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The endemic vascular plant species of Egypt: distribution patterns and implications for conservation

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General introduction

Biodiversity loss is the most serious human-caused environmental problem that is threatening human well-being (Ceballos et al. 2015). Extinction of biodiversity is a central part of our planet's past, present and future. Current understanding of ongoing extinction comes primarily from projections or assessments of extinction risk. Plants are universally recognized as a vital component of biodiversity and global sustainability (Hobohm 2014). For instance, plants provide food, fibre, fuel, shelter, medicine. Healthy ecosystems, based on plant diversity, provide the conditions and processes that sustain life and are essential to the well-being and livelihoods of all humankind. In this sense, endemic plants are not only entities in nature conservation, scientific or political efforts but also can be used regionally as ornamental, medicinal plants and further economic values (Latheef et al. 2008). Plant extinctions endanger other organisms, ecosystems and human well-being, and must be understood for effective conservation planning. In particular, extinction of seed plants is occurring at a faster rate than the normal turnover of species. Nearly 2.3 species have become extinct each year for the past 2.5 centuries (Humphreys et al. 2019). However, most species have not been known for 250 years, recently described species may have higher extinction rates than those described earlier and species may become extinct before being formally described (Pimm et al. 2014). The vulnerability of species to extinction is phylogenetically non-random, with some taxonomic groups and regions being more vulnerable to extinction than others (Cardillo & Meijaard 2012, Dirzo et al. 2014). Accordingly, identifying the main driver of biodiversity loss and also the most threatened species are the key questions at the forefront of conservation policy.

A growing body of evidence indicates that both climate change and habitat fragmentation are the major drivers of biodiversity loss and species extinction (Bellard et al. 2014), further accelerating the rate of extinction in the next decades (Durant et al. 2014). Previous studies reported that intrinsic factors (e.g. species traits and life-history) influence species response to climate change (Bellard et al. 2014). For example, endemic species are often more vulnerable to climate change than other species, due to their limited ability to track new suitable conditions and, as a consequence, they are more likely to become extinct (Bellard et al. 2014). Thus, conservation actions should be directed toward regions with high levels of endemism and species with high vulnerability to the climate change in future (Mittermeier et al. 2011). Therefore, assessing the impacts of different environmental factors and future climate change on biodiversity patterns is crucial to determine the most threatened species and vulnerable regions, which would allow for prioritising conservation efforts.

Similar to most of the arid countries, the natural vegetation of Egypt is facing two categories of threats; the first includes the natural processes as drought, floods, storms, diseases, natural enemies (rodents and insects) and invasion of exotic species (Moustafa et al. 1999). Though drought itself has effects on vegetation in arid to extremely arid ecosystems, it also exacerbating any other threat, especially human-induced ones. The second category includes the man-mediated threats which are recorded all over Egypt like over-collecting, over-cutting for fuel, over-grazing, urbanization (construction of new settlements, highways, infrastructure, water and gas pipelines, and digging new wells), quarries, power station, mining, rock crusher machines, cement factories, industrialization, air pollution, solid wastes and military activities (Moustafa et al. 1999). All of these threats result in change in habitat conditions with a subsequent alteration in vegetation structure besides pushing endemic species to the brink of extinction or disappearance from their natural habitats (Salama et al. 2012).

The term endemism is used in biogeography to refer to taxa that have small ranges or restricted to a particular geographic region or habitat type (Anderson 1994). Endemism is a function of the spatial scale used to describe the restriction of certain taxa to a definite sized area (Laffan & Crisp 2003). The majority of endemic taxa are included in the Red Data List as they are potentially threatened due to their narrow and unique distribution ranges and habitat specificity (Crisp et al. 2001). Accordingly, the increased interest of endemic-rich regions can be based on their conservation importance. Today endemism and endemic species are part of an uncountable number of scientific publications, national and international laws and conventions and internet sites (e.g. www.iucn.org) that use these terms for characterizing plants and animals, which are restricted to a small area and often threatened (Hobohm 2014). From a conservation point of view, endemic taxa may be intrinsically threatened (Işik 2011) and are therefore highly important in the global, national and regional prioritization of conservation efforts (Huang et al. 2016). Several international initiatives are in place to reduce the loss of biodiversity, nevertheless, a national approach to biodiversity protection is the most effective way for a country to protect its endemic flora (Pimm et al. 2001). Thus, endemic taxa are key elements for setting national conservation priorities and for assigning conservation tasks. In general, the higher the number of taxa endemic to a country, the greater the responsibility of that country in preserving global biodiversity. However, the high number of endemic species may require a prioritization of conservation efforts (Orsenigo et al. 2018).

In order to face biodiversity loss, particularly endemic or threatened species, it is urgent to recognize the biogeographical units and endemic species-rich areas in order to maximize the number of conserved species. And also to enhance the knowledge on potential distribution of these target species at different time points and space, and verify recent nomenclatures to help in updating vascular plants checklists.

The determination of biogeographic regions is particularly interesting when the influence of drivers of different nature is also investigated. From a conservational point of view, studies on factors related to areas with an exceptional concentration of endemic and threatened species are particularly relevant. In general, the main objective of biogeography is to categorize and mapping the biota into meaningful and interpretable hierarchical geographical units (Ficetola et al. 2017; Morrone 2018). These units have been created by present and past biological and physical forces, and will help to better understand the drivers responsible for the spatial distribution of species. The so-called biogeographical regionalization results in a hierarchical system that plays to generate geographical units in terms of their biota, in particular endemic taxa (Kreft & Jetz 2010). A regionalization is an effective approach, not limited to the reduction of ecological data complexity (Kupfer et al. 2012) but also can be used to identify biodiversity areas and its relevance with ecological and evolutionary processes. Biogeographical regionalization is also a powerful tool that can be used to understand the spatial pattern of biodiversity and explore the key elements influencing the historical distribution of species in addition to its role in knowing the conservation strategies beyond, being an applicable implementation method for maximizing the number of conserved species (Gao & Kupfer 2018; Graham & Hijmans 2006; Violle et al. 2015). Further, it is difficult to identify areas that should be protected without systematic mapping over large areas, such as multiple bioregions, climatic zones or political boundaries (Pressey et al. 2000). According to growing evidence that global changes and habitat fragmentation are producing unprecedented historical changes in species distributions, the study of regionalization patterns has also great potential for monitoring decreases in beta-diversity and homogenization of biotas (Dapporto et al. 2016). In this context, plants, and in particular endemic plants, are crucial in making a comprehensive judgment of the environment. Indeed, plants represent a key approach for biodiversity conservation and have been increasingly used as crucial units for inventory, planning and monitoring as they are good indicators of overall biodiversity and they are able to provide information about underlying abiotic components (Damschen et al. 2012). In particular, endemic plant species have a crucial role on conservation studies since they are frequently threatened and usually better studied than the complete floras and because endemism- rich areas are also likely to be of conservation interest for other biological groups (Laffan and Crisp 2003).

On the other hand, Species Distribution Models (SDMs) are one of the tools that proposed with increasing frequency throughout ecology and conservation biology. The advent of Species Distribution Models (SDMs) allows identifying species' distributions by quantifying the relationship between known species occurrences and their associated environmental conditions (Guisan & Zimmermann 2000). SDMs are powerful tools with a good performance especially in case of incomplete knowledge (e.g. under or unequally sampled species and regions) (Elith & Leathwick 2009). However, SDMs can be inefficient tools and produce unrealistic outputs if the characteristics of the species' occurrence data (quality, spatial precision error, and the number of occurrences) and the ecology of the species are not considered during the modelling process. Prior consideration of these factors allows for developing more reliable and accurate SDMs, that can be used for biodiversity assessment, current and potential distribution of endemic species and identifying biodiversity hotspot areas, and prioritising conservation efforts.

1. Study area

Egypt is located in the northwestern corner of Africa but also linked to Asia through the Sinai Peninsula as well as to Europe through the Mediterranean coast. It extends from the south at the Sudanian border to the north at the Mediterranean Sea, and from the east at the Red Sea to the west at the Libyan border with a total area of ca. one million km^2 representing ca. 3% of Africa’s total area (Zahran & Willis 2009). Egypt is situated in the south east of the Mediterranean Sea; its coast includes the delta of the Nile River which bifurcates north of Cairo into two branches that enter the Mediterranean at Rosetta and

Damietta promontories. Climatically, Egypt is located within the hot-arid climate with an annual rainfall of 100 mm and 50 mm in the extreme deserts (Hegazy & Lovett-Doust 2016). Summers are hot with mean annual temperature more than 30 °C, while winters are mild with an annual mean temperature between 10 °C and 20 °C (Zahran & Willis 2009). Low temperatures are at higher elevations in the mountains of Southern Sinai and Red Sea (Hegazy & Lovett-Doust 2016).

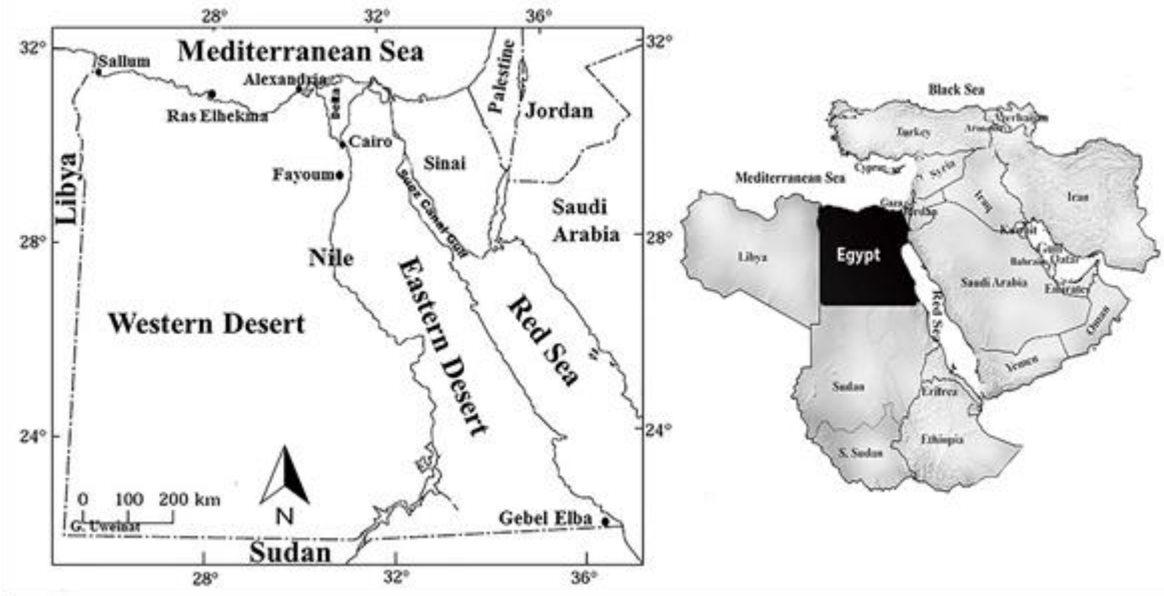

Figure. 1. Map of Egypt

Egypt is among the hot arid regions of the world, where only little attention has been given to its endemic and threatened plant species. These species represent an important factor in the Egyptian genetic, heritage, food and medicinal potentialities (Zahran and Willis 2009). Twenty Important Plant areas in Egypt (IPAs) have been identified in Egypt to date, with six proposed that require further study to confirm their status as internationally significant sites for plants (Valderrábano et al., 2018)). Of these, ten are located within the Mediterranean region and five of those contain single country endemics or very restricted range species. Floristically, the richest IPA in Egypt is the mountainous Saint Katherine IPA. It contains around 500 vascular plant species and approximately 50% of Egypt's endemic plant flora. This huge protected site covers over 5,000 km^2 of South Sinai and rises up to 2641 m; it is outside the Mediterranean region. Two Egyptian IPAs (Saint Catherine and Western Mediterranean coastal region) are included in the priorities for conservation actions. St. Catherine is a protected area occupying much of the central part of South Sinai, its diverse landscapes contain many habitats associated with wadis, caves, gorges, plains, mountains, hills, waterfalls and oases. The highest mountains Gebel Saint Katherine (2641m), Gebel Um Shomer (2586m) and Gebel Mousa (2285m), were formed during the Great African Rift around 24 million years ago which led to the creation of the Red Sea and the Aqaba Gulf. This mountainous area is bordered to the north by El-Tih calcareous plateau (540-1620m), the considerable rainfall drains into the Gulf of Suez and Aqaba through a network of deep gorges and relatively shallow wadis. This area contains around 500 vascular plant species, 30 of which are endemic to Egypt (ca 50 % of the endemic species in Egypt) such as *Silene oreosinaica*, *Primula boveana* and *Allium sinaiticum* which are classified as nationally endangered species. This area is threatened by agricultural expansion (especially downstream of the wadis), tourism development linked to transport and hotels, overgrazing, over collection of medicinal plants and drought (Valderrábano et al., 2018).

On the other hand, the Western Mediterranean coastal region is situated along the coastline west of Marsa Matrouh (about 100 km). This area contains snow-white dunes that made from coarse, calcareous oolithic sand which is more than 90% $CaCO_3$. Close to the shore, the dunes are small and active, while inland they are stabilised and vegetated. This site remains following the destruction of much the coastal dune belt west of Alexandria over the past twenty years through construction of summer resorts. A total of 219 species (116 annuals and 103 perennials), belonging to 151 genera and 44 families have been recorded. Some 30 species have unique occurrence in these dunes, most are endemic to the Mediterranean; for example, *Anthemis microsperma*, *Atractylis carduus* var. *marmarica*, *Pancratium arabicum*, *Helianthemum sphaerocalyx*, *Onopordum alexandrinum*, *Plantago crypsoides*, *Centaurea alexandrinea*, *Centaurea glomerata*, *Asphodelus aestivus*, *Ajuga iva* and *Sonchus bulbosus*. Mediterranean coastal dunes are recognised as a threatened habitat across the region (Valderrábano et al., 2018).

