of molecular variance (AMOVA) also showed that most of the variation was partitioned among populations and within individuals in the total population. There was little variation among individuals within populations. From these analyses discrete subpopulations pattern are likely for *A. marina*, this result agrees with (Parani *et al.*, 1997, Maguire *et al.*, 2000b, Le *et al.*, 2003, Kahrood *et al.*, 2008).

The results of Bayesian clustering showed that genetic structure of *A. marina* was affected by many factors such as the isolation by distances, geomorphological coastline and the direction of sea currents **(Figure 5.8 A, B)**. The isolation by distance has the weak effects of the genetic structure indicated by the Mantel test showing a weak correlation between genetic and geographic distance, For example, Population 2 and population 9 have the furthest geographical distance (the distance is 49.28 km), however they share the same genetic group. In this case, migration could have been driven by high-speed currents during winter seasons. However Population 5 is a distance of only 1.460 meters over water from the nearest population 6; these two populations had a significant differentiation between each other and each population in a different genetic group (Maguire *et al.*, 2000b, Dodd and Rafii, 2002, Cerón-Souza *et al.*, 2012).

Geomorphological coastline plays important roles in the distribution pattern of populations in the Farasan archipelago and has a strong effect on the limited dispersal ability of propagules. The populations that isolated by land and with less interconnected sea currents have smaller gene flow, as shown among populations between islands. Whereas, the higher genetic exchange occurred when population location was directly connected by the sea currents and no land barriers, such as the populations of each island in the same coast (Le *et al.*, 2003).

There is a correlation between the genetic structure and the sea circulation patterns at the Archipelago, preventing propagule exchange between Farasan Alkabir populations and Sajid Island populations. Further evidence for sea circulation at the northern part of the Archipelago reveled the mixing of some individuals from Farasan Alkabir Island and Zifaf Island **(Figure 5.4 C)**. This similar congruence between genetic structure and bifurcating sea currents was also found in *A. marina* populations in southeast Asia (Arnaud-Haond *et al.*, 2006) and Vietnam (Le *et al.*, 2003). Hence, the explicit inclusion of sea circulation patterns in phylogeographical studies of coastal even if it is straight coast and marine organisms is valuable in understanding complex genetic structure.

5.5 Conclusion

Populations of *A. marina* are threatened by complicated geomorphological outline, human-induced pressure, urbanization, wood harvesting, grazing and tourism sector development. This could lead to a loss of genetic diversity through increased population fragmentation of *A. marina* in the Farasan Archipelago. The use of microsatellite to assess the genetic diversity of natural populations support improved conservation of *A. marina* in the Farasan archipelago, which may be one of the most important issues facing the future of mangrove forestry practices. *A. marina* in Sajid and Zifaf Islands showed lower genetic diversity than populations in Farasan Alkabir Island. This suggest that sufficient genetic variation exists for the selection of superior individuals or populations to advance the genetic improvement program. These results contribute to the knowledge about the population structure in the Farasan archipelago, as consequences of restricted gene dispersal. High levels of genetic structure on local scales, are detected due to coastal geomorphology, climate change and sea currents direction. Therefore they are likely to be of interest for conservation strategies and breeding or genetic improvement programs not based only on preserving large areas, but also on small and separate ones, to encompass the different genetic patterns found between the islands

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Appendix 5

(1) Details of the 193 accessions was analyzed across 15 SSR markers. Codes of the specimens of *Avicennia marina*, geographic coordinates, and sources for the plant specimens used in the study.

No.	Lab code	Longitude	Latitude	Populations code	Islands
1	SV1_G10	42.17795	16.70861	Pop 1	Farasan Al-Kabir
2	SV2_H10	42.17777	16.70833	Pop 1	Farasan Al-Kabir
3	SV3_A11	42.17752	16.70815	Pop 1	Farasan Al-Kabir
4	SV4_B11	42.17717	16.7078	Pop 1	Farasan Al-Kabir
5	SV5_C11	42.17686	16.70772	Pop 1	Farasan Al-Kabir
6	SV6_D11	42.17656	16.7076	Pop 1	Farasan Al-Kabir
7	V7_E11	42.17614	16.70744	Pop 1	Farasan Al-Kabir
8	SV8_F11	42.17586	16.70733	Pop 1	Farasan Al-Kabir
9	SV9_G11	42.17565	16.70723	Pop 1	Farasan Al-Kabir
10	SV10_H11	42.17548	16.70716	Pop 1	Farasan Al-Kabir
11	SV11_A12	42.17084	16.70573	Pop 1	Farasan Al-Kabir
12	SV12_B12	42.171	16.70599	Pop 1	Farasan Al-Kabir
13	SV13_C12	42.17074	16.70563	Pop 1	Farasan Al-Kabir
14	SV14_D12	42.17091	16.70519	Pop 1	Farasan Al-Kabir
15	SV15_E12	42.17124	16.70519	Pop 1	Farasan Al-Kabir
16	SV16_F12	42.17129	16.70499	Pop 1	Farasan Al-Kabir
17	SV17_G12	42.17151	16.7045	Pop 1	Farasan Al-Kabir
18	2/2_E04	42.18125	16.7061	Pop 1	Farasan Al-Kabir
19	2/3_F04	42.18103	16.70583	Pop 1	Farasan Al-Kabir
20	2/4_G04	42.18051	16.7054	Pop 1	Farasan Al-Kabir
21	2/5_H04	42.18013	16.70505	Pop 1	Farasan Al-Kabir
22	2/6_A05	42.17921	16.70379	Pop 1	Farasan Al-Kabir
23	2/7_B05	42.17401	16.70217	Pop 1	Farasan Al-Kabir
24	2/8_C05	42.17316	16.70171	Pop 1	Farasan Al-Kabir
25	2/9_D05	42.1706	16.70069	Pop 1	Farasan Al-Kabir
26	2/10_E05	42.16926	16.70043	Pop 1	Farasan Al-Kabir
27	2/11_F05	42.16796	16.70045	Pop 1	Farasan Al-Kabir
28	2/12_G05	42.16451	16.69801	Pop 1	Farasan Al-Kabir
29	2/13_H05	42.16202	16.6945	Pop 1	Farasan Al-Kabir
30	32_B07	42.18054	16.71935	Pop 1	Farasan Al-Kabir
31	33_C07	42.18014	16.71749	Pop 1	Farasan Al-Kabir
32	34_D07	42.17838	16.7149	Pop 1	Farasan Al-Kabir
33	35_E07	41.99926	16.74851	Pop 1	Farasan Al-Kabir
34	SV18_H12	42.06563	16.75272	Pop 2	Farasan Al-Kabir
35	S19_A01	42.06569	16.75196	Pop 2	Farasan Al-Kabir
36	S20_B01	42.06589	16.75127	Pop 2	Farasan Al-Kabir
37	S21_C01	42.06628	16.75078	Pop 2	Farasan Al-Kabir
38	S22_D01	42.06579	16.75019	Pop 2	Farasan Al-Kabir
39	S22_D02	42.06579	16.75019	Pop 2	Farasan Al-Kabir
40	44_D09	42.17268	16.70497	Pop 3	Farasan Al-Kabir
41	45_E09	42.17211	16.70433	Pop 3	Farasan Al-Kabir

42	46_F09	42.17211	16.70433	Pop 3	Farasan Al-Kabir
43	47_G09	42.17045	16.70303	Pop 3	Farasan Al-Kabir
44	48_H09	42.17021	16.70274	Pop 3	Farasan Al-Kabir
45	49_A10	42.16998	16.70261	Pop 3	Farasan Al-Kabir
46	50_B10	42.16982	16.70254	Pop 3	Farasan Al-Kabir
47	51_C10	42.16961	16.70239	Pop 3	Farasan Al-Kabir
48	52_D10	42.16927	16.7024	Pop 3	Farasan Al-Kabir
49	53_E10	42.16903	16.70234	Pop 3	Farasan Al-Kabir
50	54_F10	42.1689	16.70223	Pop 3	Farasan Al-Kabir
51	23_A06	42.06911	16.80417	Pop 4	Farasan Al-Kabir
52	24_B06	42.0675	16.80604	Pop 4	Farasan Al-Kabir
53	25_C06	42.06857	16.80624	Pop 4	Farasan Al-Kabir
54	26_D06	42.06639	16.80584	Pop 4	Farasan Al-Kabir
55	27_E06	42.06704	16.80504	Pop 4	Farasan Al-Kabir
56	28_F06	42.06884	16.80329	Pop 4	Farasan Al-Kabir
57	29_G06	42.06853	16.7971	Pop 4	Farasan Al-Kabir
58	30_H06	42.06681	16.79535	Pop 4	Farasan Al-Kabir
59	31_A07	42.06385	16.79617	Pop 4	Farasan Al-Kabir
60	3/1_F07	42.10259	16.78879	Pop 4	Farasan Al-Kabir
61	3/2_G07	42.10259	16.7869	Pop 4	Farasan Al-Kabir
62	3/3_H07	42.10149	16.78565	Pop 4	Farasan Al-Kabir
63	3/4_A08	42.09831	16.79001	Pop 4	Farasan Al-Kabir
64	3/5_B08	42.09685	16.79374	Pop 4	Farasan Al-Kabir
65	3/6_C08	42.09777	16.79682	Pop 4	Farasan Al-Kabir
66	3/7_D08	42.09919	16.79934	Pop 4	Farasan Al-Kabir
67	3/8_E08	42.06987	16.81021	Pop 4	Farasan Al-Kabir
68	3/9_F08	42.05395	16.79754	Pop 4	Farasan Al-Kabir
69	3/10_G08	42.05361	16.79631	Pop 4	Farasan Al-Kabir
70	1_A01	42.00054	16.7476	Pop 5	Farasan Al-Kabir
71	2_B01	42.00044	16.74774	Pop 5	Farasan Al-Kabir
72	3_C01	42.00037	16.74794	Pop 5	Farasan Al-Kabir
73	4_D01	42.00027	16.74816	Pop 5	Farasan Al-Kabir
74	5_E01	41.99984	16.74896	Pop 5	Farasan Al-Kabir
75	6_F01	41.99977	16.74889	Pop 5	Farasan Al-Kabir
76	7_G01	41.99915	16.74841	Pop 5	Farasan Al-Kabir
77	8_H01	41.99932	16.74852	Pop 5	Farasan Al-Kabir
78	9_A02	42.00024	16.74891	Pop 5	Farasan Al-Kabir
79	10_B02	41.99937	16.7482	Pop 5	Farasan Al-Kabir
80	11_C02	41.99946	16.74802	Pop 5	Farasan Al-Kabir
81	12_D02	41.9995	16.74781	Pop 5	Farasan Al-Kabir
82	13_E02	41.99972	16.74757	Pop 5	Farasan Al-Kabir
83	14_F02	42.00019	16.74774	Pop 5	Farasan Al-Kabir
84	15_G02	42.00023	16.74808	Pop 5	Farasan Al-Kabir
85	16_H02	42.00028	16.7482	Pop 5	Farasan Al-Kabir
86	17_A03	42.00044	16.74897	Pop 5	Farasan Al-Kabir
87	18_B03	42.00041	16.74889	Pop 5	Farasan Al-Kabir

88	19_C03	42.00025	16.74889	Pop 5	Farasan Al-Kabir
89	20_D03	42.00015	16.74903	Pop 5	Farasan Al-Kabir
90	36_E03	41.99926	16.74851	Pop 5	Farasan Al-Kabir
91	37_F03	41.9994	16.7486	Pop 5	Farasan Al-Kabir
92	38_G03	41.99951	16.74868	Pop 5	Farasan Al-Kabir
93	39_H03	41.99962	16.74879	Pop 5	Farasan Al-Kabir
94	40_A04	42.00036	16.74861	Pop 5	Farasan Al-Kabir
95	41_B04	42.00033	16.74848	Pop 5	Farasan Al-Kabir
96	42_C04	42.00031	16.74831	Pop 5	Farasan Al-Kabir
97	43_D04	42.00028	16.7481	Pop 5	Farasan Al-Kabir
98	3/11_H08	41.99803	16.74795	Pop 5	Farasan Al-Kabir
99	3/12_A09	41.99798	16.7479	Pop 5	Farasan Al-Kabir
100	3/13_B09	42.03632	16.7461	Pop 5	Farasan Al-Kabir
101	14_C09	42.03792	16.74273	Pop 5	Farasan Al-Kabir
102	1s1_E01	42.00426	16.75676	Pop 6	Sajid
103	1W1_E07	42.00432	16.75682	Pop 6	Sajid
104	1s2_F01	42.00449	16.75694	Pop 6	Sajid
105	1W2_F07	42.00462	16.75698	Pop 6	Sajid
106	1s3_G01	42.00474	16.75719	Pop 6	Sajid
107	1W3_G07	42.00484	16.75729	Pop 6	Sajid
108	1s4_H01	42.00501	16.75743	Pop 6	Sajid
109	1W4_H07	42.00512	16.75752	Pop 6	Sajid
110	1s5_A08	42.00515	16.75758	Pop 6	Sajid
111	1W5_A08	42.00527	16.75766	Pop 6	Sajid
112	1s6_B02	42.00546	16.75779	Pop 6	Sajid
113	1W6_B08	42.00568	16.75796	Pop 6	Sajid
114	1s7_C02	42.00586	16.75813	Pop 6	Sajid
115	1W7_C08	42.00593	16.75819	Pop 6	Sajid
116	1s8_D02	42.00608	16.75832	Pop 6	Sajid
117	1W8_D08	42.00621	16.75845	Pop 6	Sajid
118	1s9_E02	42.00641	16.75864	Pop 6	Sajid
119	1W9_E08	42.00656	16.75878	Pop 6	Sajid
120	1s10_F02	42.00675	16.75897	Pop 6	Sajid
121	1W10_F08	42.00685	16.75911	Pop 6	Sajid
122	1s11_G02	42.00699	16.75932	Pop 6	Sajid
123	1W11_G08	42.00685	16.75926	Pop 6	Sajid
124	1s12_H02	42.01004	16.76434	Pop 6	Sajid
125	1W12_H08	42.0099	16.76437	Pop 6	Sajid
126	1s13_A03	42.00976	16.76444	Pop 6	Sajid
127	1W13_A09	42.00969	16.76448	Pop 6	Sajid
128	1s14_B03	42.00955	16.76458	Pop 6	Sajid
129	1W14_B09	42.0094	16.76473	Pop 6	Sajid
130	1s15_C03	42.01094	16.76427	Pop 6	Sajid
131	1W15_C09	42.0111	16.76432	Pop 6	Sajid
132	2s6_A04	42.00643	16.76814	Pop 6	Sajid
133	2W6_A10	42.00629	16.7684	Pop 6	Sajid

134	2s7_B04	42.00616	16.76869	Pop 6	Sajid
135	2W7_B10	42.00607	16.76883	Pop 6	Sajid
136	2s8_C04	42.00591	16.769	Pop 6	Sajid
137	2W8_C10	42.00573	16.76928	Pop 6	Sajid
138	2s9_D04	42.00556	16.76955	Pop 6	Sajid
139	2W9_D10	42.00553	16.7697	Pop 6	Sajid
140	2s10_E04	42.00547	16.76984	Pop 6	Sajid
141	2W10_E10	42.00536	16.76995	Pop 6	Sajid
142	2s11_F04	42.00512	16.77018	Pop 6	Sajid
143	2W11_F10	42.00493	16.77042	Pop 6	Sajid
144	2s12_G04	41.99945	16.77758	Pop 6	Sajid
145	2W12_G10	41.99942	16.77776	Pop 6	Sajid
146	2s13_H04	41.99883	16.77952	Pop 6	Sajid
147	2W13_H10	41.99876	16.77975	Pop 6	Sajid
148	2s14_A05	41.99867	16.77999	Pop 6	Sajid
149	2W14_A11	41.99859	16.78025	Pop 6	Sajid
150	2s15_B05	41.99848	16.78054	Pop 6	Sajid
151	2W15_B11	41.99823	16.78131	Pop 6	Sajid
152	S2s1_D03	41.9681	16.85642	Pop 7	Sajid
153	S2W1_D09	41.96867	16.85652	Pop 7	Sajid
154	S2s2_E03	41.96931	16.85659	Pop 7	Sajid
155	S2W2_E09	41.96965	16.85662	Pop 7	Sajid
156	2s3_F03	41.97013	6.85652	Pop 7	Sajid
157	2W3_F09	41.97052	16.8564	Pop 7	Sajid
158	2s4_G03	41.97102	16.85634	Pop 7	Sajid
159	2W4_G09	41.97132	16.85625	Pop 7	Sajid
160	2s5_H03	41.97368	16.85477	Pop 7	Sajid
161	2W5_H09	41.97388	16.85468	Pop 7	Sajid
162	3s6_H05	41.9932	16.79999	Pop 7	Sajid
163	3W6_H11	41.99345	6.799406	Pop 7	Sajid
164	3s7_A06	41.99362	16.79837	Pop 7	Sajid
165	3w7_A07	41.99354	16.79713	Pop 7	Sajid
166	3s8_B06	42.00422	16.77367	Pop 7	Sajid
167	3w8_B07	42.00447	16.77355	Pop 7	Sajid
168	3s9_C06	42.00368	16.77507	Pop 7	Sajid
169	3W9_A12	42.00356	16.77558	Pop 7	Sajid
170	3s10_D06	42.00382	16.77243	Pop 7	Sajid
171	3W10_B12	42.00395	16.7723	Pop 7	Sajid
172	3/1_C05	41.98198	16.85765	Pop 8	Sajid
173	3W1_C11	41.9822	16.85746	Pop 8	Sajid
174	3/2_D05	41.98271	16.85744	Pop 8	Sajid
175	3W2_D11	41.98288	16.85741	Pop 8	Sajid
176	3/3_E05	41.9831	16.8574	Pop 8	Sajid
177	3W3_E11	41.98329	16.85736	Pop 8	Sajid
178	3/4_F05	41.98289	16.85468	Pop 8	Sajid
179	3W4_F11	41.98296	16.8545	Pop 8	Sajid

180	S3/5_G05	41.98302	16.85432	Pop 8	Sajid
181	3W5_G11	41.98322	16.85423	Pop 8	Sajid
182	z1_E06	41.74508	16.73316	Pop 9	Zifaf
183	zW1_C12	41.74519	16.73282	Pop 9	Zifaf
184	z2_F06	41.74502	16.73218	Pop 9	Zifaf
185	W2_D12	41.7455	16.73192	Pop 9	Zifaf
186	z3_G06	41.74551	16.72948	Pop 9	Zifaf
187	W3_E12	41.7465	16.72888	Pop 9	Zifaf
188	z4_H06	41.74949	16.72783	Pop 9	Zifaf
189	zW4_F12	41.75008	6.727769	Pop 9	Zifaf
190	z5_A07	41.75295	16.72828	Pop 9	Zifaf
191	zW5_G12	41.75315	16.72921	Pop 9	Zifaf
192	z6_B07	41.74691	16.73445	Pop 9	Zifaf
193	zW6_H12	41.74623	16.73519	Pop 9	Zifaf

CHAPTER 6

Genetic variability of threatened mangrove species in the Farasan archipelago, *Rhizophora mucronata* Lam.