In the most recent checklist (Boulos 2009), Egypt's diverse flora contains over 2300 vascular plant species and subspecies (755 genera and 129 families). This reflects the long Mediterranean and Red Sea coasts combined with Egypt's position between Africa and Asia. Four floral zones are recognised: Mediterranean-Sahara regional transition zone, Sahara-Sindian regional zone, Irano-Turanian regional centre of endemism and Sahel regional transition zone. The preliminary red data list for the vascular plants of Egypt classifies nearly 450 species as threatened on a national level, although these are not necessarily threatened across the Mediterranean region. There are twenty-seven protected areas across the country, which are ecologically significant sites, twelve of these, or parts of them, are also IPAs. Taking into account the previous literature, the number of endemic flora that confined exclusively to Egypt varied from one author to another; it comprises 69 taxa (Täckholm 1974), 60 taxa (Boulos 2009) and 76 taxa (Hosni et al. 2013). Though the lowest number of endemic taxa in Egypt, compared with the other Mediterranean and neighbouring countries, there is a paucity of information about an exact number of endemic taxa and their distribution patterns.

2. Research Objectives

The main goals of this work were

1) to build an updated checklist of the endemic vascular flora of Egypt
2) to recognize the biogeographical patterns in Egypt based on presence of endemic flora together with environmental features,
3) to evaluate possible species shift according to climate change of a selected set of vascular plant species of particular interest (e.g. *Rosa arabica*)
4) to apply methods of species distribution models (e.g. MaxEnt) in order to guide field surveys for searching new or historic localities/populations for some selected rare endemic vascular plants in South Sinai, Egypt (e. g. *Primula boveana*).

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CHAPTER I

Critical checklist of the endemic vascular plants of Egypt

Mohamed Abdelaal, Mauro Fois, Giuseppe Fenu, Gianluigi Bacchetta

Abstract

After many recent findings regarding geographical distribution and nomenclatural changes, an updated and revised checklist of the Egyptian endemic flora was needed. This study provides an up to date checklist of vascular taxa exclusive to Egypt and their distribution within the administrative provinces. Egypt hosts 48 endemic taxa (including 35 species, seven subspecies and six varieties) belonging to 42 genera, 18 families and representing 2.3% of the total flora. The most represented families are Asteraceae, Lamiaceae, Caryophyllaceae, Fabaceae, Asparagaceae and Brassicaceae, while the most represented genus is Silene (three endemic taxa). Therophytes and chamaephytes are the most represented life-forms among Egyptian endemics. The richest regions in Egyptian endemic taxa are Southern Sinai (14 taxa), Northern Sinai and Matrouh (12 taxa each). Agglomerative hierarchical clustering (AHC) enabled the division of Egypt into three main regions based on the occurrence of endemic taxa: Eastern Egypt (31 taxa, 25 exclusive and six shared taxa), Western Egypt (14 taxa, seven exclusive and seven shared taxa) and Middle Egypt (12 taxa, eight exclusive and four shared taxa). This checklist will help to focus conservation efforts and provide a framework for research, protection and policy implementations for these endemic taxa.

Keywords: arid ecosystems, endemic vascular flora, North Africa, taxonomy

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1. Introduction

From a biogeographical viewpoint, the concept of endemism refers to taxa that have small distribution ranges or are restricted to a particular geographic region or habitat type (Anderson 1994). Endemism is a function of the spatial scale used to describe the restriction of certain taxa to a definite sized area (Laffan & Crisp 2003). The majority of endemic taxa are included in the Red Data List as they are potentially threatened due to their narrow and unique distribution ranges and habitat specificity (Crisp et al. 2001). Accordingly, the increased interest of endemic-rich regions can be based on their conservation importance.

Egypt is located in the northeastern corner of Africa, but it is also linked to Asia through the Sinai Peninsula, as well as to Europe through the Mediterranean coast. Egypt extends from the south at the Sudanian border to the north at the Mediterranean Sea, and from the east at the Red Sea to the west at the Libyan border, with a total area of ca. one million km^2 representing ca. 3% of Africa's total area (Zahran & Willis 2009). Climatically, Egypt is located within the hot-arid climate zone with an annual rainfall of 100 mm and as little as 50 mm in the extreme deserts (Hegazy & Lovett-Doust 2016). Summers are hot with mean annual temperatures above 30°C, while winters are mild with a mean annual temperature of between 10°C and 20°C (Zahran & Willis 2009). Lower temperatures are experienced at higher elevations in the mountains of Southern Sinai and the Red Sea (Hegazy & Lovett-Doust 2016).

According to the most recent checklist (Boulos 2009), the Egyptian flora includes 2100 taxa belonging to 755 genera and 129 families. Ten leading families (>50 taxa each) contribute ca. 56% of the total flora. These families are Poaceae (110 genera, 241 taxa), Asteraceae (98 genera, 228 taxa), Fabaceae (45 genera, 228 taxa), Brassicaceae (53 genera, 104 taxa), Caryophyllaceae (26 genera, 87 taxa), Chenopodiaceae (20 genera, 77 taxa), Scrophulariaceae (17 genera, 60 taxa), Boraginaceae (19 genera, 58 taxa), Lamiaceae (23 genera, 55 taxa) and Euphorbiaceae (eight genera, 55 taxa). The richest genera are *Euphorbia* (41 taxa), *Astragalus* (33 taxa), *Silene* (29 taxa), *Allium* (21 taxa), *Convolvulus*, *Plantago* (20 taxa each), *Trifolium*, Cyperus (19 taxa each), Lotus, *Medicago*, *Atriplex*, *Bromus* (18 taxa each), *Centaurea* (17 taxa), *Heliotropium* (16 taxa) and *Fagonia* (15 taxa). In addition, the flora of Egypt is made up of ca. 340 poorer genera that have less than two taxa each.

Previous literature provide varying numbers of endemic taxa that are confined exclusively to Egypt: e.g. 69 taxa (Täckholm 1974), 60 taxa (Boulos 2009) or 76 taxa (Hosni et al. 2013). Though Egypt has the lowest number of endemic taxa, when compared with other Mediterranean and neighbouring countries, there is a paucity of information about an exact number of endemic taxa and their distribution patterns. Hence, the goals of our paper are 1) to verify previous checklists and to present an updated checklist for the Egyptian endemic flora, and 2) to describe the distribution patterns of endemic taxa on the basis of administrative regions in Egypt.

2. Materials and methods

The checklist is based on reviews of several publications and databases. These resources include previous Floras and available literature (Täckholm 1974, Govaerts 1995, 1996, 2000, 2001, 2003, Al-Eisawi 1998, Boulos 1999, 2000, 2002, 2005, 2009, Hosni et al. 2013, Oran 2014, Shaltout & Eid 2016) and an exhaustive survey of Web of Sciences, Scopus, and Google Scholar, to check for new taxa descriptions and/or taxonomic revisions. Local herbaria (e.g. Cairo University, Agricultural Museum and Desert Research Centre) and online global databases **(see Table 1 for details)** were consulted. Two of the richest in specimens of endemic vascular plants of Egypt, the Royal Botanic Gardens Kew (K, England) and the Royal Botanic Garden Edinburgh (E, Scotland) herbaria were also visited.

Table 1. Global databases used in our study.

Database	Source
African Plant Database	http://www.ville-ge.ch/musinfo/bd/cjb/africa
Biodiversity Heritage Library (BHL)	http://www.biodiversitylibrary.org
Catalogue of Life	http://www.catalogueoflife.org/annual-checklist/2010
Euro+Med PlantBase	http://ww2.bgbm.org/EuroPlusMed/query.asp
Global Biodiversity Information Facility (GBIF)	http://www.gbif.org/occurrence
International Plant Name Index (IPNI)	http://www.ipni.org
JSTOR Global Plant Science	http://plants.jstor.org
Kew World Checklist of Selected Plant Families	http://wcsp.science.kew.org/home.do
Plants of the World Online-Kew Science	http://www.plantsoftheworldonline.org
The Plant List	http://www.theplantlist.org
Tropicos	http://www.tropicos.org/Home.aspx

Nomenclature of plant taxa follows the checklist of Boulos (2009) and was critically checked against The Plant List (TPL 2013) and the International Plant Names Index (IPNI 2017) databases. Genera and species were reported in families as recognized by the Angiosperm Phylogeny Group III (APG III 2009). Life-forms were identified following the system of Raunkiaer (1934). Distribution and habitat of endemics among the administrative regions inside Egypt were determined according to locations reported on herbarium specimen labels and in literature. The 27 administrative regions/provinces are referred to in the checklist according to the following acronyms **(Fig. 1)**: Alexandria (ALE), Assiut (ASS), Aswan (ASW), Behira (BEH), Beni-Suef (BES), Cairo (CAI), Dakahlyia (DAK), Damietta (DAM), Fayoum (FAY), Gharbia (GHA), Giza (GIZ), Ismailia (ISM), Kafr Elsheikh (KAS), Luxor (LUX), Matrouh (MAT), Menoufia (MEN), Minia (MIN), New Valley (NEV), North Sinai (NSI), Port-Said (POS), Qalyubia (QAL), Qena (QEN), Red Sea (RES), Sharqia (SHA), Sohag (SOH), South Sinai (SSI) and Suez (SUE).

A data matrix of 48 taxa and 21 administrative regions was developed and agglomerative hierarchical clustering (AHC) was carried out to construct homogeneous classes of administrative regions on the basis of their Jaccard dissimilarity in the composition of endemic taxa (Roleček et al. 2009).

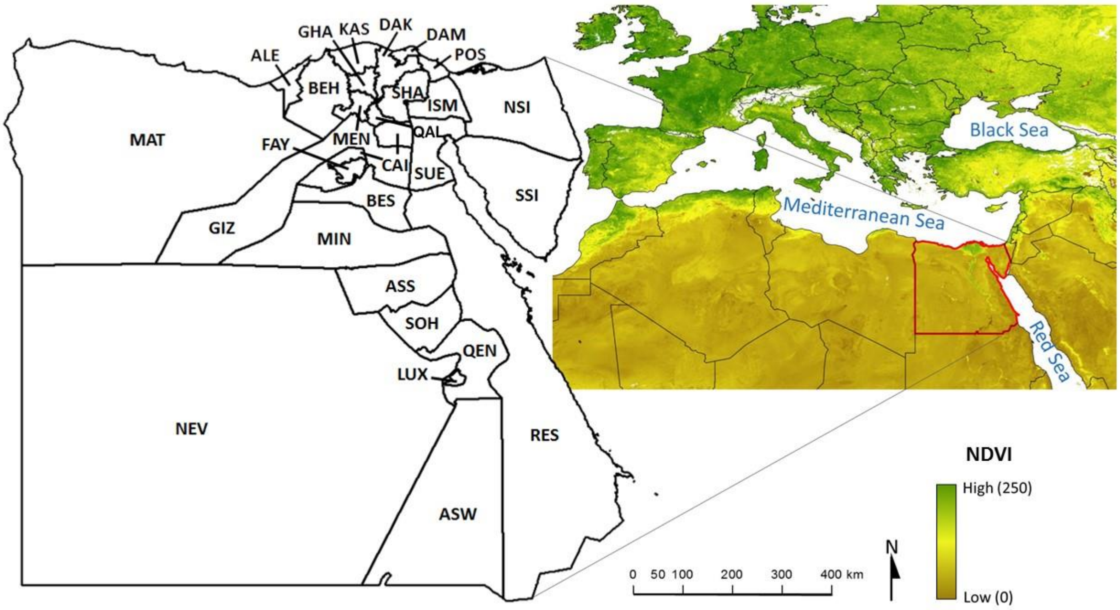

Figure 1. Map of Egypt showing the twenty-seven administrative regions. Alexandria (ALE), Assiut (ASS), Aswan (ASW), Behira (BEH), Beni-Suef (BES), Cairo (CAI), Dakahlyia (DAK), Damietta (DAM), Fayoum (FAY), Gharbia (GHA), Giza (GIZ), Ismailia (ISM), Kafr Elsheikh (KAS), Luxor (LUX), Matrouh (MAT), Menoufia (MEN), Minia (MIN), New Valley (NEV), North Sinai (NSI), Port-Said (POS), Qalyubia (QAL), Qena (QEN), Red Sea (RES), Sharqia (SHA), Sohag (SOH), South Sinai (SSI) and Suez (SUE).

3. Results

3.1. Floristic analysis of the Egyptian exclusive flora

The Egyptian endemic flora includes 48 taxa (including 35 species, seven subspecies and six varieties) belonging to 42 genera and 18 families. Ten families contain about 84% of endemic taxa in Egypt: Asteraceae (seven taxa, 15% of endemics), Lamiaceae (six taxa, 13% of endemics), Caryophyllaceae and Fabaceae (five taxa, 11% of endemics each), Asparagaceae and Brassicaceae (four taxa, 8% of endemics each), Amaryllidaceae (three taxa, 6% of endemics), Plantaginaceae, Polygonaceae and Solanaceae (two taxa, 4% of endemics each). The remaining eight families (Cistaceae, Euphorbiaceae, Molluginaceae, Plumbaginaceae, Poaceae, Primulaceae, Rosaceae and Santalaceae) are represented by only one endemic taxon each **(see Fig. 2)**.

No genera are exclusively endemic to Egypt. One genus (*Silene*) is represented by three endemic taxa, while four genera are represented by two endemic taxa each (*Allium*, *Bellevalia*, *Muscari* and *Origanum*). The remaining genera are represented by only one endemic taxon each (see checklist for details). With regard to life-forms, the Egyptian endemic flora is grouped into 16 therophytes, 12 chamaephytes, 10 hemicryptophytes, seven geophytes and three phanerophytes.

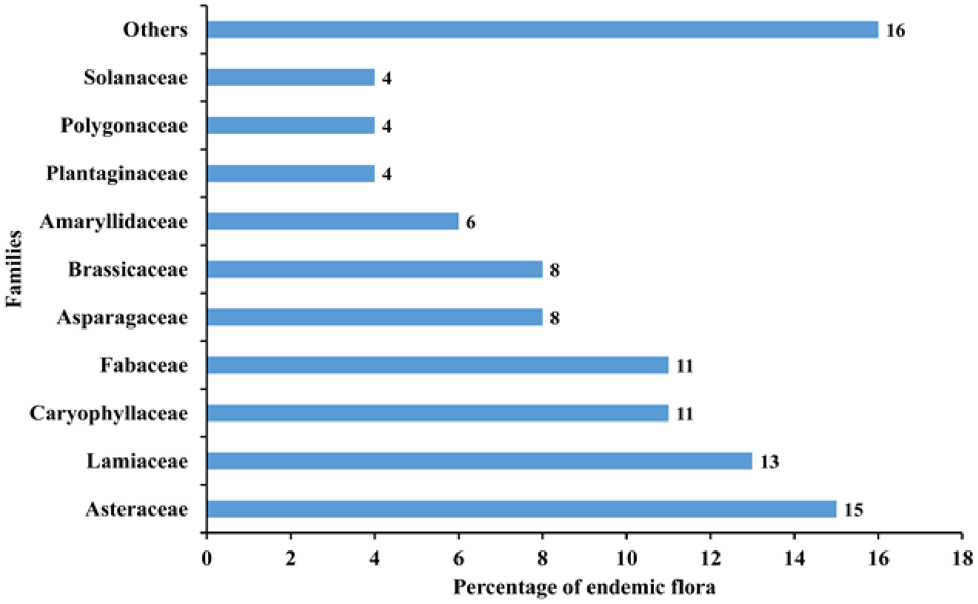

Figure 2. The proportion of Egyptian endemic taxa by families. The number next to each bar represents the percentage of the endemic flora. Families included in ‘Others’ are Cistaceae, Euphorbiaceae, Molluginaceae, Plumbaginaceae, Poaceae, Primulaceae, Rosaceae and Santalaceae, which are represented by only one endemic taxon.

3.2. Distribution of the exclusive endemic vascular flora of Egypt

Out of the 27 administrative regions in Egypt, 21 regions harbor at least one endemic taxon and six regions (POS, ISM, MEN, MIN, ASS and QEN) do not include any endemics. The most endemic-rich region is SSI with 14 endemic taxa (13 exclusive taxa and one shared taxon with other regions, 29% of endemics); followed by NSI and MAT with 12 endemic taxa each (25% of endemics each); RES and ALE with seven endemic taxa each (15% of endemics each); LUX with five endemic taxa (10% of endemics); DAK, ASW, BEH, DAM and FAY with three endemic taxa each (6% of endemics each). Four regions contain just two endemic taxa each: CAI, NEV, SHA and SOH, while six regions contain only a single endemic plant: KFS, SUE, GIZ, BES, GHA and QAL **(Fig. 3)**.

No endemic taxa occur in all of the Egyptian administrative regions. Thirty-three endemic taxa (ca. 69%) are endemics whose occurrence is confined to just a single region, seven endemic taxa are recorded only in two regions. The most widespread endemic taxa (*Bromus aegyptiacus* Tausch and *Veronica anagalloides* subsp. *taeckholmiorum* Chrtek & Osb.-Kos.) are present in six administrative regions.

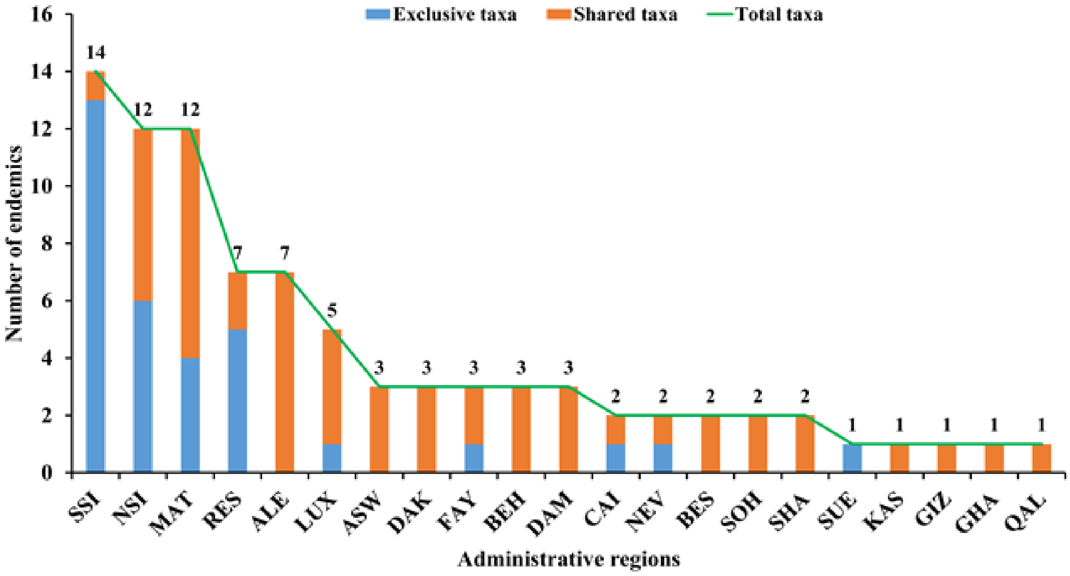

Figure 3. Number of endemic taxa by administrative regions in Egypt. See Figure 1 for administrative regions acronyms.

The AHC analysis divided Egypt into three principal regions according to the presence of endemics. These clusters were formed with a level of ca. 0.95 dissimilarities **(Fig. 4)**. Cluster I includes the administrative regions located in the east of the Nile River (hereafter, Eastern Egypt). Cluster II constitutes the administrative regions located in the west of the Nile River (hereafter, Western Egypt). While cluster III comprises all the administrative regions that are watered by Nile River water, i.e. located in the Nile region (hereafter, Middle Egypt).

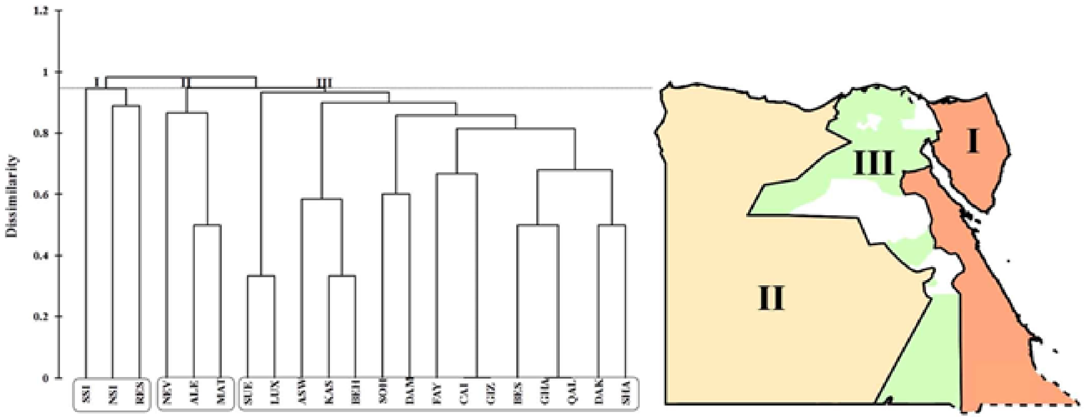

Figure 4. Agglomerative hierarchical cluster (AHC) dividing the administrative regions in Egypt into three groups: I (Eastern Egypt), II (Western Egypt) and III (Middle Egypt). In white color are the six regions that were not included in the analysis due to absence of endemic taxa. See Figure 1 for administrative regions acronyms.

Eastern Egypt constitutes of three administrative regions NSI, SSI and RES. Collectively, 31 endemic taxa are recorded in Eastern Egypt, 25 of these taxa are exclusive to this cluster and six taxa are shared with other clusters (five with Western Egypt and one taxon with Middle Egypt). Western Egypt includes the three administrative regions ALE, MAT and NEV. This area includes 14 endemic taxa, seven of these taxa are exclusive, while the remaining seven taxa are shared with other clusters (four taxa with Eastern Egypt and three taxa with Middle Egypt). Finally, Middle Egypt includes the remaining 15 administrative regions, where 12 endemic taxa are recorded, eight of these taxa are exclusive and four taxa are shared with the other two clusters (three taxa with Western Egypt and one taxon with Eastern Egypt).

4. Discussion

According to our results, Egypt hosts 48 endemic taxa representing 2.3% of the total flora. This is in partial discordance with previous checklists of Täckholm (1974; 69 endemic taxa), Boulos (2009; 60 taxa) and Hosni et al. (2013; 79 taxa). Reasons for the discrepancy are specifically explained in the annotated list of 57 doubtful endemic taxa that are excluded from our checklist **(Table 2)**. The reduced number of endemics in Egypt is due to mainly two reasons, namely updated taxonomy and updated distribution information. Eight taxa are now excluded here because they were synonymised with other taxa, and the taxonomic concept of nine taxa were expanded to include other more widespread taxa that now render them non-endemic. In addition, of the 60 endemics reported by Boulos (2009), 16 taxa were excluded here due to recent updates in their geographical distribution (for further specific details consult **Table 2**).

In comparison with some countries of the Mediterranean Basin, endemic numbers in Egypt is below the average endemism concentration, along with other southern arid countries such as Tunisia and Palestine, whilst Turkey, Spain, Greece, Morocco and Italy have the highest concentration of endemics **(Fig. 5)**. This trend is also seen when looking at number of taxa in the total flora of these countries. However, a similar trend of low endemism was found in neighbouring Sudan, Libya and Saudi Arabia (Hegazy & Lovett-Doust 2016), while countries characterized by a Mediterranean climate, high morphological diversity and presence of several islands, such as Italy, Greece, Spain and Morocco, display higher levels of endemism (Aedo et al. 2013, Rankou et al. 2013, Dimopoulos et al. 2013, Fois et al. 2017). Nonetheless, this paper is focused on taxa that are currently known only from Egypt. Many near-endemic taxa, which in some cases were even considered exclusive to Egypt until their status was changed according to new findings in neighbouring countries, may be considered in future studies. In particular, Boulos (2009) recorded 93 near-endemic taxa and Hosni et al. (2013) reported 61 near-endemics. The near-endemic taxa of Egypt are mostly concentrated in four local territories (Hosni et al. 2013): the northeastern territory (including Sinai of Egypt-central and south Palestine), the northwestern territory (including NW Egypt-NE Libya), the southeastern territory (Gebel Elba of Egypt-NE Sudan) and the southwestern territory (including Gebel Uweinat of Egypt-SW Libya and NW Sudan).

Table 2. List of taxa previously treated as endemic, but now excluded from the Egyptian endemic flora with their reasons of exclusion.

Excluded taxa	Reason
Allium blomfeldianum Asch. & Schweinf.	Reported from Libya by Govaerts (1995)
Apium graveolens var. *bashmensis*	The varieties previously distinguished under *A. graveolens* are no longer recognized and *A. graveolens* is widely distributed in Africa (Govaerts 1995, Boulos 2000, Valdés 2002, Germishuizen & Meyer 2003)
Astragalus camelorum Barbey	Reported from Jordan and Palestine (Baierle 1993, Danin 2000)
Astragalus fruticosus Forssk.	Reported from Palestine and Saudi Arabia by Govaerts (1995)
Bromus hordeaceus L.	Widely distributed in Africa (Boulos 2005)
Bupleurum nanum Poir.	Reported from Libya and Palestine (Govaerts 1996, Boulos 2000)
Centaurium malzacianum Maire	Reported from Saudi Arabia (Govaerts 1999, Boulos 2000)
Chenopodium giganteum D.Don	Considered a synonym of *C. moquinianum* Täckh. and widely distributed in Africa and Asia (Boulos 1999, Germishuizen & Meyer 2003)
Colchicum cornigerum (Schweinf. ex Sickenb) Täckh. & Drar	A synonym of *C. schimperi* Janka ex Stef., *C. szovitsii* Fisch. & C. A. Mey. and *C. deserti-syriaci* Feinbrun and distributed in Iraq, Lebanon, Saudi Arabia and Iran (Govaerts 2003)
Convolvulus spicatus Peter ex Haillier f.	Distributed in Palestine and Saudi Arabia (Govaerts 1999, Boulos 2000)
Delphinium bovei Decne.	Reported from Palestine (Boulos 2002, Govaerts 2003)
Dianthus sinaicus Boiss.	Reported from Palestine and Saudi Arabia (Boulos 1999, Govaerts 2003)
Ducrosia ismaelis Asch.	Recorded in Saudi Arabia (Migahid & Hammouda 1974, Al-Meshal et al. 1985, Govaerts 2003)
Ebenus armitagei Schweinf. & Taub.	Reported from Libya (Boulos 1999, Govaerts 2001)
Euphorbia punctata Delile	Reported from Libya by Boulos (2000)
Euphorbia sanctae-catharinae Fayed	Now it considered a synonym of *Euphorbia obovata* Decne. (Boulos 2000)
Euphorbia bivonae Steud.	A synonym of *E. bivonae* Steud. var *sinaica* Hadidi and *Tithymalus bivonae* (Steud.) Soják, and distributed in Algeria, Libya, Tunisia and Jordan (Govaerts 2003)
Fagonia arabica L.	A synonym of *F. boulosii* Hadidi and widely distributed in Africa (Boulos 2000, Germishuizen & Meyer 2003, Darbyshire et al. 2015)
Fagonia scabra Forssk.	A synonym of *F. taeckholmiana* Hadidi and *F. sinaica* Boiss. and distributed in Algeria, Libya, Morocco, Palestine and Tunisia (Boulos 2000, Govaerts 2001)
Ferula sinaica Boiss.	Reported from Jordan and Saudi Arabia by Llewellyn et al. (2010)
Fumaria microstachys Kralik ex Hausskn.	Reported from Libya by Govaerts (2001)
Fumaria parviflora Lam.	Widely distributed in the world (Boulos 1999, GBIF 2016)
Galium sinaicum (Delile ex Decne.) Boiss.	A synonym of *Asperula sinaica* Delile ex Decne. and distributed in Palestine (Boulos 1999, Govaerts 2003)
Glaucium arabicum Fresen.	Recorded in Palestine (Boulos 1999, Govaerts 2003)
Gnaphalium crispatulum Delile	A synonym of *Homognaphalium crispatulum* (Delile) Kirp., and now it considered widespread in Iran, North and South Africa (Boulos 2002, Govaerts 2003)