CHAPTER 6

Genetic variability of threatened mangrove species in the Farasan archipelago, *Rhizophora mucronata* Lam.

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Abstract: Red mangrove (*Rhizophora mucronata*) has a high value along the Farasan archipelago tidal areas in the Red Sea but a limited distribution. Despite immediate threats to this species in the area there have been no studies of the patterns of genetic variation and a population structure essential for development of effective strategies for conservation. Here we report the use of fourteen microsatellite loci (SSRs) to genotype 86 individuals across four natural populations along the coast of Farasan Alkabir and Zifaf Islands. All *R. mucronata* populations were characterized by low genetic variation and a deficiency of heterozygotes, consistent with findings in studies on other *Rhizophora* species, particularly in the Indo West Pacific region. Despite the low genetic variation, significant genetic structuring was detected across *R. mucronata* populations. Bayesian clustering analysis revealed two primary genetic groups. Analysis of molecular variance (AMOVA) showed significant population differentiations and pairwise tests consistently revealed significant differentiation between most of the population pairs (FST = 0.207). This was similar to other mangrove species around the world. In addition, Mantel tests showed some signals of correlations between genetic distances and geographical distances. To corroborate these findings, this study examined the possible barriers that contribute to the separation of the populations. We conclude that isolation by distances, land barriers, sea current directions, and possibly sea level fluctuations in the Red Sea, limit the dispersal of *R. mucronata* propagules in Farasan Alkabir and Zifaf Islands leading to a highly localised genetic structure. The consequence is that conservation action must be undertaken with populations as the basic units of protection.

Keywords: genetic structure; genetic diversity; mangrove; microsatellites; propagule dispersal; *Rhizophora mucronata*; Rhizophoraceae.

6.1 Introduction

Mangroves are tropical and subtropical forests occurring in 118 countries or territories in the intertidal areas of coastal shorelines, covering an estimated total area of 137,760 km² worldwide [1, 2]. Mangrove forests have been shown to be some of the most productive ecosystems globally [2]. They play an important socio-economic and ecological role [3-5]. They are an integral part in the support of various marine ecosystems and provide a suitable habitat for many of birds and fishes [6, 7]. Mangrove species have been used for charcoal, firewood, building, fodder and medicine [8, 9]. They can protect the coastal area from wave erosion [10] and mitigate natural disasters [11]. Despite the ecological and economic importance of the mangrove ecosystem, at least 35% of the area of mangrove forests globally has been lost in the past two decades [12]. Human disturbance has been identified as the main threat to mangroves, through the cutting of highly valued species like

Rhizophora [13]. The losses of mangrove habitats are compounded by the effects of pollution, land conversion, urban development, forestry uses and the effects of warfare [14-16]. In addition, the *Rhizophora* stands are under ecological threat: beetles, including *Coccotrypes rhizophorae*, are responsible for the highest percentage of the mortality rate for *Rhizophora* propagules and seedlings in areas of the *Rhizophora* forest. Also, global changes such as sea level fluctuations, sea salinity and natural hazards may affect mangroves [17-19]. *Rhizophora* is the most representative genus in the mangrove with broad distribution in both Indo-West Pacific, Atlantic, and East Pacific regions [20-22], it is a relatively old genus; fossils of *Rhizophora* are recorded from the Palaeocene Epoch (55.8–65.5 Ma) [23].

The occurrence of mangroves along the Red Sea was recorded in 323 BC [24]. The Red Sea represents one of the northern limits to mangrove distributions in the world with the most arid and highly saline environmental condition of all mangrove's ecosystems. Mangroves are scattered and in patchy patterns in the Red Sea, mainly due to high salinity reaching 70‰, poor soil textures and very high seawater temperatures (32°C). The mangroves in the Eastern Red Sea coast have been the subject of several studies [25-28] including distribution, coastal ecology and impact assessments. A study revealed that southern part of the Red Sea is more favourable for mangroves than the northern parts, coinciding with the gradual disappearance of stony corals and increased availability of muddier substrate, rainwater and less salinity due to the connection to the Indian ocean and the water flow from the Gulf of Aden into the Red Sea [29].

The Farasan Archipelago is one of the larger archipelagos, which is located in the southern part of the Arabian coast of the Red Sea. It was formed by uplift from a rising salt dome beneath the area [29]. Data for the Farasan Archipelago is too limited to give an accurate picture about their climatic conditions. The available information of the nearest region to the study area is that of Jizan on the mainland. The climate in Jizan is characterized by high humidity, reaching 95.4% in December, high mean annual temperatures and low rainfall [30]. Two species of mangroves occur in these islands, *Avicenna marina* and the much less common, *Rhizophora mucronata* [31, 32].

This paper will focus in *Rhizophora mucronata* Lam. (*Rhizophoraceae*) in the Farasan Archipelago, because it has a more limited distribution than *A.marina* due to their sensitivity to high salinity levels, rivers being non-existent, very low rainfall, the sea bed bottom being hard and the sea oligotrophic [14, 33]. However, a study on *R. mucronata* trees showed that they respond to high salinity by increased vessel density to facilitate increased and better water transport in hypersaline environments. The scientific literature on *R. mucronata* in the Farasan Islands is limited compared with Indo-west pacific regions [34]. In distribution and coastal ecology, it grows along channels and fringing habitats. This species is reported for two islands only, Farasan Alkabir and Zifaf [25, 35]. Migahid, 1978 recorded its presence in the Jizan Region, which might be a mistake as no other researcher has found this species there [25, 36].

R. mucronata grows in the outer fringes of the mangrove stands, and its submerged roots provide a good environment for several commercial fish species [37, 38], crustaceans, reptiles and birds, including endemic species in the Farasan Archipelago, such as the white-eyed gull *Larus leucophthalmus* and *Phalacrocorax nigrogularis* [37]. it is classified as 'threatened' on the IUCN Red List [1]. As it grows in a very hostile environment, *R. mucronata* is very sensitive to over-exploitation [28]. The degradation of *R. mucronata* in the Farasan Islands has been reported due to over-cutting, excessive browsing by camels, damming rainwater draining through valleys, pollution and coastal constructions [26, 38-41].

With the clear degradation and fragmentation of *R. mucronata* in the Farasan Archipelago, it is important to understand the genetic structure and variation of this species for the conservation of species genetic resources in their natural habitat. For *R. mucronata* and the closely related species worldwide, genetic variation and genetic structure have been reported using hypervariable markers such as microsatellites [34, 42-46], and using coding-DNA (cpDNA and nDNA) [47]. These several types of molecular marker techniques currently available, and the most suitable technique to assess genetic variation depends upon both the question addressed and the type of genetic information available for the species [84]. Since theory predicts that intraspecific genetic variation is pivotal for the persistence of species [83], SSRs can proved suitable for conservation studies interested in estimating population sizes, population structure, genetic variation, genetic drift and inbreeding (Allendorf and Luikart, 2013). **Table 6.1** summarizes the genetic diversity studies on *R. mucronata* and other mangrove species.

The connectivity and disjunction of gene flow pattern among populations of *R. mucronata*, have received much research attention recently and several studies have provided a good understanding of the role of long distance dispersal versus historical biogeographic hypothesis of vicariance, the effects of climatic change and physical barriers [48, 49]. Some previous assessments of *R. mucronata* genetic population structure revealed a significant genetic differentiation between populations and were consistent with land or sea barriers [34, 43, 47]. However, another study revealed genetic admixture between populations and no spatial clustering pattern was observed in *R. mucronata* in the Malay Peninsula [79]. There has been no study of genetic diversity and structure of *R. mucronata* on natural populations in the Farasan Archipelago, and the genetic information is unknown.

Genetic diversity and structure of *R. mucronata* populations is largely regulated by gene flow via propagule and pollen dispersal. Long-distance pollen transport is probably much less important relative to long-distance propagule dispersal, as wind pollination is usually associated with short distances within kilometres [50], and can be inhibited by the landscape matrix in between populations.

R. mucronata is thought to be pollinated by wind or general pollinators like bees [20]. It is self-compatible with a high proportion of geitonogamous fertilization [21]. The fruit is single seeded, up to 70 mm long, which germinates while still on the tree (viviparous) [82]. *Rhizophora mucronata* Mature propagules are available only in summer [51]. Propagule dispersal ability by water has a strong influence on the structuring of *R. mucronata*. It has a large viviparous, slightly curved propagule, elongated and that floats horizontally [52]. According to previous studies these seed structures are able to disperse for long distances since they may remain viable over 3–4 months [21, 53, 54]. This could lead to potentially higher genetic connectivity across populations of *R. mucronata* [55]. The dispersal of *R. mucronata* can therefore be strongly affected by geohistorical events such as the sea currents and sea level changes [52] and/or various physical barriers to gene flow, such as landmasses and distance between populations [24, 56].

In this study microsatellite markers, which have been developed for *R. mucronata* by Shinmura *et al.*, 2012, were used to (1) assess the genetic diversity of *R. mucronata* in the Farasan archipelago, (2) Identify levels of inbreeding in the populations among and between islands and (3) investigate the genetic structure found in populations of this species in the Farasan Islands. It is expected that these results will be useful in determining policy and species conservation strategies and the rehabilitation of *R. mucronata* in the Farasan Islands.

Table 6.1 Published studies using microsatellites and coding DNA to research variation amongst *Rhizophora* genus.

Study area	Species	No. populations (No. individuals)	Marker	No. loci	No. alleles	Genetic diversity	Level of Inbreeding	Data analysis	Study source
The Indo-West Pacific region (Malay Peninsula and Japan)	*R. apiculata,* *R. mucronata,* *R. stylosa*	21 (112 For *R. mucronata*)	cpDNA nDNA	6	-	Low Genetic differentiation 0.0183- single unit	High	ATGC ver. 6.0- MEGA5-Clustal W-DnaSP ver. 5.10- NETWORK ver. 4.6.1.1-Arlequin ver. 3.5-STRUCTURE ver. 2.3.4	Ng *et al*, 2014
Thailand	*R. apiculata* *R. mucronata*	3 (12-14)	cpDNA nDNA	7	-	Low	0.221 0.381	DNAsp, Ver 4.20- Arlequin ver. 3.11-HKA program.	Inomata *et al.*, 2009
The Indo-West Pacific	*R. apiculata,* *R. mucronata,* *R. stylosa*	9 (6-26) 8 (6-24) 10 (12-24)	SSRs	13	1.85- 4.54 1.92- 4.08 1.69- 6.15	0.138-0.533 0.212-0.583 0.149-0.650	-0.221 to 0.350 -0.113 to 0.495 -0.309 to 0.330	Micro-checker v2.2.3- FREENA- FSTAT Ver.2.9.3- GENEPOP- GenAlEx ver.6.5-STRUCTURE v2.3.4.	Yan *et al.*, 2016
The Indo-West Pacific	*R. mucronata*	9 (56)	SSRs	14	From 2 to 9.	Very low 0.16(0.00-0.41)	High	QDD v. 2.1- GENEPOP 4.0- Micro-checker v2.2.3.	Shinmura *et al.*, 2012
Continental Southeast Asia and Sumatra.	*R. mucronata*	13 (27-39)	SSRs	10	3-8	Low 0.108	-0.085 to 0.570	FSTAT 2.9.3.2- FREENA- GENEPOP 4.0- GenAlEx ver.6.5- POPULATIONS 1.2.31- STRUCTURE v2.3.4.-GENELAND 3.1.4	Wee *et al.* ,2014
East, South and West of the Malay peninsula	*Avicennia alba* *Sonneratia alba* *R. mucronata*	3	SSRs	4 4 3	1-6 1-3 1-3	0.000–0.877 0.000–0.647 0.000–0.558	High level	GeneMapper v4.1- GENEPOP Ver. 3.4.	Wee *et al.*, 2013
Indian and Pacific Ocean	*R. mucronata* *R. stylosa.*	24 (21-39) 12 (16-47)	SSRs	20	10.25	0.108 0.097	85% 67%	GenAlEx 6.5- FSTAT 2.9.3.2- GENEPOP 4.0- STRUCTURE v2.3.4.	Wee *et al*., 2015
Sakishima Islands	*R. stylosa*	16	nSSRs cpSSRs	10	1.7–2.7	0.031–0.216 0.000–0.489	0.323-0.778	GenAlEx 6.5- GENEPOP Ver. 3.4.-FSTAT 2.9.3.2- Micro-checker v2.2.3-ARLEQUIN ver. 3.0- STRUCTURE v2.3.4- BOTTLENECK.	Islam *et al.*, 2013
The Greater Sunda Islands, Indonesia	*R. apiculata*	15 (20-24)	SSRs	5	38	0.378	0.101	GenAlEx 6.4- PopGene Version 1.32-GENEPOP Ver. 3.4.- Micro-checker v2.2.3- STRUCTURE v2.3.4- Power Marker 3.25- SPAGeDi 1.3- MEGA4.	Yahya *et al.*, 2013
Brazilian coast	*R. mangle*	10 (145)	SSRs	8	27	0.17	-	PopGene Version 1.32- POPTREE-ARLEQUIN ver. 3.0- Migrate ver. 3.1.6	Pil *et al.*, 2011

Ecuador	*R. mangle*	2	SSRs	5	2-5	0.189 - 0.405	0.695	Genetic Data Analysis ver. 1.0- Arlequin ver. 3.0.	Basyuni et al., 2017
Caribbean and Pacific estuaries of Panama	*Avicennia germinans* *R. mangle*	(980) (940)	SSRs	11 6	-	0.459- 0.730 0.349- 0.654	0.1950 0.1327	GenAlEx 6.5- GENEPOP Ver. 3.4.- Micro-checker v2.2.3- STRUCTURE v2.3.4- GENELAND 3.1.4- INSTRUCT.	Cerón-Souza et al., 2012
The Colombian Pacific	*R. mangle*	5 (92)	SSRs	3	17	0.494	0.261	GDAver. 1.1- TFPGA 1.3	Arbela´ez-Cortes *et al.*, 2007
The north-western coast of Mexico	*R. mangle*	10 (26-48)	SSRs	6	110	0.17	0.07	FSTAT 2.9.3- GENEPOP 4.0- STRUCTUREv2.2.3- ARLEQUIN v. 3.5- MIGRATE-	Sandoval-Castro *et al.*, 2012

Figure 6.1 (A) *R. mucronata* in natural habitat in Farasan Alkabir Island, (B) the propagule of the *R. mucronata.*

6.2 Materials and Methods

6.2.1 Study area

To cover the geographic distribution of the *Rhizophora mucronata* on the Archipelago as widley as possible, sixty-eight leaves were collected during 2015-2016 from two of the Farasan Islands (the north-eastern area of Farasan Alkabir Island and Zifaf Island) **Figure 6.2.** The study sampled the four known populations; three populations from Farasan Alkabir and one population from Zifaf Island. GPS coordinates of each population are presented in **Table 6.2.** Green leaf samples of *R. mucronata* were collected from the sampled populations, some of them collected by the collaborators. Sampling size was selected based on the number of individuals in each population, at least 12 individuals of each population without endangering the small population. In order to avoid the chances of kinship, the minimum distance between any pair of sampled trees was set to approximately 10 m. For each accession, GPS coordinates were mapped using a GPS unit as shown in **Appendix 6**. A *R. mucronata* population has been reported in Dissan Island, but the island could not be visited due to the strong winds and rough movement in the Red Sea, especially from the north, where Dissan is located. The author sampled the *R. mucronata* populations with the permission of the Saudi wildlife authority in the Kingdom of Saudi Arabia, because these islands are registered as protected areas due to the presence of endemic Arabian gazelles. The collected leaf samples were desiccated and preserved with silica gel at room temperature until DNA extraction.