Helianthemum crassifolium subsp. sphaerocalyx (Gauba & Janchen) Maire	A synonym of *H. sphaerocalyx* Gauba & Janch. and distributed in Libya (Boulos 2002, Cuccuini et al. 2015)
Heteroderis pusilla (Boiss.) Boiss. var. *leucocephala* (Bunge) Rech.f.	A synonym of *Crepis aegyptiaca* (Schweinf.) Täckh. & Boulos and distributed in Iraq, Lebanon, Saudi Arabia and Iran (Léonard 1983, Govaerts 2003, Nasseh 2010)
Hypecoum littorale Wulfen	A synonym of *H. deuteroparviflorum* Fedde, *H. geslinii* Coss. & Kralik and distributed in Algeria, Iraq, Libya, Morocco, Palestine, Portugal, Spain and Tunisia (Tutin et al. 1993, Boulos 1999)
Hypericum sinaicum Hochst. ex Boiss.	Reported from Saudi Arabia, Palestine and Jordan (Danin 1997, Boulos 1999)
Kickxia macilenta (Decne.) Danin	A synonym of *Nanorrhinum macilentum* (Decne.) Betsche and *Linaria macilenta* Decne., and reported from Palestine by Boulos (2002)
Limonium narbonense Mill.	A synonym of *L. mareoticum* El Garf ex Hadidi & Fayed and widely distributed in Africa and Europe (Tutin et al. 1993, Boulos 2000, Germishuizen & Meyer 2003)
Lupinus digitatus Forssk.	A synonym of *L. varius* L. subsp. *orientalis* and distributed in Algeria, Libya, Morocco and Senegal (Lock 1989, Boulos 1999)
Lycium schweinfurthii Dammer subsp. *aschersonii* (Dammer) Feinbrun	A synonym of *L. aschersohnii* Dammer and reported from Palestine by Boulos (2002)
Muscari longistylum (Täckh. & Boulos) Hosni	A synonym of *Leopoldia longistyla* Täckh. & Boulos and reported from Palestine and Jordan by Boulos (1995, 2005)
Najas pectinata (Parl.) Magn.	A synonym of *Caulinia pectinata* Parl and widely distributed in Africa (Boulos 1995, Germishuizen & Meyer 2003)
Nepeta septemcrenata Benth	Reported from Iran, Saudi Arabia and Palestine by Boulos (2002)
Phagnalon nitidum Fresen.	Reported from Palestine, Jordan and Pakistan by Danin (1997)
Phagnalon sinaicum Bornm. & Kneuck.	Reported from Saudi Arabia and Yemen by Boulos (2005)
Pimpinella schweinfurthii Asch.	Distributed in Oman, United Arab Emirates and Saudi Arabia (Raffelli et al. 2006, Böer & Chaudhary 1999, Mosti et al. 2012)
Plantago sinaica (Barn.) Decne.	A synonym of *P. psyllium* L. var *sinaica*, *P. arabica* Boiss., *P. squarrosa* Bove and *Psyllium sinaicum* (Barn.) Holub and reported from Jordan and Palestine by Danin (1997)
Polygala sinaica Botsch var. sinaica	A synonym of *P. spinescens* Decne. and reported from Jordan by Oran (2014)
Pterocephalus arabicus Boiss.	A synonym of *Scabiosa arabica* (Boiss.) Blatter and reported from Jordan (GCEP 1998)
Pterocephalus sanctus Decne.	Distributed in Jordan, Palestine and Saudi Arabia (Boulos 2002, Oran 2014)
Scorzonera schweinfurthii Boiss.	A synonym of *S. edumea* Eig and distributed in Jordan, Iraq and Saudi Arabia (Boulos 2002)
Silene biappendiculata Rohrb.	Reported from Libya by Boulos (1999)
Silene odontopetela Fenzl	A synonym of *S. odontopetala* Fenzl var. *sinaica* Boiss., *S. odontopetala* subsp. *congesta* (Boiss.) Melzh. and *S. sinaica* Boiss., and distributed in Iran, Iraq and Turkey (Baskose & Dural 2011, Gholipour & Maroofi 2011)
Silene schimperiana Boiss.	Reported from Saudi Arabia and Yemen (Govaerts 2001, GBIF 2016)
Silene villosa Forssk.	A synonym of *S. villosa* Forssk. var. *erecta* Täckh & Boulos and distributed in Kuwait and Saudi Arabia (Halwagy & Macksad 1972)

Tetraena alba (L.f.) Beier & Thulin	A synonym of *Zygophyllum album* L.F. subsp. *album* and widely distributed in Africa (Boulos 2000, Beier et al. 2003, Germishuizen & Meyer 2003)
Teucrium leucocladum Boiss. subsp. *Leucocladum*	A synonym of *T. cuneifolium* Schimp. ex Boiss. and *T. schimperi* C.Presl and distributed in Jordan, Palestine and Saudi Arabia (Danin 1997, Govaerts 2003)
Thymus decussatus Benth.	Distributed in Saudi Arabia and Palestine (Boulos 1995, 2002, Govaerts 2003)
Trigonella occulta Ser.	Reported from Pakistan and India (Shah & Kothari 1975, Jadhav et al. 2015)
Verbascum schimperianum Boiss.	Distributed in Palestine, Saudi Arabia and Jordan (Boulos 2002, GBIF 2016)
Veronica catenata Pennell subsp. *pseudocatenata* Chrtek & Osb.-Kos.	Reported from Libya by Abd El-Ghani et al. (2010)
Veronica kaiseri Täckh.	Reported from Palestine and Jordan by Raab-Straube & Raus (2016)
Veronica musa Täckh. & Hadidi	A synonym of *V. kaiseri* Täckh. (Boulos 2000)
Zygophyllum migahidii var. isthmia A. Hosny	Reported from Saudi Arabia by Beier et al. (2003)

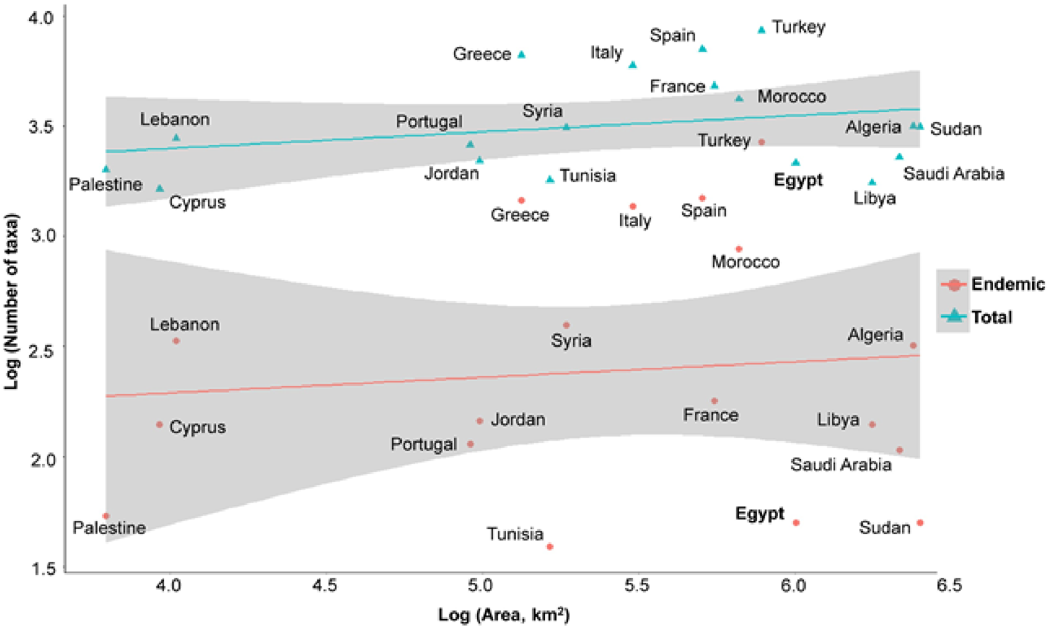

Figure 5. Logarithmic number of total and endemic taxa against Log area (km^2) of some Mediterranean and neighbouring countries compared with those of Egypt (the present study). Sources: Davis (1988), Davis et al. (1994), Aedo et al. (2013), Conti et al. (2005), Dimopoulos et al. (2013), Peruzzi et al. (2014), Rankou et al. (2013), Tohme & Tohme (2007), Greuter (1991), Hegazy & Lovett-Doust (2016), Olivier et al. (1995), Krigas et al. (2017), Boulos (1997), Gomez-Campo et al. (1984) and Enriquez & Gomez-Campo (1991).

Throughout the Mediterranean coastal belt of Egypt (ca. 970 km long), its dry climate does not support the establishment of a Mediterranean vegetation (Dallman 1998). Indeed, the low rate of endemism in Egypt is owing to predominant desert regions that occupy ca. 95% of the total surface area of the country. Wickens (1992) reported that Egypt is probably the driest country in North Africa, where hot desert conditions prevail throughout the whole country. In such extremely arid conditions, as found in the majority of the study area, plant life and Egyptian endemics are confined to restricted areas, such as mountain wadis, slopes and gorges (Shmida 1984), where springs provide sufficient moisture for plant growth. The remaining taxa are distributed along the Mediterranean coast and in the Nile region, where rainfall and the Nile River are sufficient sources of water, respectively. In arid regions, the pattern of life forms is commonly related to the amount of rainfall and topography (Zahran & Willis 2009). Prevalence of therophytes, with co-dominance of chamaephytes, supports a desert flora, and it is closely correlated with topography and climate (Hegazy et al. 1998). In particular, annuals and suffrutices are able to survive in extremely hot and dry conditions and are often influenced by human activities (Zohary 1973, Hegazy et al. 1998, Salama et al. 2013).

Eastern Egypt is the richest endemic area, followed by Western Egypt and Middle Egypt. Within Eastern Egypt, the concentration of endemics gradually increases from RES to NSI, reaching the highest number in SSI. This is in accordance with Davis et al. (1994) and Boulos (2008) who reported that the mountains of the Sinai Peninsula (NSI and SSI) and Red Sea represent a great pool of endemism. In particular, the endemic flora in Sinai is not evenly distributed. Saint Katherine Protectorate (SKP) in

Southern Sinai (SSI) is considered the most important centre of endemism in Egypt (Zohary 1973). This is due to its peculiar wet climate (Danin 1988) and physiographic features that determine specific microhabitats, which function as refugia in the desert areas (Danin 1999, Moustafa et al. 2001, Khedr 2006, Mossallam 2007). SKP is characterized by the coolest climate in Egypt and sizable outcrops in rock surface at high elevations, which contribute for the speciation and restriction of endemic and rare taxa (Moustafa & Klopatek 1995, Moustafa et al. 2001). Similarly, the northeastern Mediterranean belt and mountains in NSI (e.g. Gebel El-Halal) promote the establishment of endemic taxa. Distribution of these taxa is mainly determined by the Mediterranean coastal influence and geomorphological isolation in the mountainous regions (Abd El-Wahab et al. 2008). The importance of RES from an endemism viewpoint may be attributed to the presence of the Galala Mountains in the north and Gebel Elba Mountains in the southeast. The latter is distinguished by ecological features and the peculiar geographical location between the Saharo-Arabian Desert in the north and the highlands of Sudan in the south (Abd El-Ghani & Abdel Khalik 2006).

Within the Western Egypt cluster, native taxa (including endemics) are particularly concentrated along the northwestern Mediterranean strip, which is characterized by a high rainfall, as well as by the presence of rocky ridges and calcareous sandy soils (Boulos 2008), while the remaining Western Desert areas of Western Egypt show extreme arid conditions (Zahran & Willis 2009). The limited availability of water, which are restricted to deep wells within oases (Dakhla Oasis) in the Western Desert, allows for the survival of few endemics. Indeed, with exception of its coastal belt, Western Egypt (with its high aridity, lack of wadis, uniformity in physiography, and low elevation) is the poorest area in endemics, when compared with Eastern Egypt.