6.2.2 DNA extraction

Total genomic DNA was isolated from 500 mg of dehydrated and pulverized leaf tissue. Modified CTAB protocol was used following the method of [57]; mercaptoethanol was omitted, and 2% polyvinylpyrrolidone PVP was included in the initial extraction buffer and extra wash steps. The final DNA pellets were suspended in 50 μL of TE buffer. DNA extractions were visualized on 0.7% agarose gels in 1 × TAE buffer with gel red stain (Biotium, Glowing product for science). To record extractions, gels were illuminated by a T: Genius gel imaging system (Syngene). The size and concentration of the extracted DNA were determined using Hyper Ladder™ 1kb (from 200 bp to 10,000 bp; Bioline Reagents Ltd., London, UK) as a marker.

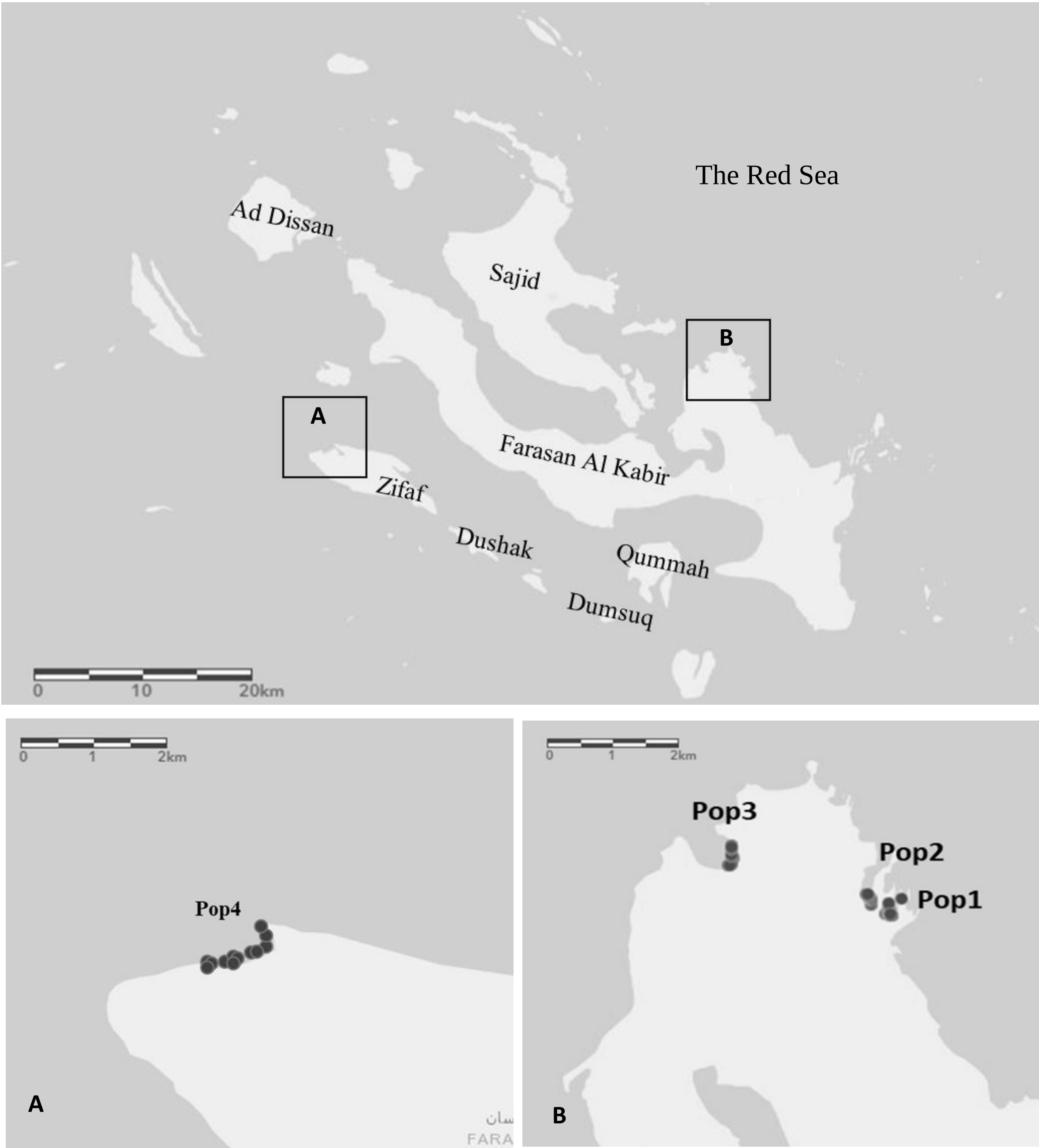

Figure 6.2 Geographic location of *Rhizophora mucronata* sampling sites along the Farasan Archipelago coast, A-Zifaf Island B-Farasan Alkabir Island.

Concentration and quality of DNA were determined with a NanoDrop machine (Thermo Fisher Scientific Inc., Waltham, MA, USA). DNA was diluted with sterile distilled water. Samples were diluted to 5 ng/µl for PCR amplification. Dilution was carried out using stock DNA solutions, and samples were stored in the freezer at -20°C.

Table 6.2 *R. mucronata* populations tested (name and code given), latitude and longitude of the location, Island area, Island habitat and inhabited status.

Island's Populations	Habitat	Inhabited area	Code	Latitude	Longitude
Farasan Al-Kabir	Rocky	Yes	Pop1	16.804166	42.069108
Farasan Al-Kabir	Rocky	Yes	Pop2	16.747602	42.000543
Farasan Al-Kabir	Rocky	Yes	Pop3	16.756755	42.00426
Zifaf	Coral sand	None	Pop4	16.733156	41.745078

6.2.3 DNA amplification by PCR

Microsatellite primer sequences (14 pairs) published by [42], were purchased from Sigma Aldrich. Four individuals were selected from the population in the study area for optimization, testing to determine the utility of the markers for the defined objectives. All 14 microsatellite markers were amplified in the individuals across populations. Dye labelled primers from Sigma Aldrich and Thermo Fisher Scientific (6FAM, VIC, PET, NED) **Table 6.3,** were used for final data production. The 86 *R. mucronata* individuals were screened by PCR with 14 microsatellite markers. The 10 µL reaction volume containing template DNA, 10-50 ng; 1×PCR buffer; dNTPs, 400 µM each, Mg2+, 2.5 mM; 0.2 µM from each primer. The initial denaturation was conducted for 5 min at 94°C; 35 cycles were run for 45 s at 95°C, 45 s at 50°C and 45 s at 72°C with a final elongation step of 10 min at 72°C [58]. Three primers (RM119- RM121- and RM103) were amplified at an annealing temperature of 55°C. The microsatellite fragments were screened on 2% agarose gels in 1 × TAE buffer, with allele size estimated using Hyper Ladder 100bp (100bp to 1000bp; Bioline Reagents Ltd., London, UK) as a marker. Amplified products were run on an ABI 3031xl automated sequencer with the GeneScan-600 LIZ size standard for final data generation. Visualization and scoring were carried out using Geneious R11 [81].

6.2.4 Basic genetic parameters: diversity and differentiation

After genotyping, the Hardy–Weinberg equilibrium (HWE) was tested following [59]. Linkage disequilibrium (LD) between all microsatellite loci pairs were estimated for all accessions using (*popper*) [60] .The number of permutations performed for the LD analysis was 999. GenAlEx v6.5 software [61] was used to determine the observed heterozygosity (Ho), expected heterozygosity (He), the number of alleles and inbreeding coefficient (F) for each population. As well, the number of alleles across loci, observed heterozygosity (Ho), expected heterozygosity (He) for each locus, and Wright's analysis of hierarchical F-statistics across all loci, were calculated using *Arlequin* 3.5.

6.2.5 Genetic structure across the Farasan Islands

A simple Mantel test was carried out to determine the relationship between the geographic distance and genetic distance of populations with 10,000 permutations [61]. The genetic differentiation between population pairs was calculated by GenAlEx v6.5.

AMOVA was carried out to examine the hierarchical partitioning of genetic variance; it was performed with GenAlEx v6.5. with 10,000 permutations. As a complementary visualization of the genetic structure, principle component analysis PCoA was conducted for *R. mucronata* accessions using GenAlEx v6.5 software. The analysis computed a matrix of mean genotypic distance values between all pairs of individuals. A scatter diagram was plotted according to the Eigenvalues along the first two principal coordinate axes. Discriminant Analysis of Principal Components (DAPC) was used to identify and describe genetic clusters. These analysis were done using *adegenet 2.00* package [62] and the visualization function for DAPC by (*find.clusters*) [63].

A model-based clustering program Structure V2.3.4, [64] was used to infer the population structure of the all accessions in *R. mucronata* and the ΔK method was used with the Structure harvester v.0.6.93 to identify the optimal K value following [65]. A UPGMA clustering with function (*hclust*) [66], in R studio was used to estimate the genetic distance of accessions.

6.2.6 Red Sea Current movement

To generate the sea surface circulation, the data were collected from literature review [67-70] and from the Earth Observatory EOS at NASA Goddard Space Flight Centre. Then, genetic structure has been examined by STRUCTURE and Circulation patterns data were compared with the genetic clusters and clusters identified on the QGIS 12.18.16.map.

6.3 Results

6.3.1 Basic genetic parameters: diversity and differentiation

DNA was successfully extracted from 86 samples of *R. mucronata*. PCR optimization and screening resulted in the use of 14 SSRs. The number of alleles per locus varied from 1 (RM103) to 4 (RM102) with a total of 31 alleles across the 14 loci.

Ten loci were polymorphic for all populations, ranging from two to four alleles per locus. Some primers lacked polymorphism (monomorphic) for all *R. mucronata* populations, such as RM103 and RM119. Other primers lacked polymorphism for some populations; RM112 and RM121 in (pop1, pop2, pop3); RM107 in (pop1, pop4); RM114 in (pop1, pop3) and RM108 in (pop2, pop4). Some primers, such as RM110 and RM119, could not be amplified in several individuals, which were subsequently treated as missing data. Missing data comprised 0.06% of the entire data set for *R. mucronata*. Alleles are linked across loci with $P < 0.001$ indicating populations were clonal. Observed heterozygosity was slightly lower than the expected heterozygosity in all the loci. Significant deviation from HWE was observed in 9 out of 14 loci for a particular population at $P < 0.05$ and is indicative of some inbreeding.

All the populations of *R. mucronata* have low genetic diversity, which ranged from 0.198 (pop1) to 0.241 (pop4). The percentage of the Polymorphism Information Content (PIC) ranged from 50.00% in pop1 to 71.43% in pop3. The average number of alleles detected across the 4 populations ranging from 1.6 (pop1 and pop2) to1.7 in (pop3 and pop4). The average number of observed heterozygotes, across all *R. mucronata* populations, was 0.208, and the number of observed heterozygotes (Ho) per population ranged from 0.131 to 0.243 (Table 2), based on population analysis.

The F (inbreeding coefficient) was negative in the pop1 from Farasan Alkabir Island, implying a slight degree of outbreeding, whereas positive F in the other populations (pop2, pop3 from Farasan Alkabir Island and pop4 Zifaf Island) showed a considerable degree of inbreeding.

Table 6.3 Descriptive statistics of overall loci for each population of *R. mucronata*. Number of individuals (N), Average number of alleles (Na), Percentage of Polymorphic Loci (Pic,%), number of effective Alleles (Ne), Observed Heterozygosity (Ho), Expected Heterozygosity (He), Shannon's Information Index (I) and Fixation Index (F).

Populations	N	Na	Ne	I	P %	Ho	He	F
Pop1	12	1.643	1.335	0.310	50.00%	0.238	0.198	-0.190
Pop2	12	1.643	1.395	0.349	64.29%	0.220	0.233	0.000
Pop3	20	1.786	1.433	0.365	71.43%	0.243	0.236	0.032
Pop4	24	1.714	1.454	0.367	57.14%	0.131	0.241	0.405

Pairwise F_{ST} values showed significant differentiation between the two islands and among the pairs of all populations ranging from 0.258 to 0.0043, **Figure 6.2** which indicated that the islands and the populations were significantly different. Pop1 and Pop4 were more differentiated from each other according to the FST value (0.258), followed by Pop2 and Pop4 were FST (0.237). The AMOVA for the four populations revealed that 57% ($P < 0.001$) of the genetic variation is found within populations, whereas 43% ($P < 0.001$) of the genetic variation is found among populations.

	Pop1	Pop2	Pop3	Pop4
Pop1	0.000			
Pop2	0.043	0.000		
Pop3	0.054	0.060	0.000	
Pop4	0.258	0.237	0.212	0.000

Figure 6.3 Coefficient of genetic differentiation Fst of natural population of *R. mucronata* for all pairwise comparison. All values are significant at a 0.001 level, for abbreviations of localities see **Table 6.1.**

6.3.2 Population structure and cluster analysis across the Farasan Islands

Significant genetic divergence between populations from different islands was detected in *R. mucronata* populations based on cluster analysis. The populations in the Farasan Alkabir Island were more closely linked together than the population from Zifaf Island. Six different genetic analyses detected *R. mucronata* populations in the Farasan archipelago: Simple Mantel tests revealed a weak positive correlation between the genetic distance matrix and the geographic distance matrix along the islands (**Figure 6.4)**, ($R^2 = 0.0328$; $p < 0.054$).

The PCoA, DAPC and the PCA showed distinct clustering of individuals based on the island of origin **Figure 6.5** and **Figure 6.6**. The first two principal component axes cumulatively accounted for 90% of the total variance in *R. mucronata* accessions on the different islands. An UPGMA tree of all the 86 accessions was constructed based on Nei's genetic distance, all the accessions were assigned to the two main clusters, **Figure 6.7**. The results from Structure V2.3.4 analysis indicated that DK peaked when the K value was 2, **Figure 6.8**. Therefore, the optimal value of K is K = 2. The clustering of accessions in the UPGMA tree was generally in agreement with the population structure, the 86 accessions divided into two groups Group1 included Pop1, pop2 and Pop3, from Farasan Alkabir Island, Group 2 included pop4 from Zifaf Island.

Table 6.3 SSR primers screened for SSR-PCR in *R. mucronata*. Primer sequence, Primer repetitive, Range size (Pb), Total number of Alleles per primers over all localities (A), Observed Heterozygosity (Ho), Expected Heterozygosity(He) , Gene flow(Nm) and F-statistic (Fis,Fit,Fst).