Finally, Middle Egypt (i.e. the Nile region) is ecologically divided into three subregions: the Nile Valley (from Sudan in the south to Cairo in the north), Nile Fayoum (southwest of Cairo) and the Nile Delta with its Mediterranean coast (from Cairo to the Mediterranean Sea in the north) (Zahran & Willis 2009). Middle Egypt has the most fertile cultivated lands in Egypt due to the alluvial deposits from the Nile River. Therefore, endemic weeds [such as Bromus aegyptiacus, *Sinapis arvensis* subsp. *allionii* (Jacq.) Baillarg., Melilotus serratifolius Täckh. & Boulos and *Sonchus macrocarpus* Boulos & C. Jeffrey] are established, in association with field crops, on the irrigation and Nile bank habitats, or on its sand deposits along the Mediterranean coast.

5. Conclusion

Taking into account current distribution ranges and nomenclatural changes, the Egyptian territory hosts a low number of exclusive endemic vascular plants (48 taxa). Indeed, the low rate of endemism in Egypt is a result of hot-dry climate and topography. The majority of endemic taxa are confined to the mountains of the Sinai Peninsula. Based on endemism levels, Egypt is classified into three regions as follows: Eastern Egypt (31 endemic taxa, 25 exclusive and six shared taxa), Western Egypt (14 endemic taxa, seven exclusive and seven shared taxa) and Middle Egypt (12 endemic taxa, eight exclusive and four shared taxa). Regular updates to this checklist is welcomed, as the associated further appropriate documentation for distribution maps and conservation assessment against IUCN Red List categories and criteria, enable better allocation of resources and efforts for habitat and species conservation. The present endemic plant distribution analysis highlights areas of particular conservation concern among administrative regions, which may be of help for conservation programs. In addition, further studies, such as the biogeographical classification of Egypt or investigating drivers of endemism, could also be crucial for a more comprehensive view of endemic patterns.

Checklist of Egyptian endemic taxa

Checklist of taxa endemic to Egypt sorted alphabetically by families and then by genera. Full accepted names are followed by synonyms (if available), life forms, administrative regions and habitats respectively. Life-forms include therophyte (T), chamaephyte (Ch), hemicryptophyte (H), geophyte (G) and phanerophyte (P). The administrative regions include: Alexandria (ALE), Aswan (ASW), Behira (BEH), Beni-Suef (BES), Cairo (CAI), Dakahlyia (DAK), Damietta (DAM), Fayoum (FAY), Gharbia (GHA), Giza (GIZ), Kafr Elsheikh (KAS), Luxor (LUX), Matrouh (MAT), New Valley (NEV), North Sinai (NSI), Qalyubia (QAL), Red Sea (RES), Sharqia (SHA), Sohag (SOH), South Sinai (SSI) and Suez (SUE).

Family: Amaryllidaceae

***Allium crameri* Asch. & Boiss. ex Boiss.**
G; NSI and RES; rocky ground and sand stony places.

***Allium mareoticum* Bornm. & Gauba**
G; ALE and MAT; calcareous hills, sandy and rocky places.

***Pancratium arabicum* Sickenb.**
=Pancratium aegyptiacum M.Roem.
G; ALE, MAT and NSI; coastal sandy hills and sandy maritime seashores.

Family: Asparagaceae

***Bellevalia flexuosa* Boiss. var. *galalensis* Täckh. & Drar ex Täckh. & Boulos**
=Hyacinthus flexuosus (Boiss.) Baker, *nom. illegit.* non Thunb
(1794) G; RES; rocky ground, flint and coarse sandy soils.

***Bellevalia salah-eidii* Täckh. & Boulos**
G; MAT and NSI; rocky ground and sandy soils.

***Muscari albiflorum* (Täckh. & Boulos) Hosni**
=Leopoldia albiflora Täckh. & Boulos
G; MAT; rocky ground and sandy soils.

***Muscari salah-eidii* (Täckh. & Drar) Hosni**
=Leopoldia salah-eidii Täckh. & Boulos
G; NSI; rocky sandy soils.

Family: Asteraceae (Compositae)

***Anthemis microsperma* Boiss. & Kotschy**
=Anthemis ballii Stapf; *=Anthemis microsperma* Boiss. & Kotschy var. *ballii* (Stapf) Täckh.
T; ALE, MAT and NSI; sandy soils.

Atractylis carduus **(Forssk.) C.Chr. var. *marmarica* Täckh. & Boulos**
=Centaurea carduus Forssk.; *=Atractylis flava* Desf.
H; MAT; calcareous sandy soils.

Echinops taeckholmianus **Amin**, as ‘taeckholmiana’
H; DAK and DAM; maritime sand dunes and flats.

Ifloga spicata **(Forssk.) Sch.Bip. subsp. *elbaensis* Chrtek**
T; RES; sandy wadis, desert plains and rocky ground.

Scorzonera drarii **Täckh.**
Ch; NSI; edges of cultivated lands.

Senecio belbeysius **Delile**
=Acleia belbeysia (Delile) DC.; *=Cineraria belbeisia* Spreng.; *=Senecio belbeyticus* Poir.
T; SHA, LUX and ASW; edges of cultivated lands and on roadsides.

Sonchus macrocarpus **Boulos & C.Jeffrey**
= Sonchus gigas Boulos
Ch; ALX, MAT, LUX and ASW; canal banks and moist ground.

Family: Brassicaceae (Cruciferae)

Biscutella didyma **L. var. *elbensis* (Chrtek) El Naggar**
=Biscutella elbensis Chrtek
T; RES; rocky wadis.

Brassica deserti **Danin & Hedge**
=Erucastrum deserti (Danin & Hedge) V.I.Dorof.
T; NSI; stony wadis and gravelly plains.

Nasturtiopsis integrifolia **(Boulos) Abdel Kahlik & F.T.Bakker**
=Rorippa integrifolia Boulos
T; NSI; sandy soils.

Sinapis arvensis **L. subsp. *allionii* (Jacq.) Baillarg.**
=Sinapis allionii Jacq.; *=Raphanus turgidus* Pers.; *=Sinapis turgida* (Pers.) Delile
T; ALE, MAT, BEH, KAS, SOH and LUX; cultivated lands.

Family: Caryophyllaceae

Bufonia multiceps **Decne.**
H; SSI; stony ground and wadi beds of moist sites.

Dianthus guessfeldtianus **Muschl.**
H; RES; stony grounds.

Silene apetala **Willd var. *glabrata* Hosny & E.Shamso**
T; MAT; sandy soils.

Silene leucophylla **Boiss.**
H; SSI; stony ground and rocky slopes.

Silene oreosinaica **Chowdhuri**

=Silene sinaica Boiss.
H; SSI; stony ground and rocky slopes.

Family: Cistaceae

***Helianthemum schweinfurthii* Grosser**
=Helianthemum calycinum Dunal
Ch; SUE; hillsides.

Family: Euphorbiaceae

***Euphorbia obovata* Decne.**
=Euphorbia bounophila Boiss. (Tackh.); *=Euphorbia sanctae-catharinae* Fayed; *=Euphorbia prolifera* Ehrenb. Ex Boiss.
H; SSI; rocky slopes, stony ground and terraces.

Family: Fabaceae (Leguminosae)

***Astragalus fresenii* Decne.**
=Tragacantha fresenii (Decne.) Kuntze
Ch; SSI; rocky crevices, sandy soils and high altitude wadis.

***Melilotus serratifolius* Täckh. & Boulos**
T; NEV; cultivated lands.

***Tephrosia kassasii* Boulos**
Ch; LUX and ASW; sandy soil near the Nile.

***Trigonella media* Delile**
T; CAI; alluvial soils.

***Vicia sinaica* Boulos**
T; NSI; sandy plains.

Family: Lamiaceae (Labiatae)

***Ballota kaiseri* Täckh.**
Ch; SSI; stony slopes and shaded gorges.

***Micromeria serbaliana* Danin & Hedge**
=Satureja serbaliana (Danin & Hedge) Greuter & Burdet
P; SSI; rocky crevices, sheltered mountain fissures and cliffs of smooth red granite.

***Origanum isthmicum* Danin**
Ch; NSI; hard limestone cliffs.

***Origanum syriacum* L. subsp. *sinaicum* (Boiss.) Greuter & Burdet**
=Origanum maru L. var. *sinaicum* Boiss.; *=Origanum syriacum* var. *sinaicum* (Boiss.) Ietsw.; *=Majorana syriaca* (L.) Raf., *nom. illegit.*, non Kostel (1834); *=Majorana nervosa* Benth.; *=Origanum nervosum* (Benth.) Vogel
Ch; SSI; stony wadi beds and gorges.

***Phlomis aurea* Decne.**
=Phlomis flavescens Mill.; *=Phlomis angustifolia* Mill. var. *flavescens*
Benth. Ch; SSI; stony wadi beds, shaded gorges and closed wadis.

Teucrium leucocladum **Boiss. subsp. *sinaicum* Danin**
Ch; SSI; rocky crevices.

Family: Molluginaceae

Glinus runkewitzii **Täckh. & Boulos**
T; LUX; Nile banks.

Family: Plantaginaceae

Anarrhinum forskaohlii **(J.F.Gmel.) Cufod. subsp. *pubescens* (Fresen.) D.A.Sutton**
=Anarrhinum pubescens Fresen.; =*Anarrhinum pubescens* Loudon; =*Anarrhinum orientale* Benth. var. *pubescens* (Fresen.) Rouy; =*Cardiotheca pubescens* (Fresen.) Ehrenb. ex Steud.; =*Simbuleta pubescens* Kuntze
H; SSI; rocky crevices and sandy soils in high altitude wadis.

Veronica anagalloides **Guss. subsp. *taeckholmiorum* Chrtek & Osb.-Kos.**
H; DAK, BEH, CAI, GIZ, FAY and SOH; irrigation canals and ditches, swamps, lake shores and around wells and springs.

Family: Plumbaginaceae

Limonium sinuatum **(L.) Mill. subsp. *romanum* Täckh. & Boulos**
=Limonium romanum (Täckh. & Boulos) Domina
P; MAT; moist ground around wells.

Family: Poaceae

Bromus aegyptiacus **Tausch**
=Bromus japonicus Houtt. var. *aegyptiacus* (Tausch) Asch.; *=Bromus brachystachys* Hornung; *=Bromus aegyptiacus* Tausch subsp. *palaestinus* Melderis
T; DAK, SHA, GHA, QAL, DAM and NSI; weed of barley fields, gardens and on roadsides.

Family: Polygonaceae

Persicaria obtusifolia **(Täckh & Boulos) Greuter & Burdet**
=Polygonum obtusifolium Täckh & Boulos
Ch; FAY; irrigation canal banks.

Rumex aegyptiacus **L.**
=Rumex comosus Forssk.
T; ALE, BEH, DAM, FAY and BES; Nile and irrigation canal banks.

Family: Primulaceae

Primula boveana **Decne. ex Duby**
=Primula verticillata Forssk.
H; SSI; rocky crevices, moist ground in the vicinity of wells, sheltered mountain areas, caves and shaded gorges.

Family: Rosaceae

Rosa arabica **Crép.**
=Rosa agrestis Savi; =*Rosa rubiginosa* L.
P; SSI; rocky mountain ridges adjacent to water springs, rocky gorges and caves.

Family: Santalaceae

Thesium humile **Vahl var. *maritima* (N.D.Simpson) Sa’ad**
=Thesium humile forma *maritima* N.D.Simpson
T; ALX and MAT; coastal sandy grounds.

Note: This variety should be revised as it may be considered as a synonym of *Thesium humile* Vahl

Family: Solanaceae

***Hyoscyamus boveanus* (Dunal) Asch. & Schweinf.**
=Scopolia boveana Dunal
Ch; MAT, NEV, NSI, SSI and RES; sandy plains, wadi beds with silty ground and disturbed areas.

***Solanum nigrum* L. var. *elbaensis* Täckh. & Boulos**
T; RES; sandy soils and wadi beds.

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CHAPTER II

Biogeographical characterization of Egypt based on environmental features and endemic vascular plants distribution

Mohamed Abdelaal, Mauro Fois, Giuseppe Fenu, Gianluigi Bacchetta

Abstract

Biogeographical studies are considered effective for investigations on macroecology and evolution, as well as for delineating patterns of endemism and identifying the key drivers influencing the historical distribution of species. Clustering techniques, based on environmental datasets and distribution of endemic species, have been largely used in biogeography and for the definition of endemic-rich regions where conservation actions should be implemented. Despite a few earlier studies have been dealt with the biogeographical territories in Egypt, none of them have provided a replicable method to support such regionalization. We propose in this study a two steps procedure for the biogeographical regionalization of Egypt consisting in (1) the definition of environmental clusters (based on 24 climatic, three topographic, two soil and four habitat heterogeneity) and (2) the spatial clustering of such environmental clusters according to the distribution of 140 endemic vascular plants. Fifteen environmental clusters were defined by using the k-nearest neighbors algorithm in the ArcGIS environment. Therefore, hierarchical clustering and indicator values analyses, based on the presence-absence matrix of endemic taxa in each cluster, were performed to define two cut-off levels of biogeographical units (sectors and subsectors). A total of six sectors and nine subsectors were identified. Climatic-related variables, elevation and soil organic carbon are the most important determinants for environmental clustering of Egypt. The highest endemic richness was recorded in the Egyptian Mediterranean coast (71 species), South Sinai- Egyptian Arabian Desert (62 species) and Nile region (16 species) sectors, and in South Sinai (54 species), North Sinai (45 species) and Mariut coast (40 species) subsectors. Nonetheless, the sectors with the highest percentage of protected surface area were Gebel Elba and Egyptian Red Sea coast (62.73 and 29.05%, respectively) while the lowest sectors were the Nile region and Egyptian Mediterranean coast (9.86 and 13.26%, respectively). This two steps procedure confirms the usefulness of environmental attributes together with the spatial distribution of endemic vascular plants to define the biogeographical units in Egypt. Furthermore, the presented regionalization will help to identify weaknesses in current protection actions and to understand biogeographical processes.

Keywords: areas of endemism, environmental clusters, phytogeography, plant conservation, Northern Africa.

This research under preparation

1. Introduction

The main objective of biogeography is to categorize and mapping the biota into meaningful and interpretable hierarchical homogeneous geographical units (Ficetola et al., 2017; Morrone, 2018). These units have been determined by present and past biological and physical forces and help to better understand the drivers for the spatial distribution of species. The so-called biogeographical regionalization results in a hierarchical system that categorize geographical units in terms of their biota, in particular endemic taxa (Kreft & Jetz, 2010). Biogeographical definitions are powerful approaches not limited to the reduction of ecological data complexity (Kupfer et al., 2012) but also for understanding spatial patterns of biodiversity and to explore the key elements influencing the historical and current distribution of species. In addition, it is an applicable implementation method for maximizing the number of conserved species, due to its role in planning conservation strategies (Gao & Kupfer, 2018; Graham & Hijmans, 2006; Violle et al., 2015), attenuating difficulties to identify areas that should be protected without systematic mapping over large areas, such as multiple bioregions, climatic zones or political boundaries (Pressey et al., 2000).

For a long time, to do such biogeographical delineations, the qualitative data collection of experts and researchers has been considered, which directly or indirectly influenced biogeographical assessments (Gao & Kupfer, 2018; Williams, De Klerk, & Crowe, 1999). Nevertheless, the development of clustering algorithms, together with the availability of extensive environmental datasets and global species distribution, raised the interest of biogeographers and macroecologists to release and assess the biogeographical unit boundaries, from broad to fine scale, by the use of replicable methods (Hattab et al., 2015; Kreft & Jetz, 2010; Mackey, Berry, & Brown, 2008; Rueda, Rodríguez, & Hawkins, 2013). Delineating such units at small scale is crucial to define biodiversity areas that have been driven by micro-environmental factors and also provide a tool for filtering species and areas of priority, not only for the presence of endangered species, but also for the conservation of elements of biogeographical interest (Fenu, Fois, Cañadas, & Bacchetta, 2014; Fenu, Mattana, Congiu, & Bacchetta, 2010; Rodrigues, Figueira, Vaz Pinto, Araújo, & Beja, 2015).

There is a great variety of previous studies on the subject that have based biogeographical regionalization on different taxonomic levels and groups (Brown & Bredenkamp, 2018; Fenu et al., 2014; González-Orozco, Laffan, Knerr, & Miller, 2013; Kreft & Jetz, 2010; Rodrigues et al., 2015). To identify biogeographical areas, the spatial distribution of vascular flora or fauna (Linder et al., 2012; Moreno Saiz, Donato, Katinas, Crisci, & Posadas, 2013) and, in particular, the co-occurrence of endemic taxa is especially used for conservational purposes (Cañadas et al., 2014; Escalante, Morrone, & Rodríguez-Tapia, 2013; Fenu et al., 2014; González-Orozco et al., 2013; González-Orozco, Thornhill, Knerr, Laffan, & Miller, 2014; Morrone, 2008, 2018). The main advantage of using endemic taxa in recognizing biogeographic units is that their spatial distribution is not random and uneven through specific areas or habitat-type (Bradshaw, Colville, & Linder, 2015; Casazza, Zappa, Mariotti, Médail, & Minuto, 2008; Laffan & Crisp, 2003). In addition, endemics are often vulnerable because of their narrow distributions, distinctive evolutionary history and somewhat low population size, (Huang et al., 2016; Orsenigo et al., 2018). Accordingly, their conservation is highly important in the global and local prioritization efforts, and the recognition of areas with the highest endemic richness is the preliminary step for practical conservation policies (Moreno Saiz, Castro Parga, & Sainz Ollero, 1998; Orsenigo et al., 2018).

Several factors contribute for distribution of endemic taxa, such as climate, altitudinal ranges, geographical barriers, human impacts, biotic interactions and stochastic events (Fenu et al., 2014; Fois, Fenu, Cañadas, & Bacchetta, 2017; Morrone, 2018); it is therefore common to include abiotic information for biogeographic classifications (e.g. Blasi & Frondoni, 2011; Cañadas et al., 2014; Escalante et al., 2013; Fenu et al., 2014), which is allowing the investigations of biogeographic dynamics related to environmental changes (Burns, 2016; Ferrier et al., 2006). Multivariate and clustering partitioning techniques, such as k-means algorithm (Mateo, Vanderpoorten, Muñoz, Laenen, & Désamoré, 2013; Razavi & Coulibaly, 2013; Rueda, Rodríguez, & Hawkins, 2010), unweighted pair-group method (Bradshaw et al., 2015; Dapporto, Ciolli, Dennis, Fox, & Shreeve, 2015; Hattab et al., 2015; Kreft & Jetz, 2010), Ward's clustering (Rodrigues et al., 2015; Wohlgemuth, 2006) were used in regionalization methods in conjunction with spatial distribution of flora and/or fauna and have been succeeded in biogeographical delineations at different scales. Examples are the regionalization at global (Kreft & Jetz, 2010), European (Moreno Saiz et al., 2013; Rueda et al., 2010), Saharan Africa (Linder et al., 2012), tropical Africa (Droissart et al., 2018) and Mediterranean Basin scales (Buira, Aedo, & Medina, 2017; Cañadas et al., 2014; Fenu et al., 2014). In order to depict a biogeographical unit, two means can be used separately or together: the occurrence of endemic taxa (flora or fauna) and the environmental conditions (Fenu et al., 2014; Rodrigues et al., 2015).

Egypt is an interesting country belonging to both the Saharo-Arabian and Mediterranean regions, and characterized by the presence of long coasts of both the Mediterranean and Red Sea, the Nile River, and by a high geological, environmental and climatic heterogeneity (Boulos, 2009; Zahran & Willis, 2009). Moreover, Egypt is the meeting point of four floristic territories: African-Zambezian, Irano-Turanian, Sahara-Sindian and Mediterranean-Sahara (El-Hadidi, 2000). Hence, recognizing the biogeographical units and endemic species-rich areas is useful for implementing effective conservation plans and measures in order to maximize the number of conserved species.

Despite of many earlier studies have been investigated the biogeographical territories in Egypt (El-Hadidi, 2000; El Hadidi & Fayed, 1995; Hassib, 1951; Täckholm, 1974), all of them were based on native flora and physiognomy of vegetation without any special reference for environmental variables, species and/or endemism richness. In addition, these studies were based on expert-based delineations, which unable other authors to replicate, update or improve their works.

In this study, we strived to fill a knowledge gap in biogeographical units and endemic plant diversity patterns to underpin conservation planning efforts in Egypt. The main aim of this study was to set out biogeographical units (sectors and subsectors) of Egypt based on a two-step procedure that first considers the regional environmental features together and then the spatial distribution of endemic vascular taxa.

2. Material and methods

Our study involved several steps concerning data sources and analysis **(Fig. 1)**. Two overlapping approaches were applied to define the biogeographical units in Egypt. First, we used a preliminary step including the environmental classification of Egypt, in terms of environmental variables such as climatic, soil, topographic, and habitat heterogeneity. This step is important to assess the drivers that characterize the main environmental clusers. Moreover, this allowed to avoid a zero-inflated presence/absence data set to be used for the subsequent hierarchical biogeographic regionalization.

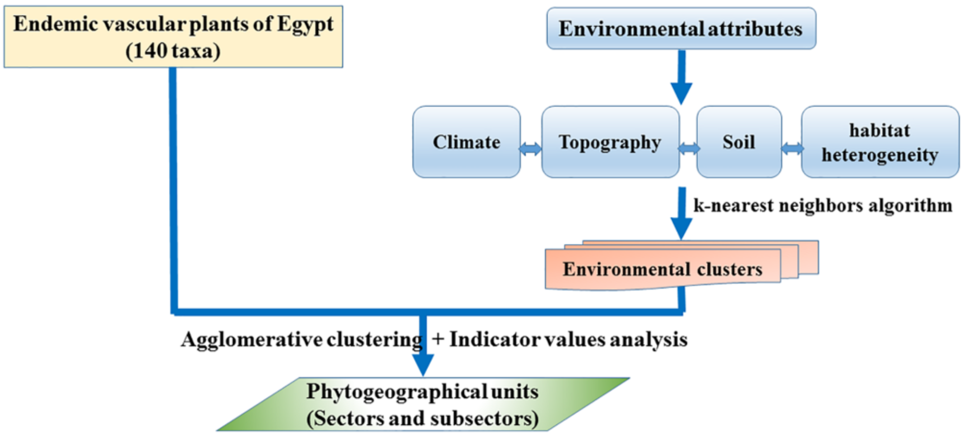

Figure 1. A conceptual diagram of the biogeographical approach.

2.1. Study area

This study was conducted on the whole of Egypt **(Fig. 2).** It extends from the south at the Sudanian border to the north at the Mediterranean Sea and from the east at the Red Sea to the west at the Libyan border with a total area of c. 1,019,000 km^2 representing c. 3% of Africa's total area (Zahran & Willis, 2009). Egypt is a portion of Sahara of North Africa, in the hyperarid zones. Egypt is distinguished by a hot and dry climate. Over the whole country, the average annual rainfall is only c. 10 mm (Zahran & Willis, 2009). The scanty rainfall indicates that the majority of the Egypt is infertile and deserted. Summers are hot with a mean annual temperature of more than 30°C while winters are mild with an annual temperature between 10°C and 20°C. The lowest temperatures are at mountains of Southern Sinai and the Red Sea (Hegazy & Lovett-Doust, 2016). Moreover, the general pattern of climate is largely similar, temperature rising and rainfall declining speedily inland from the northern Mediterranean coast (where most of the rain occurs, average annual rainfall c. 100 mm) and then more steadily south over the rest of the country (southwards). According to bioclimatic map of the world (http://www.globalbioclimatics.org), Egypt is located in the Mediterranean region and belongs to two climatic provinces: desertic-oceanic province (includes all the Mediterranean coastal region of Egypt) and the hyperdesertic-oceanic province (includes the rest of the Egypt) (Rivas-Martínez, Rivas-Sáenz, & Penas-Merino, 2011).

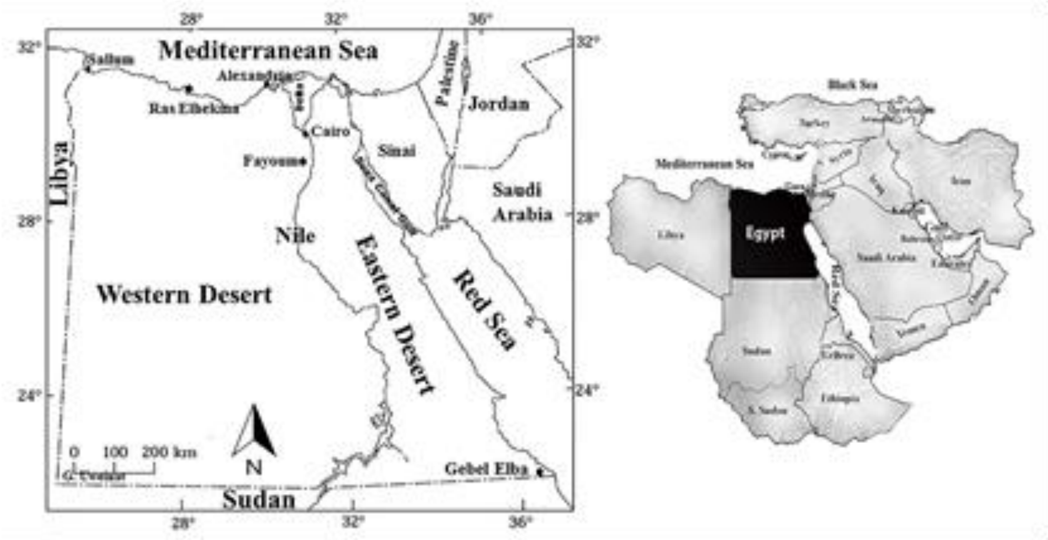

Figure 2. Map of Egypt.

2.2. Datasets and environmental clustering

The environmental features used in this study were 33 variables, categorized into four datasets as follow: 1) climate, 2) topography, 3) soil and 4) habitat heterogeneity **(Appendix A)**. The climate dataset includes 24 bioclimatic variables, 19 of them were downloaded from the WorldClim dataset v.2 (http://worldclim.org/version2) (Fick & Hijmans, 2017), while the remaining five variables were retrieved from the ENVIREM dataset v.1.0 (http://envirem.github.io/, (Title & Bemmels, 2018). Topography was classified into three layers: elevation, slope and aspect. Elevation layer was also downloaded from the ENVIREM dataset v.1.0, while slope and aspect were generated based on elevation data through ArcGIS v.10.4.1. Both layers of soil dataset, pH (in H_2O) and organic carbon content at a depth interval of 0-100 cm were obtained from IGBP-DIS SoilData V.0 available from (Global Soil Data Task, 2014). Habitat heterogeneity was quantified by the spatial heterogeneity of habitats based on the textural features of Enhanced Vegetation Index (EVI) imagery. This dataset includes four metrics: coefficient of variation of EVI, evenness of EVI, range of EVI and Shannon diversity of EVI, and were retrieved from the EarthEnv v.1.0. (http://www.earthenv.org/texture) (Tuanmu & Jetz, 2015). Finally, all of these datasets were cropped to the spatial extent of Egypt ranging from 22˚ to 32˚ N latitude with a further WGS84 projection and resampled with 20×20 km resolution. Only the grid cells with at least 35% of their surface area not covered by water were considered (Buira et al., 2017).