Locus	Primer's sequence	Repetitive sequence	Range size (bp)	A	Ho	He	Nm	Fis	Fit	Fst
RM102	F:GGTTTTCCCAGTCACGACGTGCTGCTACTGATCAGGAATG R:GTTTCAGATCCTACCCACCATCAG	(TG)	167-187	4	0.375	0.291	3.196	-0.291	-0.197	0.073
RM103	F:GGTTTTCCCAGTCACGACGCCGGTCCATTATAGAACCCA R:GTTTCAAATCTCAAGCTCAGTTTCCA	(AG)16	122–130	1	0.000	0.000	#N/A	#N/A	#N/A	#N/A
RM106	F:GGTTTTCCCAGTCACGACGCCCTGGCTCTTACCGTTCTT R:GTTTAGAACCAAACTCCAAGGGTC	(GA)13	192–200	2	0.073	0.191	0.318	0.617	0.786	0.440
RM107	F:GGTTTTCCCAGTCACGACGAACAAGCATGGGCAGGTAAC R:GTTTGCCCATTTGGAATATGTGT	(CT)13	232–254	2	0.208	0.163	1.741	-0.277	-0.116	0.126
RM108	F:GGTTTTCCCAGTCACGACGCTTCGTCGTTTGGCATGTAA R:GTTTGACCCGAGAATACCTCTGC	(AT)13	127–139	2	0.271	0.187	0.163	-0.451	0.428	0.606
RM109	F:GGTTTTCCCAGTCACGACGAGGCCAGTTCTCGTCACACT R:GTTTGTCTTTGGGAATTTGGGAA	(GA)13	100–122	3	0.277	0.353	0.967	0.215	0.376	0.205
RM110	F:GGTTTTCCCAGTCACGACGCAACAACCTCCAACAGGACA R:GTTTATGGGTAGGACATCGTGTGAG	(AC)13	80–100	3	0.538	0.490	4.163	-0.098	-0.035	0.057
RM111	F:GGTTTTCCCAGTCACGACGAACCGTTACTCGCGTATGCT R:GTTTCATTGCCTCCATTCCATT	(TC)13	141–157	2	0.258	0.406	7.464	0.364	0.385	0.032
RM112	F:GGTTTTCCCAGTCACGACGTTGAAGGTTGCGGTGAAAT R:GTTTACATTCTTACCCTGCGCACT	(AG)13	197–203	2	0.050	0.045	3.000	-0.111	-0.026	0.077
RM113	F:GGTTTTCCCAGTCACGACGATTATTGGCTCTATAATTTCACTGC R:GTTTAAAGACATGAGCAGATAATACATCC	(AT)13	139–151	2	0.246	0.434	2.382	0.433	0.487	0.095
RM114	F:GGTTTTCCCAGTCACGACGATTGGCATAGGCGTTGAATC R:GTTTGTGGCTCAATTGTTGGCTA	(AT)13	226–238	3	0.146	0.124	0.102	-0.175	0.660	0.711
RM116	F:GGTTTTCCCAGTCACGACGATAAGACCATATGTAACACCCATTT R:GTTTCCTCCTCTCATTCTTCATTTCA	(TA)12	137–161	2	0.458	0.481	8.842	0.048	0.074	0.027
RM119	F:GGTTTTCCCAGTCACGACGCTGGCCCTGAGTTTCACATT R:GTTTGGAACAAGAGTGACAGAATGA	(AG)12	130–132	1	0.000	0.000	#N/A	#N/A	#N/A	#N/A
RM121	F:GGTTTTCCCAGTCACGACGTGGCCTATAGAGAAAGCGGA R:GTTTCCTTCAATCCCAAACAGC	(ATC)12	130–132	2	0.013	0.012	13.000	-0.026	-0.006	0.019

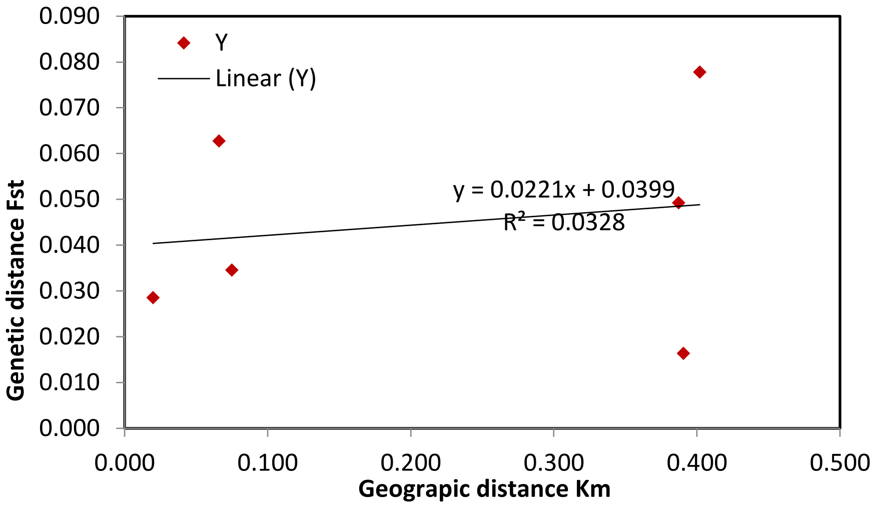

Figure 6.4 Mantel's test for correlation between Fst genetic distance and geographic distance (km) of natural populations of *R. mucronata* ($R^2 = 0.0328$; $P < 0.05$).

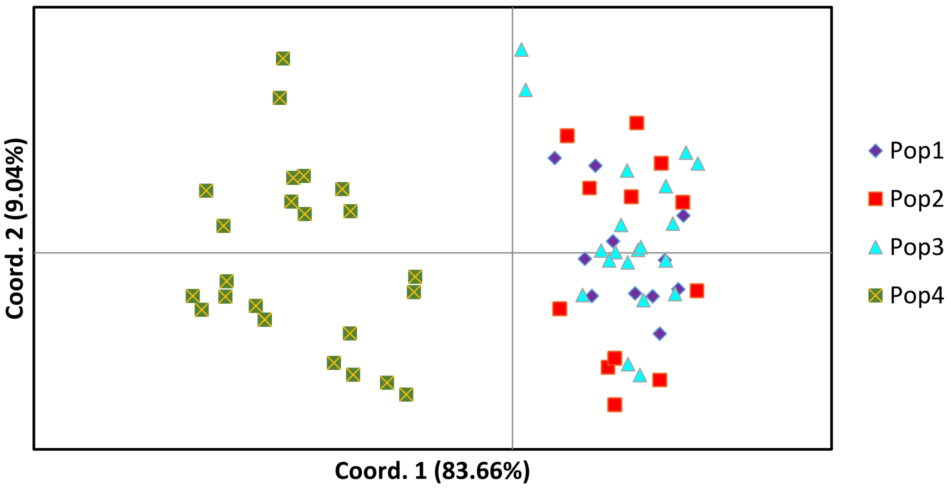

Figure 6.5 Principal coordinate analysis (PCoA) of microsatellite diversity among the 68 accessions of *R. mucronata, the* samples are colour coded according to their membership in the four populations.

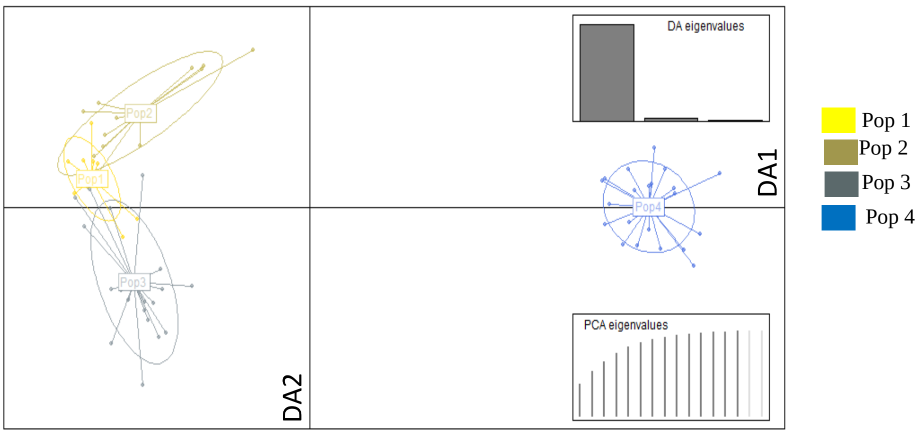

Figure 6.6 Discriminant analysis of principal components (DAPC) among four natural populations of *R. mucronata* across the Farasan archipelago, eigenvalues are presented here.

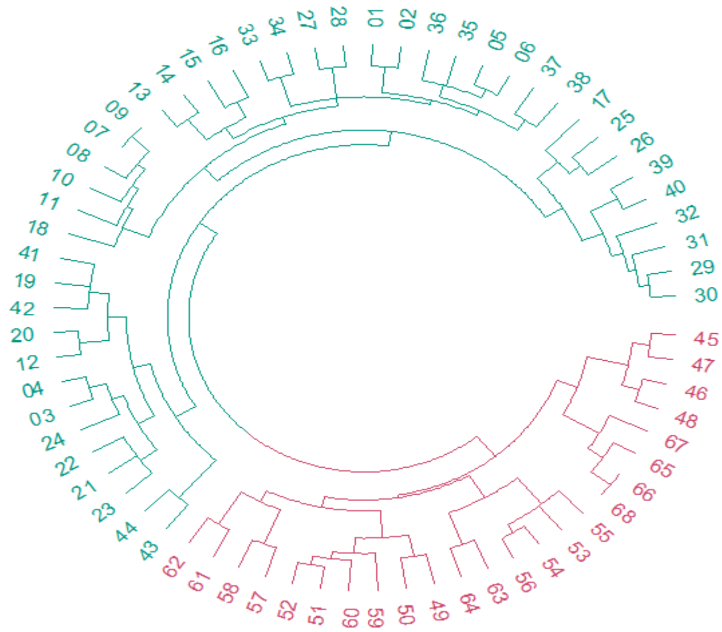

Figure 6.7 Unweighted Pair Group Method with Arithmetic (UPGMA) tree showing the relationships among accessions. The colour outlines the clusters of accessions. Green colour denotes *Rhizophora mucronata* populations in Farasan Alkabir Island; Red colour denotes *R. mucronata* population in Zifaf Island.

6.3.3 Red sea current surface simulation

The Red Sea current flows from the southeast direction from the Indian Ocean to the northwest direction (January) and a strong northwest and east west current drifts in winter season **Figure 6.7B**. Whereas, during the summer season (June) that is the maturation period of the *R. mucronata*, the maps of surface circulation climatology **Figure 6.8A**, indicate that the current direction from the north to south direction and the flow through the north part is stronger than south part of the Islands.

6.4 Discussion

Although the number of *R. mucronata* individuals in the Farasan Archipelago appeared to be limited and most were in a challenging habitat (dense aboveground prop roots and some populations were inaccessible due to the depth of water), the author and collaborates collected as many accessible specimens as possible, without endangering the small population. That lead to this study being more comprehensive and representative for analysing the pattern of genetic diversity and structure of *R .mucronata* than the previous studies in *R. mucronata* at local scale, which used fewer numbers of samples per population [42] and /or SSRs loci from five to nine only [46, 71].

In general, the pattern of genetic diversity strongly supports low genetic variation in all populations, agreeing with previous studies which found a low genetic diversity in *Rhizophora* species such as *R. stylosa* a sister of *R. mucronata* by [72] in Sakishima Islands, *R. mangle* on the Brazilian coast and the north western coast of Mexico [73] and *R. mucronata* on the Continental Southeast Asian and Sumatran coasts [43]. The low genetic diversity of the populations of *Rhizophora mucronata* is probably because they are not continuous distribution, especially at a local level. This may be an effect of unsuitable habitat and anthropogenic pressure which have been the main threat to diversity, which most likely corresponds to the peripheral population in *R. mangle* in the north of Mexico [73].

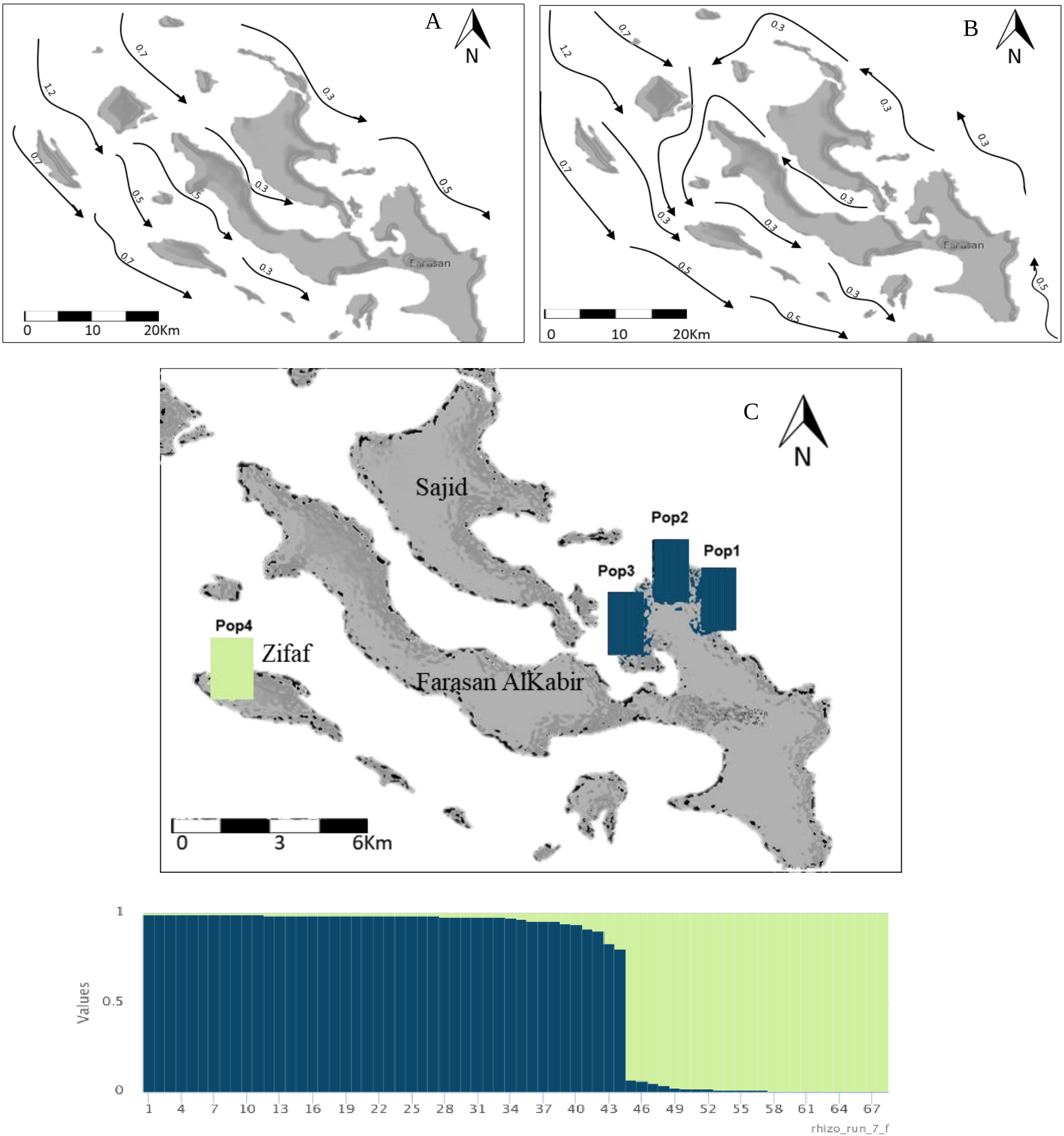

Figure 6.8 Maps depicting the genetic structure among populations of *R. mucronata* and the sea surface circulations in the Farasan archipelago. (A and B) Surface current climatology from the model is shown for (A) summer season (B) winter season, the number indicates the current speed in m/s. (C) Structure bar plots showing the assignment of individuals into two distinct genetic clusters (K=2).

The other reason for the reduced level of genetic diversity of these populations is the demographic instability inducing low effective population size, repeated bottlenecks or founder events. However, the genetic diversity of some populations of *R. mucronata* in the Indo-West Pacific region [34, 44] is reported to be three times higher than the present study found in the Farasan Archipelago despite same not continues populations. With the lower diversity of Farasan Archipelago populations, more attention should be paid.

Biologically, the high level of inbreeding and self-fertilization are common characters among mangrove species, as previous reported in [52, 73, 74]. This factor contributes to the heterozygote deficiency of all populations in the Farasan Archipelago. The deviation of SSR loci from HWE might be due to a high rate of self-fertilization and/or anthropogenic factors especially in Farasan Alkabir Island. The linkage disequilibrium in the study is similar that found in [75] for *R. mangal* in the Colombian Pacific.

For genetic structure, the result obtained from Bayesian analysis is the most likely to explain the population genetic structure of *R. mucronata* along the Farasan Archipelago coast. One cluster comprises populations situated in Farasan Alkabir (Pop1-Pop2-Pop3) while a second cluster includes the population located in Zifaf Island (Pop4). This suggests that Sajid Island and the southern part of Farasan Alkabir Island act as an effective barrier that limits gene flow between populations from Farasan Alkabir Island and the isolated population in Zifaf Island, similar to previous reported for *R. mangle* in the northern coast of Mexico [43]. Not only land barrier, but also the Red Sea current movement may have contributed to the population structuring of *R. mucronata* as that is proposed for *R. mucronata* in Southeast Asia [43]. An analysis of regional sea circulation patterns in the Red Sea, during the north-south monsoon, indicates strong currents flow from the north of the Red Sea (Jordan and Egypt border) to the south of the Red Sea (Yemen border). As mature propagules of *Rhizophora mucronata* appear in the summer season, these sea currents may act as the barrier for gene flow and a mechanism for the currents to prevent admixture across the populations in Farasan Alkabir Island and Zifaf Island. A suggested from previous studies, the repeated fluctuation of sea levels during the Pleistocene may have affected the populations structure [76]. Similar observations have been reported for *Rhizophora mangle* across the Atlantic Ocean [73].

So, the analysis in this study indicates that sea currents and land barriers, preventing the mixing of waters at the boundary between the east Red Seaside and the west Red seaside, thereby preventing propagule exchange between the Farasan Alkabir populations and the Zifaf Island population **Figure 6.8C**.

Within populations of Farasan Alkabir Island, the low differential between the populations of *R. mucronata* in the Farasan Alkabir Island, may be because of the presumption that within the coast, propagules are being retained locally due to the action of the surface marine currents that affecting the zone[55]. As well, it can be assumed that the ground of the *Rhizophora* stand is made up of a massive network of prop roots, potentially trapping and reducing the mobility of the propagules, limiting dispersal as the previous study by [76].

6.5 Conclusions

This study provides the first description of genetic variation and structure using microsatellite markers in *R. mucronata* populations in the Farasan archipelago. The study indicates low genetic diversity among populations, and this provides knowledge to support management plans and conservation efforts of the species in the Archipelago. The populations are clustered into two groups, one group contained populations from Farasan Alkabir Island and other from Zifaf Island. The pattern of the Red Sea current movement and the land barrier between the islands are likely to be the most influential factor on the differentiation of *R. mucronata* populations. Therefore, the efforts to conserve the species in this Archipelago should not be based only on preserving large areas, but also on small and separate ones, to encompass the different genetic patterns found between the islands within the archipelago.

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Appendix 6

(1) List of *R. mucronata* samples collected from different geographical locations of the Farasan Archipelago.

No.	Lab code	Longitude	Latitude	Population name	Island
1	RF1	42.098707	16.788426	Pop1	Farasan Alkabir
2	Rw1	42.098694	16.788771	Pop1	Farasan Alkabir
3	RF2	42.098744	16.789184	Pop1	Farasan Alkabir
4	Rw2	42.098688	16.789367	Pop1	Farasan Alkabir
5	RF3	42.098489	16.789806	Pop1	Farasan Alkabir
6	Rw3	42.098557	16.789759	Pop1	Farasan Alkabir
7	RF4	42.098375	16.790131	Pop1	Farasan Alkabir
8	Rw4	42.098442	16.790118	Pop1	Farasan Alkabir
9	RF5	42.09812	16.790346	Pop1	Farasan Alkabir
10	Rw5	42.098051	16.790457	Pop1	Farasan Alkabir
11	RF6	42.097757	16.790522	Pop1	Farasan Alkabir
12	Rw6	42.097805	16.790542	Pop1	Farasan Alkabir
13	RF1*	42.068999	16.798494	Pop2	Farasan Alkabir
14	Rw1*	42.069061	16.798361	Pop2	Farasan Alkabir
15	RF2*	42.068962	16.797776	Pop2	Farasan Alkabir
16	Rw2*	42.068685	16.797341	Pop2	Farasan Alkabir
17	RF3*	42.068276	16.797013	Pop2	Farasan Alkabir
18	Rw3*	42.068307	16.796838	Pop2	Farasan Alkabir
19	RF4*	42.06882	16.79889	Pop2	Farasan Alkabir
20	Rw4*	42.068754	16.799177	Pop2	Farasan Alkabir
21	RF5*	42.068796	16.800491	Pop2	Farasan Alkabir
22	Rw5*	42.068816	16.800337	Pop2	Farasan Alkabir
23	RF6*	42.068622	16.801004	Pop2	Farasan Alkabir
24	Rw6*	42.068642	16.800881	Pop2	Farasan Alkabir
25	55	42.101895	16.786208	Pop3	Farasan Alkabir
26	R55	42.172392	16.704384	Pop3	Farasan Alkabir
27	56	42.102174	16.786496	Pop3	Farasan Alkabir
28	R56	42.102368	16.786506	Pop3	Farasan Alkabir
29	57	42.102508	16.786742	Pop3	Farasan Alkabir
30	R57	42.102573	16.786814	Pop3	Farasan Alkabir
31	58	42.102724	16.787019	Pop3	Farasan Alkabir
32	R58	42.102788	16.787101	Pop3	Farasan Alkabir
33	59	42.102788	16.787101	Pop3	Farasan Alkabir
34	R59	42.102548	16.787546	Pop3	Farasan Alkabir
35	60	42.102465	16.787874	Pop3	Farasan Alkabir

36	R60	42.102479	16.787961	Pop3	Farasan Alkabir
37	61	42.102569	16.788342	Pop3	Farasan Alkabir
38	R61	42.102573	16.788756	Pop3	Farasan Alkabir
39	62	42.102754	16.786106	Pop3	Farasan Alkabir
40	R62	42.102874	16.786168	Pop3	Farasan Alkabir
41	64	42.103112	16.786127	Pop3	Farasan Alkabir
42	R64	42.103199	16.786096	Pop3	Farasan Alkabir
43	RZ2M	42.102707	16.786075	Pop3	Farasan Alkabir
44	Rx2M	42.102827	16.786198	Pop3	Farasan Alkabir
45	RZ1	41.745327	16.733282	Pop4	Zifaf
46	Rx1	41.745404	16.73322	Pop4	Zifaf
47	RZ2	41.745222	16.732686	Pop4	Zifaf
48	Rx2	41.745158	16.732522	Pop4	Zifaf
49	RZ3	41.745996	16.731576	Pop4	Zifaf
50	Rx3	41.746536	16.731463	Pop4	Zifaf
51	RZ4	41.744369	16.730344	Pop4	Zifaf
52	Rx4	41.744586	16.730303	Pop4	Zifaf
53	RZ5	41.745124	16.730159	Pop4	Zifaf
54	Rx5	41.74536	16.729933	Pop4	Zifaf
55	RZ6	41.745585	16.72944	Pop4	Zifaf
56	Rx6	41.745835	16.729275	Pop4	Zifaf
57	RZ1 *	41.749468	16.727799	Pop4	Zifaf
58	Rx1 *	41.749801	16.727685	Pop4	Zifaf
59	RZ2*	41.750263	16.727644	Pop4	Zifaf
60	Rx2*	41.749675	16.728887	Pop4	Zifaf
61	RZ3*	41.749895	16.728887	Pop4	Zifaf
62	Rx1 *	41.752795	16.7279	Pop4	Zifaf
63	RZ4*	41.753015	16.728168	Pop4	Zifaf
64	Rx2*	41.753063	16.728621	Pop4	Zifaf
65	RZ5*	41.75313	16.729146	Pop4	Zifaf
66	Rx1 *	41.746898	16.73464	Pop4	Zifaf
67	RZ6*	41.74654	16.73504	Pop4	Zifaf
68	Rx2*	41.74601	16.735368	Pop4	Zifaf

CHAPTER 7

Regional conservation assessment of the threatened species in a coastal zone: a case study of six plant species in the Farasan Archipelago

Regional conservation assessment of the threatened species in a coastal zone: a case study of six plant species in the Farasan Archipelago

RAHMAH AL QTHANIN and ALASTAIR CULHAM

Abstract: Assessing species at the regional level for their conservation is a vital first step in identifying and prioritizing species for both ex-situ and in-situ conservation actions. The complex coastal geomorphology of the Farasan Archipelago gives rise to promontories and bays that fragment the coastal flora. Climate change studies, combined with a case study of anthropogenic land use changes such as urbanization, tourism and fishing, highlight the threat to the fragmented plant populations. In this study, the regional IUCN categories and criteria have been used to assess the conservation status of six targeted taxa of the Farasan Archipelago coast based on the data collected during field surveys and a literature review. According to our results, two species have been categorized as endangered, two species as near-threatened and two species as least concern. Compared to an earlier assessment at the global level, *Avicennia marina* and *Rhizophora mucronata* have been re-categorized with a high degree of threat and four species have been assessed for the first time. An effective action plan for the protection of the coastal zone biodiversity of the Archipelago is crucial for the control of erosion and for the maintenance of fisheries.

Keywords: Farasan Archipelago, regional Red List, conservation, threatened species, Coast zone.

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7.1 Introduction

The Farasan Archipelago is an Important Plant Area in Arabia (Hall *et al*., 2010). It is the second largest Red Sea Archipelago after the Archipelago of Dahlek (Al-Hammad, 2016), and has high priority in terms of conservation and the management of its marine and coastal area resources (Gladstone, 2002).

The interior surface of the islands is a subtropical desert of fossil limestone (Bruckner *et al.*, 2012) interspersed with many short water runnels that provide fertile farmland. The coastal zone is comprised of a mix of natural beaches that are rocky, sandy (fine or coarse coral fragments) or vegetated (El-Demerdash, 1996, Tomas *et al.*, 2010) as seen in **Figure 7.1**. The coastal area of the Farasan Archipelago is a major source of income for local inhabitants and communities (Spurgeon, 2006, cited in Gladstone, 2009). It is an area of national and international significance for breeding seabirds, shorebirds and marine mammals in the Red Sea, including the endemic *Larus leucophthalmus* and *Dromas ardeola* (PERSGA, 2003). It is the site for the unique annual aggregation of parrotfish (Gladstone, 1996). To coincide with this aggregation, the Al Harid Festival occurs in March or April every year in one of the inner bays of Farasan Alkabir Island. The parrotfish, in large numbers, move into the shallow water of the bay where people can easily harvest them in large quantities by wading into the water with nets (Gladstone *et al.*, 1999). In addition, it supports a large number of marine, mangrove and wetland species (Gladstone, 2000).
Threats to the island ecosystem have developed over recent decades, **Figure 7.2**

shows some of that threats**.** The rise in sea level (AlRashidi *et al.,* 2012) due to the melting of frozen water mainly in the Antarctic and Arctic regions (Meehl *et al.,* 2006) has caused changes to the coastlines and extent of the islands. The sea level rise in the Farasan Archipelago is predicted to be between 0.18m to 1.2 m by 2100 (Rahmstorf *et al.*, 2007). As the sea level rises, coastal habitats are inundated, eroded, or washed away, which can result in habitat loss (Mander *et al.,* 2007).

The coastline has suffered vast changes in land use through anthropogenic factors including urbanisation and sand extraction, fishing, shipping, pollution, military purposes, tourism, off-road driving and farming practises that allow the incursion of invasive species. The development of beach resorts, particularly on Farasan Alkabir Island (Gladstone, 2000) and the sandy beach areas, face special problems due to the removal of beach sand for local construction projects. This has destroyed the low-lying shoreline vegetation (Gladstone, 2002), and has disrupted shoreline dynamics and obstructed tidal flows (Gladstone, 2008). Between 59 and 76% of artisanal fishing occurs on the bays of the Farasan Archipelago (Gladstone, 2000). In addition, cutting down the mangroves for the purpose of making traps for catching migratory birds on the uninhabited islands (Tomas *et al.,* 2010) has led to a loss of the mangrove ecosystem.

The Farasan Archipelago is a major international shipping route, used for an estimated 25,000–30,000 ship transits annually (Gladstone *et al.*, 1999). This means that the coastal biodiversity is subject to oil pollution. Most sewage is dumped inland, with disposal into the sea occurring only at one site inside Farasan Port.

Expansion has happened in the tourism sector, particularly with the new vision of the government of Saudi Arabia by 2030 (Saudi Vision 2030, 2018). Around 4000 to 5000 domestic tourists visit the Farasan and Sajid Islands during the school vacations putting added pressures on the sewage system, water demands and through activities such as recreational off-road driving which damages vegetation and disrupts the soil surface.

All of these threats affect the connectivity between plant populations (Gladstone *et al.*, 1999), making the maintenance of viable species more difficult. Mangroves, *Avicennia marina* and *Rhizophora mucronata* (Hariri *et al.,* 2014), and *Tetranea* ssp. (previously known as *Zygophyllum* ssp.) (Gladstone, 2000) are particularly prone to being threatened by these factors. Moreover, mangrove species are, both regionally and globally threatened (Hall *et al*., 2010, Gladstone, 2008). These species may help drive the conservation of the coastal island ecosystem.

In recent years, the IUCN Red list categories and criteria (2003) have been increasingly used at the regional level. A first attempt to make the IUCN regional guidelines work at a regional level was made by the Regional Application Working Group (RAWG) (Gärdenfors *et al.*, 1999), after which they had received many suggestions to amend the guidelines and to test them in real situations (Gärdenfors *et al.*, 2001). A final version of the regional guidelines was adopted by IUCN in 2002 and published in 2003 (IUCN, 2003). Although the Saudi Wildlife Commission (SWC) recorded the Farasan Archipelago as a protected area in 1996 (Hall *et al.*, 2010), the conservation status of the more vulnerable species in the Farasan Archipelago coastal zone has had only a limited amount of attention compared to the Swedish coastline and Carrabin Islands (Wikström *et al.*, 2016, Maunder *et al.,* 2008). There has been no previous regional IUCN Red list published available on the Farasan Archipelago.

The Regional Red List assessments are important in order to monitor the status of the biodiversity of the taxa at a regional level, and this may theoretically prevent or delay species extinction globally (Rodríguez *et al*., 2011).

The increase in the public awareness of the human impact on biodiversity affects the realities of conservation planning and funding (Brooks *et al*., 2006). The aims of this research are: (1) to assess conservation status and to produce a red list of six exemplar species in the coastal area; (2) to provide an analysis and information on the status of those species, and on any trends and threats in order to inform and catalyse actions for biodiversity conservation; (3) to create a reference and baseline for a series of studies for the assessment of the other species in the critical habitat of the Farasan Islands.

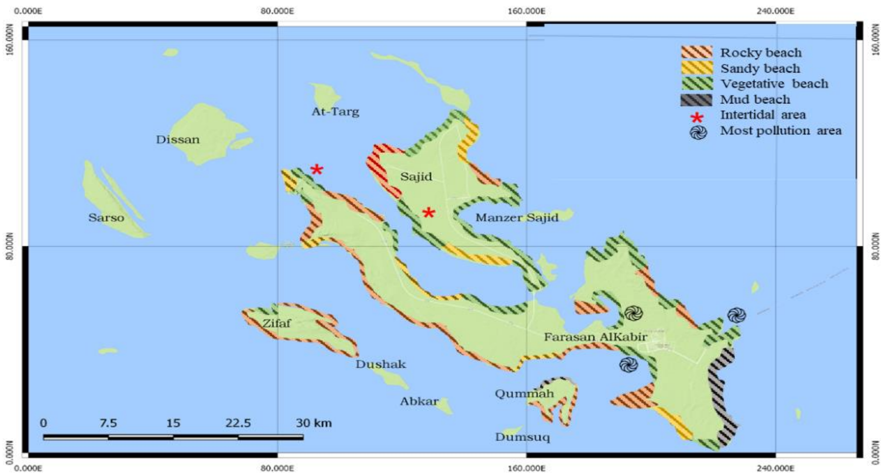

Figure 7.1. The vegetative beach in the Farasan archipelago, A spiral show the most pollution area along the coast zone and asterisks show the intertidal zone in the Farasan archipelago.

7.2 Material and methods

Six species, two species of mangroves and four species of the Zygophyllaceae, were selected following initial literature review. Names were updated following the Plant List (2013), and Integrated Taxonomic Information System ITIS (2018) (**Table 7.1**). A preliminary assessment including (habitat, ecology, population, uses and any threats of species), and mapping of the distribution range of the targeted species was conducted based on published records (Ezzat, 1971, Sayari *et al.*, 1984, Migahid, 1989, Alwelaie *et al.*, 1993, Mandura and Khafaji, 1993, Chaudhary, 1998, Collenette, 1999, Chaudhary *et al.*, 2000, Kathiresan and Bingham, 2001, Rahman *et al.*, 2002, Bailey *et al.*, 2007, Zhou *et al.*, 2010, Waly *et al.*, 2011, Batanouny and Bruckner *et al.*, 2012, Cooper and Zazzaro, 2014, Ghazanfar and Osborne, 2015, Alfarhan *et al.*, 2016, El-Amier *et al.*, 2016, Al-Hammad, 2016, Almalki *et al.*, 2017, Alzahrani and Albokhari, 2017, Alzahrani and Albokhari, 2018).

This was followed by additional data gathering from herbarium records. The locality was derived from specimen labels seen at Royal Botanic Garden, Kew (K) and Royal Botanic Garden Edinburgh (RBGE) herbaria. Label data were mapped using this georeferenced data in using ArcView GIS 10.6 (Bachman *et al.*, 2011).

Further data were gathered through a combination of interviews with local people and field trips in April 2015 and April 2016. After data was gathered, this study was followed IUCN criteria and categories (IUCN, 2001) and the regional IUCN guidelines (IUCN, 2003), to do the Red listing.