A propaedeutic exploratory data analysis, including a normality test, correlation matrix and multicollinearity statistics, was carried out to examine the relevance of the environmental attributes and spatial autocorrelation. To detect the multicollinearity and identify the influential variables to be used for clustering analysis of grid cells, variance inflation factors (VIFs) was calculated. Variables with VIF value greater than 5 were neglected as their contributions are negligible (Hair, Black, Babin, & Anderson, 2006). VIF was implemented using "sdm" package in the R environment (Naimi & Araújo, 2016). The 11 uncorrelated variables retained for next analyses are reported in **Table 1**.

Table 1. List of the environmental variables used in clustering analysis with their variance inflation factors (VIF< 5).

Environmental attribute	Code/unit	VIF
Climate dataset		
Mean temperature of wettest quarter	Bio8 (°C)	1.5
Mean temperature of driest quarter	Bio9 (°C)	3.4
Precipitation seasonality	Bio15	4.5
Aridity index	aridity index	2.9
Continentality	continentality (°C)	4.7
Topographic dataset		
Elevation	Elev (m a.s.l.)	1.4
Soil dataset		
Organic carbon	OC (mg/m^2)	3.1
Habitat heterogeneity dataset		
Coefficient of variation of EVI	CV-EVI	4.1
Evenness of EVI	evenness-EVI	4.2
Range of EVI	range-EVI	3.7
Shannon diversity of EVI	Shannon-EVI	4.9

A total of 2610 grid-cells for Egypt, each of 20 × 20 km UTM, were grouped on the basis of 11 non-linear environmental variables using ArcGIS version 10.4.1. We used the k-nearest neighbors algorithm and spatially constrained multivariate clustering tool to collect near features in the same cluster of similar grid cells and each feature will be a neighbor of at least one other feature in the cluster in order to create spatially contiguous clusters that are geographically connected (Assunção, Neves, Câmara, & Da Costa Freitas, 2006; Duque, Ramos, & Suriñach, 2007). The neighbor relationships were based on the spatial k-nearest neighbor where we specify the default integer value of 8 for the number of neighbors (Everitt, Landau, Leese, & Stahl, 2011). The Euclidean distance method was used to specify how distances are calculated between specific features to neighboring features. The optimal number of clusters was tested by pseudo F-statistics in ArcGIS environment. The largest F-value indicates the optimal number of clusters. Moreover, we carried out k-means clustering for all grid cells to test the stability of clustering and follow the evolution of variances among and within clusters (Buira et al., 2017; Mateo et al., 2013; Razavi & Coulibaly, 2013; Xu et al., 2014). Clusters will not be divided further if there is no variation in the analysis field values. To determine the key predictors in the clustering process, the value of R^2 for each variable was calculated and released in ArcGIS report. The larger the R^2 value (≥ 0.70) is for a particular variable, the better that variable is at discriminating among different features. The significance of different variables was determined using the Kruskal-Wallis test followed by Dunn's method as a multiple pairwise comparisons and Bonferroni's correction. Finally, the importance of variables within clusters was expressed by the lowest share value that released in ArcGIS report. This value ranges from 0 to 100 and was generated for each variable within the different clusters. This value is the ratio of the range of this variable within the cluster and its range within the whole country and calculated as follows:

Share value = $\frac{\text{Variable range within a cluster (maximum} - \text{minimum)}}{\text{Overall variable range (maximum} - \text{minimum)}} \times 100$. Variables with the lowest share value (< 30%) in each cluster were considered the most important in the grouping process of this cluster.

2.3. Biogeographic regionalizion

Endemic plants used for this second step analysis (see appendix B) include all exclusive endemics to Egypt and other taxa shared between Egypt and only one neighboring countries. A list of vascular plants exclusive to Egypt was taken from Abdelaal, Fois, Fenu, & Bacchetta (2018), while the list of endemics shared with other neighboring countries was obtained after Shaltout, Ahmed, Diab, & El-Khalafy (2018). The distribution of endemic taxa was inferred from bibliographic information (Abdelaal et al., 2018; Boulos, 2009; Hosni, Hosny, Shamso, & Hamdy, 2013; Shaltout et al., 2018; Täckholm, 1974), herbaria and field surveys. The distribution of each taxon was recorded in the form of point information within the identified environmental clusters in order to create a contingency table using presence-absence coding. Agglomerative Hierarchical Clustering analysis (AHC) was used to make up uniform biogeographical units (hereafter sectors and subsectors) on the basis of endemic taxa presence (Hattab et al., 2015; Kreft & Jetz, 2010). AHC is an iterative automated classification method based on Jaccard dissimilarity coefficient and a complete linkage as an agglomeration method. The resulting biogeographical sectors and subsectors were named in relation to their local toponymy in Egypt after Täckholm (1974).

The two levels of clusters corresponding to the two biogeographical units (sectors and subsectors), were objectively determined through the indicator value (IndVals) analysis. This analysis was proposed by Dufrêne & Legendre (1997) as a possible stopping rule for determine the optimal number of final clusters (Beaugrand, Reid, Ibañez, Lindley, & Edwards, 2002; Perrin, Martin, Barron, & Roche, 2006), as IndVal will be low when groups are too finely or too broadly defined, peaking at some intermediate, most informative level of clustering (Dufrêne & Legendre, 1997). IndVals analysis was run on the output from the hierarchical clustering yielding all possible number of groups with 1000 randomisations used in the Monte Carlo tests. Maximum cumulated number of significant indicators ($P > 0.05$) and average P values were selected as criteria (Beaugrand et al., 2002; Perrin et al., 2006). We calculated the IndVal using “indval” function which is included in the “labsdv” R package (Roberts, 2016), where a species is recognized as an indicator for a particular sector or subsector when its IndVal > 0.50 at $P < 0.05$.

Finally, the percentage of areas (number of grid cells) of the identified biogeographical sectors included within the protected areas was calculated. The protected area data for Egypt was downloaded from the World Database on Protected Areas (https://www.protectedplanet.net).

3. Results

3.1. Environmental clusters

Based on pseudo F-statistics, the maximum values were obtained for k=15 **(Fig. 3a)**, hence 15 environmental clusters of Egypt were defined and mapped **(Fig. 3b)**. The number of grid cells in each cluster as well as the R2 and the average value of characteristics variables are reported in Appendix C. Except for habitat heterogeneity variables (CV-EVI, evenness-EVI, range-EVI and Shannon-EVI), the rest of the variables were significantly differed as shown by Kruskal-Wallis test among clusters.

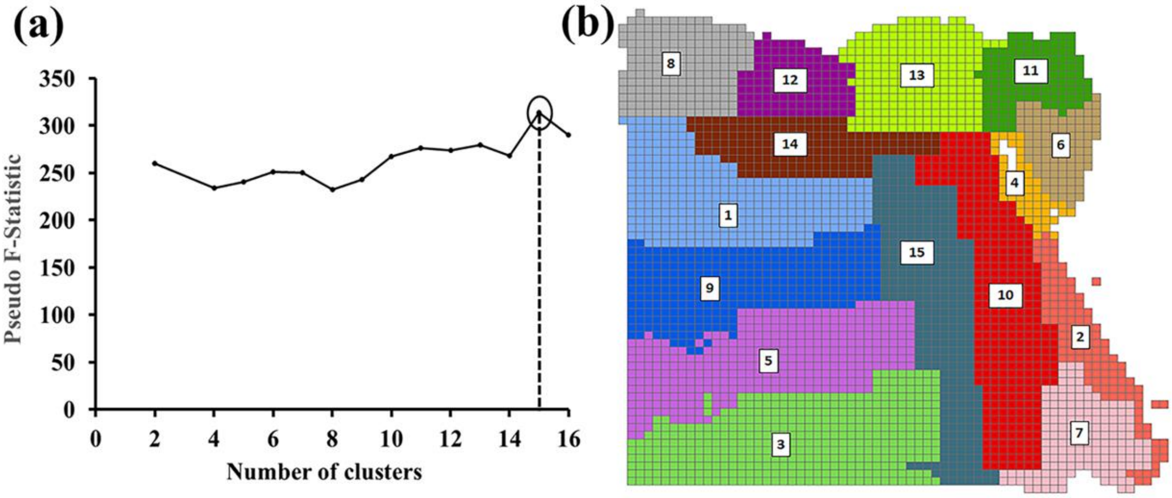

Figure 3. (a) Pseudo F-statistic chart for evaluating the optimal number of clusters. The dashed line indicates the highest F-value, and (b) environmental clusters of Egypt based on the selected environmental attributes.

In most cases, the environmental clusters were delineated by climatic factors which were unique to those clusters and distinct from the other clusters **(Appendix C).** The key predictors that have together contributed for environmental clustering of Egypt with highest R^2 value (≥ 0.70) were mean temperature of wettest quarter (Bio8, R^2= 0.88), aridity index (R^2= 0.81), precipitation seasonality (Bio15, R^2= 0.80), continentality (R^2= 0.79), mean temperature of driest quarter (Bio9, R^2= 0.78), soil organic carbon (R^2= 0.76) and elevation (R^2= 0.70). While the remaining four related habitat heterogeneity variables showed a lower percent in clustering process (R^2< 0.20) **(Appendix C)**. The shared percent of variables as an indicator of their importance in each cluster is displayed in **Table 2**. Bio8 was the most important variable for separation of clusters 1, 2, 11, 13 and 14, while aridity index was the most influential factor for separation of clusters 3, 5, 7, 10 and 15. Bio15 was the main factor for separation of clusters 8, 9 and 12. Finally, continentality and elevation were the most important factor for separation of clusters 4 and 6, respectively.

Table 2. The share values of variables as a measure for their importance in each environmental cluster. Important variables with low shared values < 30% in each cluster are in bold.

Variable	Environmental cluster														
	1	3	5	9	13	14	15	8	11	12	6	10	7	2	4
Bio8	**11**	62	**28**	**13**	**12**	**16**	52	**4**	**23**	**12**	**22**	52	52	**26**	**22**
Bio9	**16**	64	64	**10**	**20**	44	48	**5**	48	**17**	64	59	48	86	34
Bio15	**18**	**24**	45	**4**	**15**	40	**27**	**3**	42	**11**	**16**	68	**27**	86	**18**
Aridity Index	73	**0**	**7**	47	70	**23**	**0**	40	47	41	**18**	**20**	**0**	54	33
Continentality	**29**	**14**	**24**	**28**	43	71	**28**	**28**	57	**28**	**28**	**28**	**28**	71	**14**
Elevation	**12**	32	37	**12**	75	70	36	**11**	**25**	40	**0**	94	35	75	69
OC	58	**12**	30	28	60	90	31	**23**	72	45	46	35	31	40	**24**
CV-EVI	77	86	93	64	39	100	88	53	100	58	86	86	88	95	59
Evenness-EVI	97	91	95	43	59	96	98	33	96	38	93	97	97	92	95
Range-EVI	90	83	87	60	45	98	93	**20**	98	85	73	83	93	89	87
Shannon-EVI	94	75	81	53	31	89	76	37	90	54	76	93	76	75	95
Biogeographic sector	Egyptian Libyan-Nubian Desert				Nile region			Egyptian Mediterranean coast			South Sinai-Egyptian Arabian Desert		Gebel Elba	Egyptian Red Sea coast	

3.2. Biogeographical sectors and subsectors of Egypt

The resulted 15 environmental clusters were grouped into six biogeographical sectors and nine subsectors were identified through the AHC analysis on the basis of endemic taxa distribution **(Fig. 4a, b)**. The sectors include (1) Egyptian Libyan-Nubian Desert except the northern coast, (2) Nile region, (3) Egyptian Mediterranean coast except that of Nile Delta, (4) South Sinai- Egyptian Arabian Desert, (5) Gebel Elba and (6) Egyptian Red Sea coast with its Suez Gulf **(Fig. 5a, b, Table 3).**

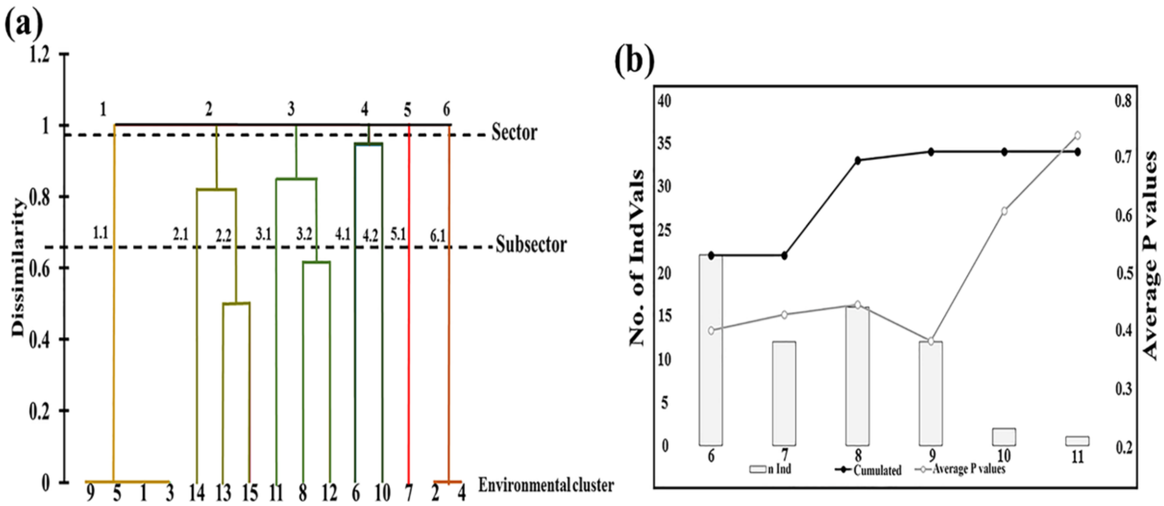

Figure 4. (a) Agglomerative hierarchical cluster (AHC) dendrogram showing two cut-off levels to define sectors and subsectors, based on (b) variation in the number of significant indicators (full points) identified by IndVal analysis and the average p value of all species (empty points) at each step of hierarchical cluster analysis.