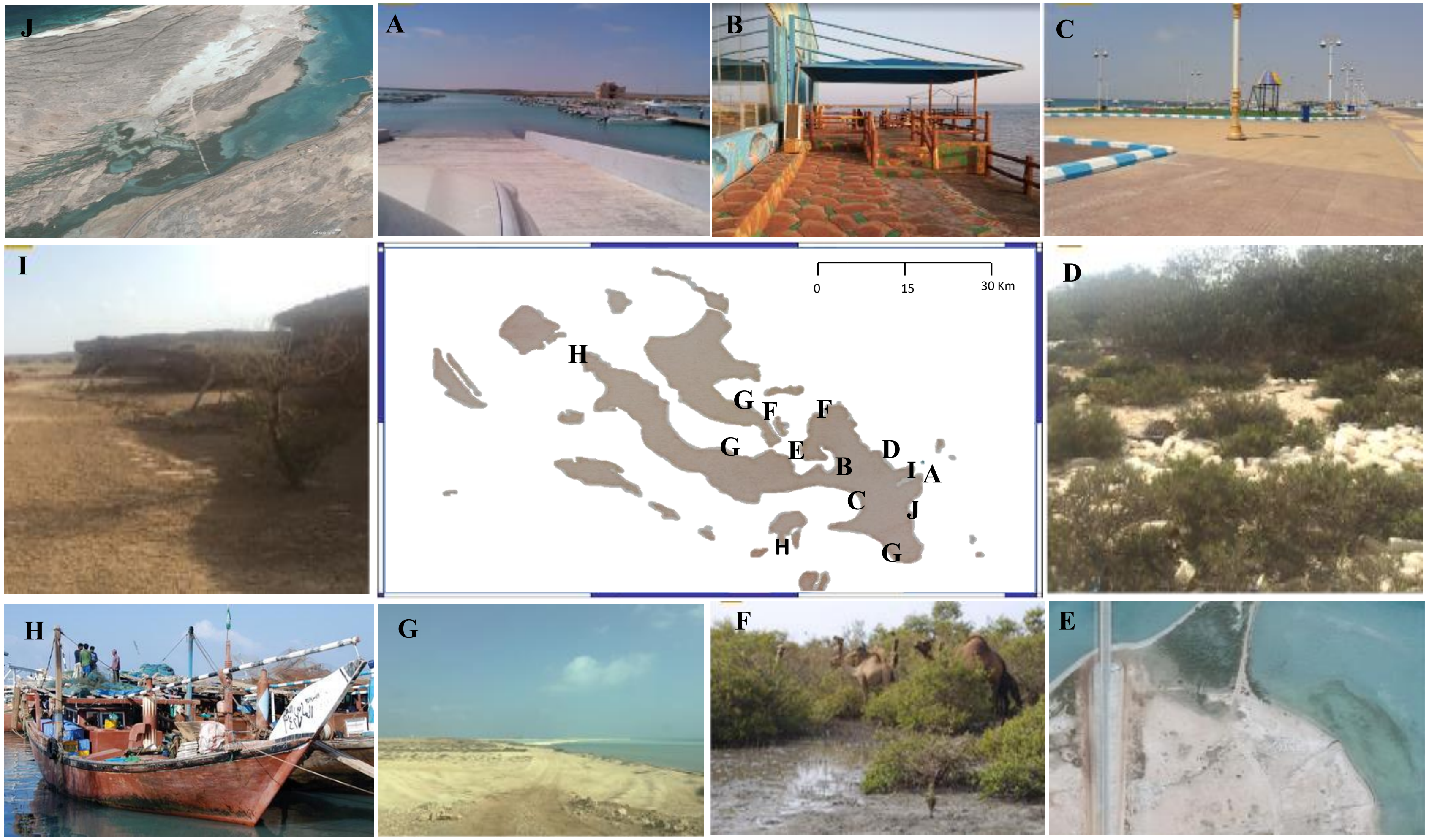

Figure 7.2. The Farasan archipelago map of the most threatened areas in the coastal zone. A. the Farasan Island port, B. Al Hasa resort (SWA), C. Jannabah beach gardens, D. waste disposal in *A. marina* area, E. Off-road around and within *A. marina* population behind Sajid Island Bridge, F. Camel grazing (SWA) within *A. marina* population in Farasan Alkabir Island, G. Off-road around along low-shoreline (mostly of *Tetraena* ssp. habitat). H. Small boats in a fishing area, I. *A. marina* population suffering of a high mortality rate in north of Farasan Alkabir Island, J. New road by the sand dividing the mangroves area into two areas, closing the water channels to the internal part.

The classification obtained from the IUCN assessment was adjusted based on the status of the species populations outside of the country **Appendix 7 (1,2,3).** Depending on whether the outside populations could pose a rescue effect on the risk of extinction of the national population, a downgrade, upgrade or no change was applied to the categories (IUCN, 2003).

The combined data from all three sources and any updates in distribution based on recent data were used in the IUCN Species Information Service (SIS) to provide updated distribution maps of the species created by with Arcview GIS software (Moat, 2007) and GeoCAT software (Bachman *et al*., 2011). The extent of occurrence was calculated by constructing the minimum convex polygon around known occurrences, and the area of occupancy was calculated by overlaying a grid of 2 × 2 km^2 and counting the occupied grid cells (IUCN, 2001).

There are no long-term climatological records of the Farasan Islands. The only available information is from Jizan, the nearest region of mainland to the study area (Tomas *et al*., 2010).

Table 7.1. Summarizes the changes in the nomenclature (updates, references, Family and the status of conservation assessment by IUCN Red list at global level).

Old species name	New species name	References	Family	Assessment at global level
***Avicennia marina* (Forssk.) Vierh.**	*Avicennia marina* (Forssk.) Vierh.	(Chaudhary, 2000)	Acanthaceae	Assessed in 2008
***Rhizophora mucronata* Lam.**	*Rhizophora mucronata* Lam.	(Chaudhary, 2000)	Rhizophoraceae	Assessed in 2008
***Zygophyllum simplex* L.**	*Tetraena simplex*(L) Beier and Thulin	(Norton *et al*., 2009, Alzahrani and Albokhari, 2018)	Zygophyllaceae	Has not yet been assessed
***Zygophyllum album* L.f.**	*Tetraena alba* var. *alba* (L.f.) Beier and Thulin	(Norton *et al*., 2009, Mosti *et al*., 2012, Sakkir *et al*., 2012, Alzahrani and Albokhari, 2017)	Zygophyllaceae	Has not yet been assessed
***Zygophyllum coccineum* L.**	*Tetraena coccinea* (L) Beier and Thulin	(Ghazanfar and Osborne, 2015, Alzahrani and Albokhari, 2018)	Zygophyllaceae	Has not yet been assessed
***Tetraena boulosii* (Hosny) M.Hall**	*Tetraena propinqua* ssp. *migahidii* (Decne.)Ghaz. &Osborne, comb.nov.	(Ghazanfar and Osborne, 2015, Alzahrani, 2017)	Zygophyllaceae	Has not yet been assessed

7.3 Results and Discussion

7.31. *Avicennia marina* (Forssk.) Vierh.

Status and Criteria: EN then down list to VU because the presence of populations outside the islands.

B1ab (i, ii, iii, v) +2ab (i, ii, iii, v)

Assessment date: 15-4-2017

Synonyms:

Avicennia alba Blume; *Avicennia alba* var. *latifolia* Moldenke; *Avicennia intermedia* Griff.; *Avicennia marina* var. *alba* (Blume) Bakh.; *Avicennia marina* f. *angustata* Moldenke; *Avicennia marina* var. *anomala*

Moldenke; *Avicennia marina* var. *intermedia* (Griff.) Bakh.; *Avicennia marina* f. *intermedia* (Griff.) Moldenke; *Avicennia marina* subsp. *marina*; *Avicennia marina* var. *marina*; *Avicennia mindanaensis* Elmer; *Avicennia officinalis* var. *alba* (Blume) C.B.Clarke; *Avicennia sphaerocarpa* Stapf ex Ridl.; *Avicennia spicata* Kuntze; *Avicennia tomentosa* var. *arabica* Walp.; *Sceura marina*

Forssk.; *Avicennia balanophora* Stapf & Moldenke ex Moldenke.

<u>Common Names</u>:

Grey Mangrove, White Mangrove, and Tivar.

<u>Local Names in the Farasan Islands:</u>

Qurm, Gurm and Shorah.

This species is not endemic to the Farasan Archpeligo. It spreads in the intertidal mudflats which have extremely limited wave action below the high watermark along the shores of the seas and oceans (Al-Hammad, 2016). It is distributed through the western Indian Ocean, including Madagascar and Mozambique, northwards to Egypt and Saudi Arabia where it occurs on the coast of the Red Sea (Alwateed, 2010).

In relation to the local distribution range, it can be found on the east coast of Farasan Alkabir (a large number occur in the port area), Sajid Island and on the sea cliffs of Zifaf Island (Alwelaie *et al*., 1993; Mandura and Khafaji, 1993). It is a shrub up to a medium-sized tree; at 2-5 m tall. It has an extensive underground root system with pneumatophores up to 9 cm long, sticking up out of the mud in dense stands spreading out from tree. The leaves are in opposite pairs, thick, leathery, shiny olive green above, with a margin that is entirely sharp or with a bluntly pointed tip, with the base narrowing and a short petiole around 5 mm long.

The flowers are creamy yellow, small, in dense round heads in leaf axils or terminally. The fruit is green, oval and seed developing on the tree, with the fruit usually splitting after falling. The seed is water-dispersed (Chaudhary, 2000).

The population trend in Zifaf and Sajid Islands is probably stable, because it has the ability to re-colonise disturbed sites when the environment becomes favourable again, due to its effective dispersal mechanism. However, in Farasan Alkabir Island, there has been a significant local degradation of coastal habitats associated with the growth of domestic tourism (Saifullah *et al*., 1989, Alwelaie *et al*., 1993, Saifullah, 1996, Gladstone, 2000, Gladstone *et al*., 2003, Gladstone, 2009, Kumar *et al*., 2010, Hariri *et al*., 2014). Currently this Island has the largest area of suitable habitat and largest populations of the species. These threats are due to habitat loss caused by urban and industrial development along the coast specifically near to the port of Farasan Alkabir where a large population has been subjected to massive human activities, such as the construction of the sea port, highway, mersa and a side road across the khor, leading to destruction on a massive scale (Mandura and Khafaji, 1993).

Infrastructure development related to transport such as roads and bridges has also caused damage. Many of the populations of *A. marina* on Sajid Island have been lost due to construction of a bridge connecting Farasan Alkabir and Sajid Island (Persga, 2004). There is evidence of mortality in a large number of *A. marina* on the other side of the port where engineering work has prevented water flow (Mandura and Khafaji, 1993). Many sand dams were created, which closed the water channels for several *A. marina* populations. Local people harvest this species for medicinal uses, such as treating skin diseases in folk medicine. This suggests that it possesses some natural antimicrobial, anti-bacteriophage and cytotoxic activities (Khafagi *et al*., 2003). The wood is often used for fuel (Mandura and Khafaji, 1993).

In two localities, Farasan Alkabir (Al Qandal area) and Zifaf Island, this species shares the same shore-line habitat with *Rhizophora mucronata* and they are seen growing side by side. Pollution from sewage has been recorded, especially in relation to the port area and over-fishing activities. Browsing and trampling by camels, gazelle and goats causes habitat degradation (Gladstone *et al*., 1999). These threats are ongoing and increasing, especially given the new plans for recreation on the islands (Hagan, 2006).

The category has been down listed from Endangered (EN) to Near Threatened (NT) at the regional level due to the presence of the populations of this species in neighbouring countries and islands. The extent of occurrence (EOO) is 380 km². The area of occupancy (AOO) is estimated to be 56 km² (possibly ranging from 40-60 km²). However, the probability of immigration from neighbouring locations is unknown.

7.3.2 *Rhizophora mucronata* Lam.

Status and Criteria: EN then down list to VU because the presence of populations outside the islands.
B1ab (i, ii, iii, v) +2ab (i, ii, iii, v)

Assessment date: 15-4-2017
Synonyms:
Mangium candelarium Rumphius; *Rhizophora candelaria* Wight & Arn; *Rhizophora longissima* Blanco; *Rhizophora macrorrhiza* Griff.; *Rhizophora longissima* Blanco; *Rhizophora mangle* Roxb. (non-L.); *Rhizophora mucronata* f. *reducta* Hochr.; *Rhizophora rugens* Ehrenb. ex. Schweinf.

Common Names:
Mangrove, Red Mangrove, Seebasboom and Asiatic Mangrove.

Local Name in the Farasan Islands:
Kendal.

A small to medium-sized tree starting from 2–5 m and growing up to 10 m tall, with strong apical dominance and distinctive aerial roots which are rough and reddish. The leaves are compact, simple, opposite, broadly elliptic to oblong-elliptic, leathery, hairless, glossy, dark green to yellowish green, crowded towards the end of branches and with smooth margins with a pointed apex. It has creamy white flowers, with a few arranged in the form of axillary heads. The fruit is single seeded and up to 70 mm long germinating while still on the tree (viviparous) (Chaudhary *et al.,* 2000). It is found in the intertidal zone between the land and sea of tropical and subtropical habitats (Zhou *et al.,* 2010). Globally, it occurs along the intertidal regions of tropical and sub-tropical coasts (Kathiresan and Bingham, 2001). It is not endemic to the Farasan Islands. In this archipelago, this species occurs in the Al-Qandal area, north east of Farasan Alkabir Island and Zifaf Island (Almalki *et al.,* 2017; Mandura *et al.,* 1987).
Habitat loss is due to erosion in the available habitats, urbanization and a side road put down by Saudi Wildlife Authority SWA and the Border Guards, as it is located at the edge of Farasan Al Kabir. This species has a more limited distribution than *A. marina,* this may be because it is at the edge of its natural climatic distribution (Mandura *et al.,* 1987). It is threatened by overgrazing and ecotourism (PEGA, 2012). The population trend is near-stable, with a limited distribution (Mandura *et al.,* 1987). Local people harvest this species for medicinal uses such as to treat angina, diabetes, diarrhoea, dysentery, hematuria and haemorrhage (Duke and Wain, 1981). The wood is also used for fuel and for building ships due to the high quality (Lézine *et al.,* 2002; Tengberg, 2005). The regional extent of occurrence (EOO) is 43 km². The area of occupancy (AOO) is estimated to be 16 km². The category has been down listed from Endangered (EN) to Near Threatened (NT) at the regional level, because of the presence of this species on neighbouring Islands.

7.3.3 *Tetraena simplex* (L) Beier and Thulin

Status and Criteria: VU then down list to NT because the presence of populations outside the islands.
B1ab (ii, iii, v) +2ab (ii, iii, v)

Assessment date: 15-4-2017
Synonyms:

Zygophyllum Simplex L., Mant. Pl. 68 (1767); *Zygophyllum portulacoides* Forssk. Fl. Egypt. arab.:88 (1775); *Fabago portulacifolius* Medik. *Zygophyllum dregeanum* C.Presl; *Zygophyllum microphyllum* Eckl. & Zeyh. *Zygophyllum obtusum* Vicary; *Zygophyllum portulacoides* Forks. *Zygophyllum simplex var. herniarioides* Chiov.

Common Names:
Brakkies, Brakspekbos, Brakspekbossie, Panspekbos, Rankspekbos, Volstruisdruiwe, Volstruis-slaai.

Local names in the Farasan Islands:
Harm, Om thoreyb, Hamd and Qarmal.

This species is not endemic to the Farasan Islands. It has a provincial distribution from the Mediterranean through to Central Asia, South Africa and Australia (Migahid, 1989, Boulos, 2005, Waly *et al.*, 2011). *Tetraena simplex* differs from other *Tetraena* species in some of its morphological characteristics. The species is an annual herb, and the leaves are simple and sessile. The colour of the flower is yellow, the staminal appendages are bipartite and the fruit shape is obovoid and 5-lobed (Chaudhary, 2000). It has been used traditionally to treat gout, asthma and inflammation (Kakrani *et al.*, 2011; Haroun and Abualghaith, 2015; Abdallah and Esmat, 2017). High soil salinity is probably the cause of the low species density in this area. Rain, inundation by the sea, and the depth of the water table plays a prominent role in regulating the community of this species (Aziz and Khan, 1996). The habitat is sandy and has degraded because of the sand removal for urbanization and the development of gardens (Gladstone, 2000). The dramatic loss of habitat leads to the fragmentation and isolation of *T. simplex*. Livestock overgrazing, escalating sand mining activities and the demand for sand by new development schemes can lead to the disappearance of some of the smaller beaches (PERSGA, 2004). The regional extent of occurrence (EOO) is 826 km². The area of occupancy (AOO) is estimated to be 555 km². This results in the categorisation of Near Threatened (NT), because of the presence of this species on neighbouring islands.

7.3.4 *Tetraena alba* var. *alba* (L.f.) Beier and Thulin

Status and Criteria: CR then down list to EN because the presence of populations outside the islands.
B1ab (ii,iii,v) + 2ab(ii,iii,v); C2a(i);D

Assessment date: 15-4-2017
Synonyms:
Zygophyllum album L.f.; *Zygophyllum album* var. *amblyocarpum* (Bak. fil. ex Oliv.) Hadidi; *Zygophyllum amblyocarpum* Bak. Fil. *Zygophyllum proliferum* Forsk.

Common Names:
Weißes Jochblatt (DE); White Bean-caper (EN)

Local names in the Farasan Islands:
Rotreyt, Qarmal, Harm.

The species is small shrub, perennial, and the stem is green or greenish grey. The leaves are fleshy, 2-foliolate cylindrical with acute apex. The colour of the flower is white, arranged in clusters. The fruit shape is obconical, 5-ridged at the upper end (Alzahrani and AlBokhari, 2018).
Worldwide, it is found in Egypt, Jordan, Tunisia, Palestine, Somalia, South Africa and Greece (Migahid, 1978, Chaudhary *et al.*, 2000). It is distributed in Saudi Arabia along the Red Sea coast (Collenette, 1999, Waly *et al.*, 2011, Alzahrani and Albokhari, 2018). It is distributed on three locations in the Farasan Archipelago; two in Farasan Alkabir and one area of Dumsuq Island. The habitat of this species is coastal and inland on saline sandy soils, sand dunes and plains and saline depressions (Rahman *et al.*, 2002). This

habitat is subject to loss, and consequent fragmentation resulting in the isolation of the remaining communities. These fragmented vegetation patches grow in high soil salinity on exposed shorelines, suffering heat and strong winds in open coastal areas (Elhalim *et al.*, 2016). Human factors have a further impact on the coastal habitat that leading to the area being unable to provide conditions that can ensure the continued viability of the species. This species has a very limited distribution. Medicinally, it is used for hypertension complications (Mnafgui *et al.*, 2012). It is used in traditional medicine as a remedy for rheumatism, gout, hypoglycaemia, and as anti-eczema treatment (Hmamouchi, 1999, Nasrine, 2011). The regional extent of occurrence (EOO) is 7 km². The area of occupancy (AOO) is estimated to be 7 km². It is critically endangered locally but possible migration in from neighbouring countries results in a threat category of endangered.

7.3.5 *Tetraena coccinea* (L) Beier and Thulin

Status and Criteria: VU then down list to NT because the presence of populations outside the islands.
B1ab (ii, iii, v) + 2ab (ii, iii, v)

Assessment date: 15-4-2017
Synonyms:
Zygophyllum berenicense (Muschl.) Hadidi; *Zygophyllum berenicense* Schweinf.; *Zygophyllum coccineum* L.; *Zygophyllum coccineum* var. *berenicense* Muschl.; *Zygophyllum desertorum* Forsk.; *Zygophyllum propinquum* Decne.; *Zygophyllum desertorum*; *Zygophyllum coccineum* var. *coccineum* L.

Local names in the Farasan Islands:
Harm, Rotreyt and Batbat.

The most widespread Tetraena species in Egypt and Saudi Arabia, occuring near to saline and sandy habitats (Batanouny and Ezzat, 1971, El-Amier *et al.*, 2016). The flowering time starts from October through to November (Chaudhary *et al.*, 2000). The species is small shrub, perennial, green. The leaves are fleshy with 2-foliolate cylindrical. The colour of the flower is white. The fruit shape is cylindrical (Alzahrani and AlBokhari, 2018). It is distributed across Farasan Al Kabir, Sajid, Qummah and Dumsuq. The populations of *T. coccinea* grow under severe, dry climatic conditions and are stable because they have a good tolerance for these harsh conditions (Hammad and Qari, 2010). However, sandy coastal archaeological sites are being lost to coastal developments and damage by vehicle traffic and road works (Gladstone, 2000). *Tetraena coccinea* has antimicrobial activity (Abdel-Ghaffar *et al.*, 2016) and it is used as a traditional medicine for diabetes, gout, hypertension and rheumatism (Middleditch and Amer, 2012). The regional extent of occurrence (EOO) is 783 km². The area of occupancy (AOO) is estimated to be 583 km². It is vulnerable locally but possible migration in from neighbouring countries results in a threat category of Near Threatened.

7.3.6 *Tetraena propinqua* ssp. *migahidii* (Decne.) Ghaz. & Osborne, comb. nov.

Status and Criteria: CR then down list to EN because the presence of populations outside the islands.
B1ab (ii,iii,v) + 2ab(ii,iii,v); C2a(i); D

Assessment date: 15-4-2017
Synonyms:
Zygophyllum boulosii A.I. Hosny; *Tetraena propinqua* (Decne.) Ghaz. & Osborne, comb. nov.; *Tetraena propinqua* (Decne.) Ghaz. and Osborne, ssp. *migahidii* (Hadidi ex Beier & Thulin).

Common Names:

Weißes Jochblatt (DE); White Bean-caper (EN)

<u>Local names in the Farasan Islands</u>:

Abu rokaiba (from a label on Rawi & Ilkas 16274), arid, harm (a generic name for several species of *Tetraena*).

Tetraena propinqua ssp. *migahidii* is not endemic to the Farasan Islands. This species has been found to be very difficult to separate from the collections identified as *Zygophyllum propinquum* and *Z. migahidii* hadidi. Hadidi (1977) notes that his new species, *Z. migahidii*, is closely related to *Z. propinquum*, but distinguished from them in having solitary flowers and fruits in the former, and flowers and fruits in clusters in the latter.

This distinction was not applicable to the collections that they were identified from, so they placed *Z. migahidii* under *T. propinquum*. (Ghazanfer, 2011).

The species is Small shrub, perennial, green. The leaves are fleshy with 2-foliolate with rounded apex. The flowers are white-creamy. The fruit is ovate-oblong to obconical, 5-angled at the upper end (Ghazanfar and Osborne, 2015, Alzahrani, 2017). It is distributed from Egypt (Sinai) eastwards through to Iraq and Pakistan (Chaudhary *et al.*, 2000). In the Farasan archipelago, it is distributed in the west of Farasan Alkabir Island only. It produces both flowers and fruits, mainly in April – June and Sept-Oct, and occasionally throughout the summer months of July and August (Alzahrani, 2017).

Many threates exists where *Tetraena propinqua* ssp. *migahidii* is located: continuous land reclamation projects, the construction of roads along the west coast, tourism development (El-Bana, 2006) and the discarding of fish offal, old nets, and oil drums. Improved access to the seashore through current construction projects could stimulate beach erosion, damage coastal environments and lead to the further loss of the beaches (Persga, 2004, El-Wahab, 2016) so destroying the habitat of this species.

The regional extent of occurrence (EOO) is 6 km². The area of occupancy (AOO) is estimated to be 9 km². It is critically endangered locally but possible migration in from neighbouring countries results in a threat category of endangered.

Of the five species of Zygophyllaceae in the Farasan Archipelago, four were distributed in the coastal zone, and assessed using the IUCN Red List criteria. The fifth species of Zygophyllaceae was excluded from the assessment, due to being widely distributed over the islands and with its habitat not being degraded.

Although the Farasan Archipelago is an important plant area for conservation, no previous regional assessments of biodiversity in the Archipelago have taken place. The principal threats are similar across the six species **Figure 7.3**, namely habitat loss, degradation and fragmentation (Gladstone, 2000, Hall *et al.*, 2010). All coastal habitats are under similar threat due to development. These results provide further evidence of immediate threat to coastal plant species in general on the Farasan Archipelago. This study is the first initiative toward the protection of the threatened species in the Farasan Archipelago, using to the IUCN criteria and categories.

In our study of the Red Listing of the targeted species in the coastal area of the Farasan Islands **Table 7.3**, the assessments did not use criterion A or E for any of the species assessed. This was because the first two requirements could not be met (the generation length and population reduction rate in the past, present and future). This is because of the lack of quantitative data and the population trend rates. Criterion B was the most commonly used because of the data availability, namely the distribution range points (collected from herbarium labels, databases, and locality visits) and the number of locations for each of the species. We used criteria C and D for some species, for which there was a very restricted distribution, small

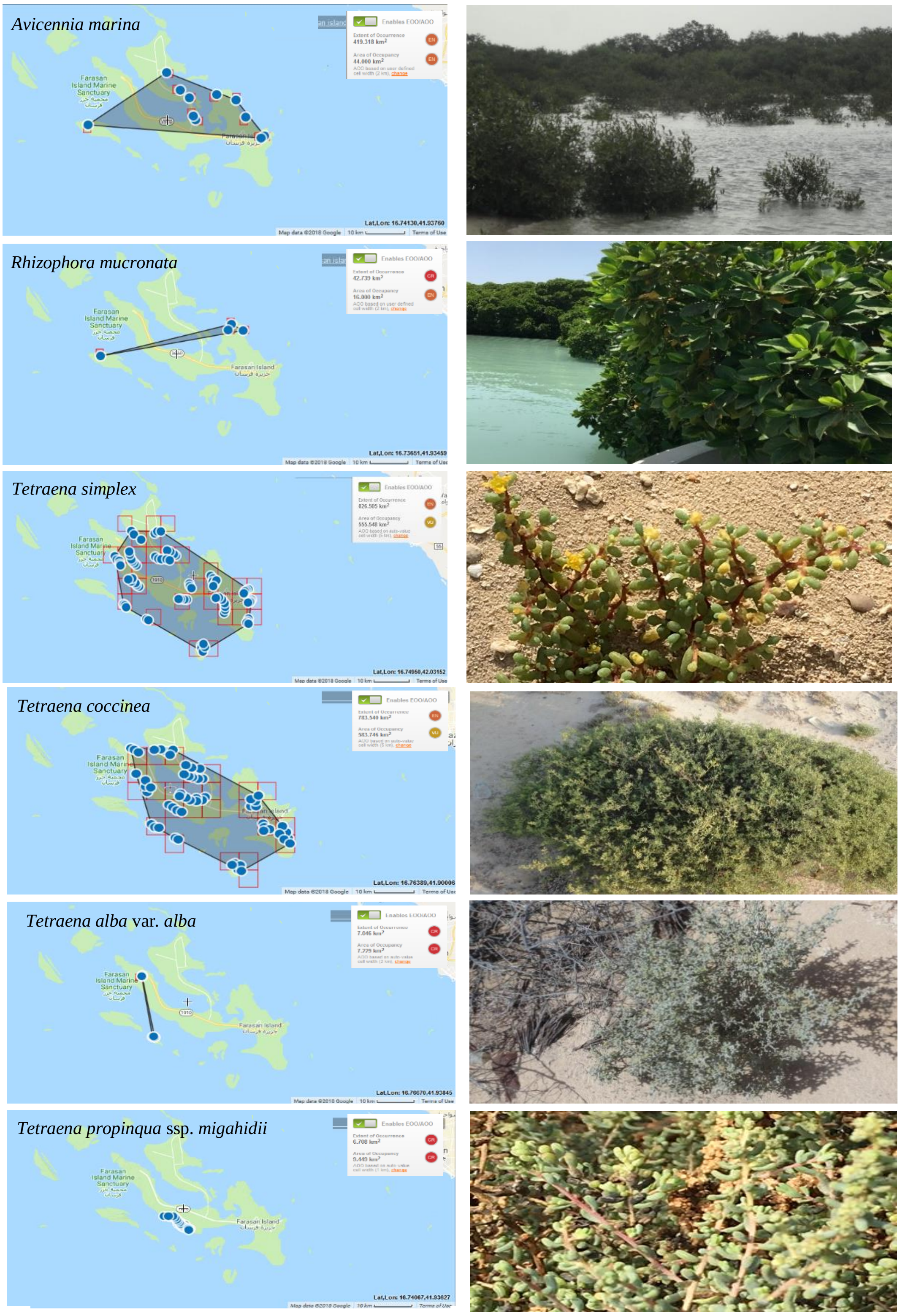

Figure 7.3. Geographical distribution of the six threatened species in the coastal zone of the Farasan Archipelago.

Table 7.2 Red listing status of the six taxa including the Taxon name and the distribution of species in the Farasan archipelago: Farasan Alkabir (1), Sajid (2), Zifaf (3), Dawshak (4) and Qummah (5). Endemic status, National category and criteria and its global category was also noted.

Species	**Distribution In the Farasan Islands**	**Endemic**	**National IUCN category**	**IUCN criteria**	**International Category**
Avicennia marina	1,2,3	No	VU	B1ab(i,ii,iii,v)+2ab(i,ii,iii,v)	LC
Rhizophora mucronata	1,3	No	VU	B1ab(i,ii,iii,v)+2ab(i,ii,iii,v)	LC
Tetraena simplex	1,2,3	No	NT	B1ab(ii,iii,v)+2ab(ii,iii,v)	NE
Tetraena alba* var. *alba	1,4	No	EN	B1ab(ii,iii,v)+2ab(ii,iii,v);C2a(i);D	NE
Tetraena coccinea	1,2,3,4,5	No	NT	B1ab(ii,iii,v)+2ab(ii,iii,v)	NE
Tetraena propinqua* ssp. *migahidii	1	No	EN	B1ab(ii,iii,v)+2ab(ii,iii,v);C2a(i);D	NE

population size and a small number of mature individuals and for which the percentage of mature individuals in each subpopulation was known.

Several limitations and issues may impact the Red list process, such as taxonomic uncertainly, the shortfall in threat knowledge for a given taxon, restricted availability of relevant data and the lack of regular population trend data. However, in our case, taxonomic dynamism does not present a problem to the Red listing process because this study carried out intensive reviews of the Farasan archipelago flora, including the vulnerable six species. In addition, field surveys and collaborating with stakeholders (local people, herbalists, local and visiting foreign botanists) has supported the accurate conservation assessment and IUCN rating.

7.4 Conclusion

These six assessments illustrate the extinction risk for the coastal flora of the Farasan Archipelago. The IUCN list reports two endangered species, two near threatened species and two of least concern at the regional level. *Tetraena propinqua* ssp. *migahidii* and *Tetraena alba* var. *alba* are the most threatened with a low density. The categories for the whole species was upgraded by one level, because these species not endemic to the islands, which is inconstant with Rodríguez *et al.* (2011) and their modified Regional Red List assessments. The widespread changes in the coastal area, whether intentionally or not, especially of the beach vegetation, have prompted great concern about the conservation of the local biodiversity, which may suffer a decline due to the growth of international and domestic tourism, which is one of the most promising parts of the kingdom's diversification efforts with its Vision 2030 plans. The targeted species in the critical coastal habitats are suffering from urbanization, increasing infrastructure development, and pollution that are the most threatening factors. Therefore, the conservation of the species in the most important habitats in the islands (coastal zone) is required, because they are more vulnerable to natural and unnatural pressure and it is important to raise awareness, education and to increase the eco-tourism to reduce threats to the Archipelago coast.

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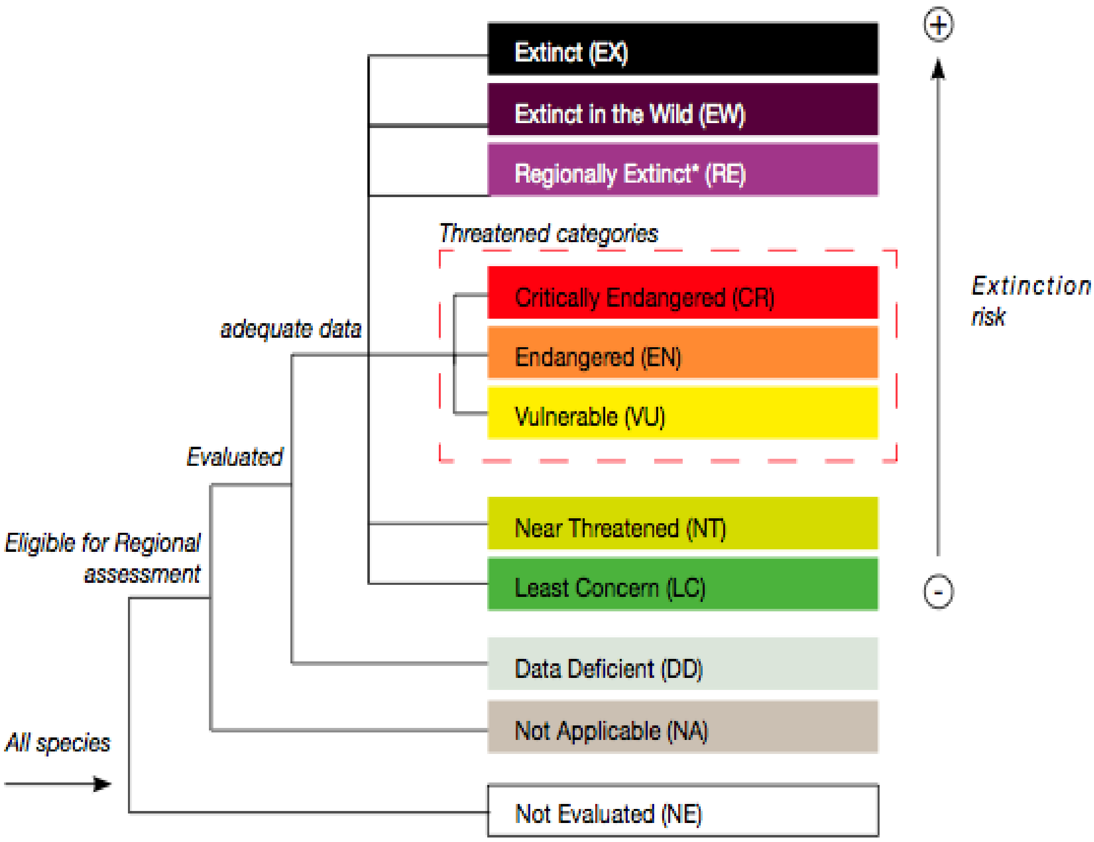
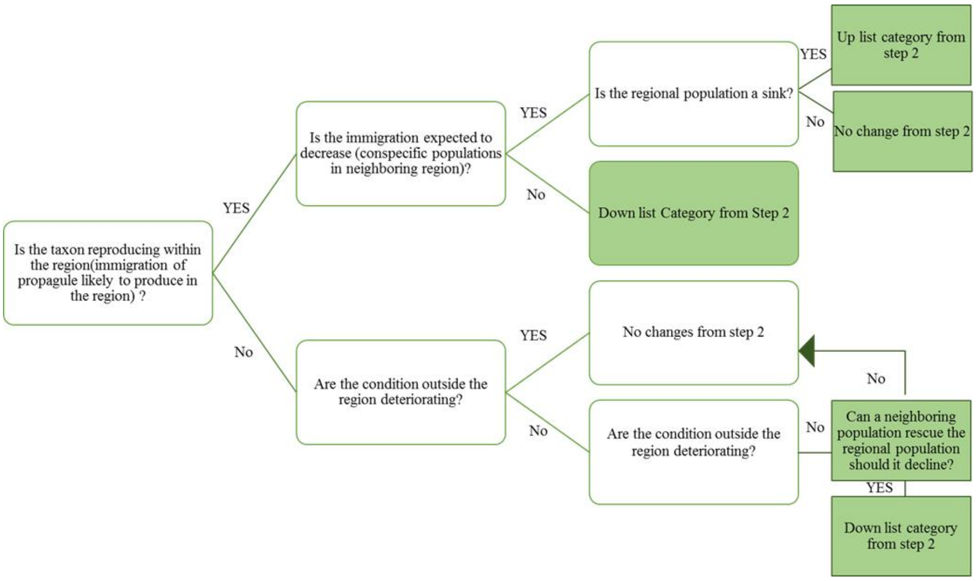
Appendix 7:

1. Structure of the IUCN categories at the regional level (adapted from IUCN 2003).



2. . Proposed conceptual scheme for adapting the preliminary IUCN Red list category to the regional level.



3. The IUCN Relisting criteria for assessing the extinction risk of species at the regional level.

A. Population size reduction. Population reduction (measured over the longer of 10 years or 3 generations) based on any of A1 to A4

	Critically Endangered	Endangered	Vulnerable
A1	≥ 90%	≥ 70%	≥ 50%
A2, A3 & A4	≥ 80%	≥ 50%	≥ 30%

A1 Population reduction observed, estimated, inferred, or suspected in the past where the causes of the reduction are clearly reversible AND understood AND have ceased.

A2 Population reduction observed, estimated, inferred, or suspected in the past where the causes of reduction may not have ceased OR may not be understood OR may not be reversible.

A3 Population reduction projected, inferred or suspected to be met in the future (up to a maximum of 100 years) *[(a) cannot be used for A3]*.

A4 An observed, estimated, inferred, projected or suspected population reduction where the time period must include both the past and the future (up to a max. of 100 years in future), and where the causes of reduction may not have ceased OR may not be understood OR may not be reversible.

based on any of the following:

(a) direct observation *[except A3]*

(b) an index of abundance appropriate to the taxon

(c) a decline in area of occupancy (AOO), extent of occurrence (EOO) and/or habitat quality

(d) actual or potential levels of exploitation

(e) effects of introduced taxa, hybridization, pathogens, pollutants, competitors or parasites.

B. Geographic range in the form of either B1 (extent of occurrence) AND/OR B2 (area of occupancy)

	Critically Endangered	Endangered	Vulnerable
B1. Extent of occurrence (EOO)	< 100 km^2	< 5,000 km^2	< 20,000 km^2
B2. Area of occupancy (AOO)	< 10 km^2	< 500 km^2	< 2,000 km^2
AND at least 2 of the following 3 conditions:			
(a) Severely fragmented **OR** Number of locations	= 1	≤ 5	≤ 10

(b) Continuing decline observed, estimated, inferred or projected in any of: **(i)** extent of occurrence; **(ii)** area of occupancy; **(iii)** area, extent and/or quality of habitat; **(iv)** number of locations or subpopulations; **(v)** number of mature individuals

(c) Extreme fluctuations in any of: **(i)** extent of occurrence; **(ii)** area of occupancy; **(iii)** number of locations or subpopulations; **(iv)** number of mature individuals

C. Small population size and decline

	Critically Endangered	Endangered	Vulnerable
Number of mature individuals	< 250	< 2,500	< 10,000
AND at least one of C1 or C2			
C1. An observed, estimated or projected continuing decline of at least (up to a max. of 100 years in future):	25% in 3 years or 1 generation (whichever is longer)	20% in 5 years or 2 generations (whichever is longer)	10% in 10 years or 3 generations (whichever is longer)
C2. An observed, estimated, projected or inferred continuing decline AND at least 1 of the following 3 conditions:			
(a) **(i)** Number of mature individuals in each subpopulation	≤ 50	≤ 250	≤ 1,000
(ii) % of mature individuals in one subpopulation =	90–100%	95–100%	100%
(b) Extreme fluctuations in the number of mature individuals			

D. Very small or restricted population

	Critically Endangered	Endangered	Vulnerable
D. Number of mature individuals	< 50	< 250	**D1.** < 1,000
D2. *Only applies to the VU category* Restricted area of occupancy or number of locations with a plausible future threat that could drive the taxon to CR or EX in a very short time.	-	-	**D2.** typically: AOO < 20 km^2 or number of locations ≤ 5

E. Quantitative Analysis

	Critically Endangered	Endangered	Vulnerable
Indicating the probability of extinction in the wild to be:	≥ 50% in 10 years or 3 generations, whichever is longer (100 years max.)	≥ 20% in 20 years or 5 generations, whichever is longer (100 years max.)	≥ 10% in 100 years

CHAPTER 8

General discussion

Chapter 8
General discussion and conclusion

8.1 General discussion

This is the first time that a complete infrastructure has been presented that spans field biology, an e-flora, multi-access keys, population genetics and conservation assessment spanning a complete flora. Such systems are ultimately a key part of the achievement of the GSPC targets, particularly Targets 1, 2, 5 & 8.

Current floras are the product of centuries of development in the way plants are recorded in geographic areas. They are usually published in printed form as books or book series but there is a growing tendency to make those floras available online as portable documents (pdf.) or as more sophisticated online systems. Identification keys started use at least 320 years ago (Waller 1689) in printed floras (Griffing, 2011, Brach and Song, 2005) and have been widely used since then. They present some difficulties for identification of species such as following leads in keys over several pages which can create a barrier to identification, particularly in large families with 50 species and more (Brach and Song, 2006). Such keys often lack illustrations (Scharf, 2009), however, these are an essential part of the identification process (Kur, 2018). Published volumes of paper-based floras have provided good reference material on the flora for many countries; however, these copies have been restricted in circulation, mainly due to price.

Today, through advances in digital technology, with the pressing issues of world plant-species conservation, online floras can provide the tools to revolutionize education and research (such as cataloguing and plant species identification). Botanists are able to provide regional floras to users worldwide and update them regularly as the taxonomies of the groups are studied (Brach and Song, 2006). Several current major flora projects are available online, such as the Flora of Australia https://profiles.ala.org.au/opus/foa , Flora of Nepal http://www.floraofnepal.org/, and Flora of Gibraltar http://floraofgibraltar.myspecies.info/. These online floras are a primary data-source for the comprehensive guide of their country flora. E-floras are designed to provide open and up-to-date access to all local flora information that generated to reach the first target of the 2020 Global Strategy for Plant Conservation (GSPC), which is to produce an online flora database for all known plants (Jackson and Miller, 2015, Martellos and Nimis, 2015). In addition to the latest research data, such as images and collection details for representative herbarium specimens, many other forms of supplemental scholarly content can be linked to each plant species and identification tools. Automated species identification is a technique of great potential value to biological recorders. That can help for current and rapid identification of plant species, which includes photographic images, illustration, video and/ or audio recordings (Burkmar *et al.*, 2014).

There are many web-based identification keys such as Delta intkey (Dallwitz, 1980, Dallwitz, 1996), ActKey (Brach and Song, 2005) and Lucid key http://www.lucidcentral.com/. These keys present a simple alternative to lengthy, indented keys. Lucid key is a widely-used web resource where digital photographs can be posted and identified by a very broad community of users and readily available characteristics to identify a specimen.

In this thesis the Farasan Archipelago flora is used as an exemplar for regional e-flora construction. The islands have a small total land area and harsh environment and are considered as an important plant area for conservation in Saudi Arabia (Hall *et al.*, 2010). Coupled with this, the increase in the local human and tourist activities is endangering the Farasan Archipelago's plants making research and policy development both timely and urgent. Since 1993 many revisions, checklists and vegetation notes have been recorded (Alwelaie *et al.*, 1993, Alfarhan *et al.*, 2001, Rahman *et al.*, 2002, Hall *et al.*, 2010). However, records are already out of date due to the major changes in land use and human occupancy. This research presents the first modern single comprehensive electronic resource for the plant species in the Farasan Archipelago with reference images, multi-access online key and their geographical distribution, and is based on Scratchpad software http://ffa.myspecies.info/. The result of this research will help the assessment of biodiversity for conservation and deliver an accessible flora to a wider audience, free and in a medium that can be easily updated. The availability of necessary information online helped to compile the data on the plant families rather than generating them afresh. This is comparable to the approach in the E-flora of South Africa project, the knowledge sharing of the treatment of many species in the subtropical province can be derived from the treatments of the bordering Eastern Cape, Free State, and Northern Provinces (Crouch *et al.*, 2013). It will also help to conserve regional biodiversity for sustainable utilization, as target 15 of the new Vision of Saudi Arabia 2030, which includes ‘to protect, restore and promote the sustainable use of terrestrial ecosystems, to halt and reverse land degradation and to halt biodiversity loss’, according to the 1st Voluntary National Review, Kingdom of Saudi Arabia (2018).

At present, the world is losing species at a level comparable with the mass extinctions signifying the major transitions of geological time periods (Butchart *et al.*, 2010) but at a far greater rate. Worldwide, 60% of threatened plant species should be included in active conservation programmes. That is linked to target eight of GSPC which has a focus on underpinning the conservation of threatened plant species. The priority should be given to those species that are in immediate danger of extinction, either locally, nationally or globally and species that are local economic importance, such as minor food crops, medicinal plants and wild or cultivated plants providing the basis of local industries, agriculture, horticulture, and crafts. The emergence of genetic tools particularly population genetics in traditional and applied biological science have brought important theoretical and practical insights within the fields of conservation biology (Allendorf and Luikart, 2009). Genetic population studies are important to identify priority areas for conservation of genetic resources (Gardiner *et al.*, 2017). In general, genetic diversity within and between plant-populations can vary. This may be a result of propagule pressure and post-introduction evolutionary processes like inbreeding, drift and hybridization (Nuñez *et al.*, 2011, Lee, 2002, Prentis *et al.*, 2008). Island populations are much more disposed to extinction than mainland populations (Frankham, 1997, Hufford *et al.*, 2014), although this is not always the case.

Mangroves are an ecologically and economically important group of plants, worldwide (Basyuni *et al.*, 2017, Nehemia and Kochzius, 2017, Salas-Leiva *et al.*, 2008) and therefore make a good model to study conservation needs on the Farasan Archipelago. Many studies have been used previously to assess the genetic diversity in mangroves particularly in the Indo West Pacific region (Ng *et al.*, 2013, Yan *et al.*, 2016), and they reflect the low genetic variation and a deficiency of heterozygotes in these populations. This is because the mangrove species have buoyant water-borne propagules, their dispersal can be constrained by many factors, such as repeated extinction-colonisation events induced by Pleistocene sea-level fluctuations (Ge and Sun, 2001, Nettel and Dodd, 2007, Yang *et al.*, 2017, Guo *et al.*, 2018), the sea current direction and the geomorphological line of coast (Wee *et al.*, 2014, de Ryick, 2016). Such limitations usually confine a species to a particular region, depending on its dispersive range and on its ability to become established in a new location (Pil *et al.*, 2011).

The presence of mangroves in the Protected Area of the Farasan Archipelago is no guarantee of their conservation. The focus is on specific groups of animals rather than the whole diversity of that area. Increasing local population growth, tourism and anthropogenic activity have a serious impact on mangrove ecosystem services and functions in the Archipelago. The continued survival of the target species is not ensured. This makes mangroves a good test case to study the population level variation, and the implications for conservation. The previously published microsatellites designed for the two species of mangroves, *Avicennia marina* and *Rhizophora mucronata,* were successfully applied in this study. The Farasan Archipelago populations had low genetic variation and the discrete subpopulations model fits the pattern of diversity, as seen in other comparable systems. The result highlights the importance of available data sources which can be used to aid in decision making regarding biodiversity conservation and spatial planning. This is likely to be of interest to conservation strategies for archipelagos worldwide as it demonstrates the value of small and separate areas in order to encompass the different genetic patterns found between the islands within the archipelago.

Molecular methods such as microsatellites SSRs and sequencing region (cpDNA and nDNA) are useful for genetic variation studies in mangrove species so far. Both these molecular methods used for germplasm conservation purposes (Huang *et al.*, 2008, Inomata *et al.*, 2009). However, SSRs still the most used because they have a series of characteristics that make them ideal to analyse plant genomes. They are single locus co-dominant markers, automatable, reproducible, easily multiplexed, and usually show a high level of polymorphism and several alleles can be detected for a single SSR locus (Powell *et al.*, 1996). In other hand, SSRs have an important limitation compared with sequences region is that their data cannot be historically ordered (Avise, 2004). That mean it provides information on population histories ((Urashi *et al.*, 2013, Zhou *et al.*, 2011). That conclude to recommend for using sequence region with SSRs in plant conservation genetics interested in gene flow (Guo *et al.*, 2011, Zhou *et al.*, 2005). and phylogenetic histories reconstruction.

Population-level studies such as these often conclude with recommendations for the future conservation of their study species and similar species, highlighting the need for in situ protection of sites, the collection of seeds and plants for *ex situ* seedbanks, and the cultivation of species in botanic gardens and field gene banks. However, it is widely recognised that *ex-situ* conservation is a route of last resort.

In order to prioritise conservation action effectively it is essential to assess the conservation status facing each species such as the threat of extinction (Le Breton *et al.*, 2019). In recent times, human activities have been the main cause of contemporary species extinctions (Pimm *et al.*, 2014). Many studies have made considerable advances in studying the actual processes of extinction in individual species, notably using the IUCN Red List Programme. Given the difficulties of approaching species conservation at a global scale most efforts are being made at regional level. Many regional IUCN listings of plant species have been produced such as those for Sweden, Italy and Southern Africa (Gärdenfors *et al.*, 2001, Foggi *et al.*, 2015, Golding, 2004). These regional red lists contribute to achieving target 2 of GSPC which is declared the necessity to enhance the knowledge about the conservation status of the national flora in order to set up an effective conservation strategy by 2020. Worldwide, geographic range is important to the listing of approximately half of the species on the IUCN Red List (Gaston and Fuller 2009). Extinction risk is increased in species with small range sizes because there is a greater likelihood that all populations can be affected by a single threat. In this study, IUCN Criterion B also was the most frequently used criterion for listing the Farasan Archipelago plants as threatened.

Despite accumulating data gained through a series of reports showing the importance of the biodiversity of the Farasan Archipelago (Hall *et al.*, 2010, Ali *et al.*, 2018), the Saudi wildlife authority and stockholders have made no significant progress in terms of conservation policies. Particularly, concerning the global strategy for plant conservation GSPC, and achieving the targets of GSPC itself. As confirmed by this research, threats were found in the coast zone plant species of the Archipelago. The intention in this work was to highlight the utility of rapid assessments and precautionary approaches in conservation prioritisation. The data collected in this project represent a very important conservation data source, as a first step towards a Red List of the whole Farasan Archipelago flora including a georeferenced data-set equipped with distribution and trend information. However, to make the database an effective tool for conservation, it is necessary to frequently update it with a continuous flow of information from experts.

Conservation measures of non-endemic species at regional level should be improved, both inside and outside the region. Developing regional Red Lists for threatened species will provide a comprehensive overview of their extinction risk and distributions at a global level and will contribute to guiding policy decisions and conservation actions.

8.2 Conclusion

The challenge for plant conservation of any region is to act on the knowledge of the regional flora and field knowledge to create long-term, sustainable approaches to reversing the status of all threatened diversity in that region. This is the first study on regional flora that includes such a wide range of approaches including infrastructural ones such as the online checklist, a single, comprehensive, electronic documentation source for the plants with well-detailed species description, images, geographical distribution and online multi-access keys. This digital technology combined with IUCN Red Listing and genetic diversity approaches, especially of the most economically and environmentally important species has confirmed that the Farasan Archipelago flora is high in plant diversity for a small land area (<600km²). The flora can now be updated in real time at regular intervals and is easy to share with worldwide bio resource communities. The combining of IUCN Red Listing and a genetic diversity illustrate that even some of the most environmentally sensitive areas for the island are prone to large scale destruction. This represents an opportunity to develop a framework for dialogue among stakeholders and to share successful examples of plant conservation initiatives with local communities.

For the future, these approaches together can work as an indicator allow botanists to make their decisions for effective conservation. A new project working on digitalization of the entire flora of Saudi Arabia is now in progress to be funded by the Ministry of Environment Water & Agriculture. This should provide the long-term mechanism for floristic reporting and conservation planning.

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