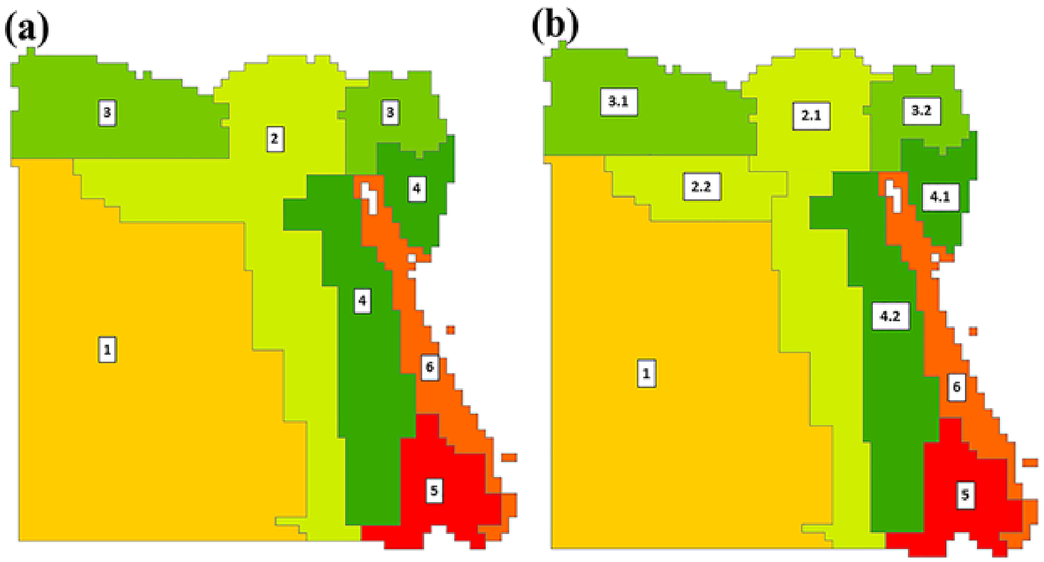

Figure 5. (a) six biogeographical sectors: 1) Egyptian Libyan-Nubian Desert, 2) the Nile region, 3) Egyptian Mediterranean coast, 4) South Sinai-Egyptian Arabian Desert, 5) Gebel Elba and 6) Egyptian Red Sea coast, and b) biogeographical subsectors: 2.1) Nile Delta and Valley, 2.2) Nile Fayoum, 3.1) Mariut coast, 3.2) North Sinai, 4.1) South Sinai and 4.2) Egyptian Arabian Desert.

In terms of surface, the largest sector is the Egyptian Libyan-Nubian Desert sector (434400 km^2), followed by the Nile region (223600 km^2), South Sinai- Egyptian Arabian Desert (178400 km^2) and the Egyptian Mediterranean coast (140000 km^2), while the smallest one was Gebel Elba sector (52400 km^2) **(Table 3)**. Only three sectors 2, 3 and 4 were subdivided into subsectors **(Fig. 5b)**. The Nile region sector was classified into two subsectors: The Nile Delta and Valley, and Nile Fayoum, while sector of the Egyptian Mediterranean coast was also subdivided into two subsectors: Mariut coast (from Alexandria to Sallum) and North Sinai. Finally, sector 4 was distinguished into two subsectors: South Sinai and the Egyptian Arabian Desert.

Table 3. Main characteristics of the identified biogeographic sectors and subsectors of Egypt.

Sectors	Subsectors	Environmental clusters	Area (km^2)	No. endemics	No. of indicator species	Percent of protected area
1. Egyptian Western Desert		1, 3, 5, 9	434400	6	1	13.51
2. Nile region		13, 14, 15	223600	16	4	9.86
	2.1. Nile Delta and Valley		166000	13		
	2.2. Nile Fayoum		57600	7		
3. Egyptian Mediterranean coast		8, 11, 12	140000	71	19	13.26
	3.1. Mariut coast		100800	40		
	3.2. North Sinai		39200	45		
4. South Sinai-Egyptian Eastern Desert		6, 10	138800	63	10	22.65
	4.1. South Sinai		30800	54		
	4.2. Egyptian Eastern Desert		108000	22		
5. Gebel Elba		7	52400	7	-	62.73
6. Egyptian Red Sea coast		2, 4	54800	2	-	29.05

All sectors were characterized by the presence of a specific number of endemic taxa ranging from two to 71 taxa **(Table 3, see appendix B for details)**. At the sector level, the highest number of endemics was found in the Egyptian Mediterranean coast (71 taxa, 52 exclusive and 19 shared taxa), followed by South Sinai- Egyptian Arabian Desert (62 taxa, 50 exclusive and 12 shared taxa) and the Nile region (16 taxa, nine exclusive and seven shared taxa) whereas Gebel Elba and the Egyptian Libyan-Nubian Desert sectors host seven and six exclusive taxa, respectively. At subsector level, the highest number of endemics was recorded in South Sinai (54 taxa), followed by North Sinai (45 taxa) and Mariut coast (40 taxa).

Of the 140 analyzed endemic taxa, 33 species indicated a significant IndVal and were thus considered as indicator species for each identified phytogeographic sectors **(Table 3, see appendix B for details)**. The Egyptian Mediterranean coast sector was characterized by 19 indicator species, while South Sinai- Egyptian Arabian Desert had 10 indicator species. The Nile region was characterized by the presence of four indicator species. On the other hand, the Egyptian Libyan-Nubian Desert sector hosts one significant indicator species (*Melilotus serratifolius* Tackh. & Boulos) while Gebel Elba and the Egyptian Red Sea coast sector lacks the presence of any indicator species.

Our analysis displayed that, the identified biogeographical sectors and subsectors for endemic vascular plants are not well represented within the already established protected area network in Egypt **(Table 3)**. The

Nile region and the Egyptian Mediterranean coast sectors were the least represented sectors (9.86 and 13.26%, respectively), whereas Gebel Elba and the Egyptian Red Sea coast sectors were the most represented sectors within the protected areas (62.73 and 29.05%, respectively).

4. Discussion

The present study is the first contribution for delineating phytogeographical sectors and subsectors of Egypt depending on environmental features and spatial distribution of endemic vascular taxa.

This study provides a replicable method to cluster biogeographical areas, using a reiterative approach which will firstly consider abiotic factors and then will ensemble the obtained units by the presence/absence of relevant biotic elements. This approach was for the phytoregionalization of Egypt, by considering the distribution of endemic plant species, but the same initial environmental units can constitute the baseline for further regionalization with other species groups. The main strengths in our method are 1) it can be used at any geographical scale in other arid countries that host poor sampling regions, 2) it avoids the effect of sampling or extrapolation biases, 3) the grid cells in the same cluster are geographically connected (spatial contiguity constraint) and 4) nearly all the biogeographical sectors and subsectors are continuously connected.

Unfortunately, there is no comprehensive study conducted on the biogeographical regionalization of Egypt using quantitative evidence for the distribution of native vascular plants. By comparing with previous studies which relied on the qualitative support of experts, the phytogeographical scheme identified in this study was relatively concordant with the definitions of El-Hadidi (2000) and Täckholm (1974), although differences in some extent at the subsectors level. All sectors were well-defined, not only due to the endemic flora or indicator species that they include but also due to their environmental features that contribute to the clustering process.

The use of other species groups will be used to improve such first results. For instance, the biotic information of El-Saadawi, Shabbara, Refai, & Abou-Salama (2003), who used the distribution of mosses species in Egypt and recognized 15 territories, or by Hoath (2009), who defined seven zoogeographical regions of Egypt by using mammals, can be used to repeat and then compare our proposed method. Indeed, all of these previous studies focused their definition on the only biotic aspects, without directly including the environmental factors in their analyses.

For instance, the Egyptian Libyan-Nubian Desert sector was possible to be defined, in spite of the presence of only six endemic species, with one indicator species (*Melilotus serratifolius*). Such results, which are quite consistent with Zahran & Willis (2009), are in this case determined more by climatic factors (Bio8, Bio15 and aridity index) than by the presence of endemics. Also Zahran & Willis (2009) indeed highlighted the consideration of the Egyptian Libyan-Nubian Desert (i.e. known previously as the Western

Desert) as a biogeographical region with a low flora, determined by extremely arid conditions, lack of isolation barriers and historical constraints. In Täckholm definition (Täckholm, 1974), the scattered oases in this sector, such as Siwa, Bahariya, Farafra, Dakhla and Kharga, were ecologically separated from the rest of the Egyptian Libyan-Nubian Desert. However according to our results, no sharp change in species composition or clear environmental variation can be distinguished.

The Nile region sector was subdivided into two subsectors (Nile Delta and Valley, and Nile Fayoum) mainly on the basis of two climatic factors (Bio8 and aridity index), eight exclusive species and four indicator species. In this sector, climatic aridity gradually increases from Nile Delta, Nile Valley until Nile Fayoum. The Nile Fayoum depression connected with the Nile River through an irrigation canal and this support its floristic and endemicity similarity with the rest of the Nile (Delta and Valley). This finding was also confirmed by El-Saadawi et al. (2003) for mosses and Zahran & Willis (2009) in terms of vegetation composition.

The Egyptian Mediterranean sector includes all the northern Mediterranean coast of Egypt, except the northern coast of the Nile Delta. Of most attention, through this sector, North Sinai is separated from the Sinai Peninsula in addition to an exclusion of the northern Mediterranean sector of the Nile Delta. In this sense, the Nile Delta is considered a land barrier preventing the continuity of the Mediterranean coastal strip of Egypt. Two climatic factors (Bio15 and Bio8) in coupling with exclusive (52 species) and indicator species (19 species) played as key drivers for the partition of this sector and its subsectors. The most distinctive features are the relatively high rainfall and low temperature, which in turn support a wide range of plant diversity and endemic species. Amongst endemics, there are Anthemis microsperma, Pancratium arabicum, Allium mareoticum and Verbascum letourneuxii. Our results resemble to some extent the studies of Zahran, El-Demerdash, & Mashaly (1990), Zahran & Willis (2009) and Frihy & El-Sayed (2013). The main difference was the exclusion of the northern Mediterranean sector of the Nile Delta. This difference may be addressed the effect of fresh water of the Nile River (Zahran & Willis, 2009) and the impact of recent human activities in this area (Shaltout, Sharaf El-Din, Ahmed, 2010), which, in addition to the differences in temperatures and precipitations, might have influenced the current flora. According to Wickens (1977), further studies might consider comparisons with historical data in order to measure the effect of human disturbances. The physiographic differentiation of the Mariut coast subsector into two subregions, Alexandria- Ras Elhekma and Ras Elhekma-Sallum (Bidak, Kamal, Halmy, & Heneidy, 2015), is consistent with our regionalization according to the environmental factors, but was not supported by enough significant indicator species. Unfortunately, this coastal sector is one of the most threatened sectors in Egypt due to excessive tourism activity. With the exception of El-Omayed Biosphere Reserve, no land or species in this sector is protected or conserved (Hoath, 2009).

According to our results, South Sinai and North Sinai cannot be grouped into one region under the so-called Sinai Peninsula. Therefore, South Sinai can be better represented as a continuation of the Egyptian

Arabian Desert, and North Sinai as a subsector in the Egyptian Mediterranean coast. This finding is also supported by geological and zoogeographical characterizations (Hoath, 2009). Both South Sinai and the Egyptian Arabian Desert are characterized by mountain terrains dissected by water-eroded wadis (Hoath, 2009). Although both subsectors (South Sinai and the Arabian Desert) are environmentally similar, only 11 shared species were found. This may be attributed to the presence of the Gulf of the Red Sea (Suez Gulf) which acted as a water barrier. However, South Sinai- Egyptian Arabian Desert hosts 50 exclusive endemic species (see Appendix B), ten of them are indicator species (e.g. *Centaurea scoparia*, *Iphiona mucronata*, *Salvia deserti*, *Echinops hussonii*, *Echinops glaberrimus*, *Galium sinaicum*). These xerophytic species are exclusive to this sector, as a result of isolation factors, wet climate and physiographic features that function as refugia in the desert areas (Abdelaal et al., 2018; Moustafa, Zaghloul, Wahab, & Shaker, 2001). The main factors that played an important role in the separation of this sector were elevation and aridity index. Both South Sinai and the Egyptian Eastern Desert are characterized by high and rugged mountains (Zahran & Willis, 2009); in particular, South Sinai is the highest elevated land in Egypt (1500-2600 m. a.s.l.) (Ayyad, Fakhry, & Moustafa, 2000). Nonetheless, our results differed than the ones reported by other authors (Hassib, 1951, El-Hadidi, 1980, El-Ghani, Huerta-Martínez, Hongyan, & Qureshi, 2017). Hassib (1951) outlined the Egyptian Eastern Desert into three main biogeographical regions: Northern Arabian Desert, Southern Arabian Desert and the Red Sea, while Abd El-Ghani, Salama, Salem, El-Hadidy (2017) divided it into two units: the Eastern Desert and the Red Sea, with a sequential subdivision of the former into Galala Desert and the Arabian Desert. The floristic composition of the Egyptian Arabian Desert differs from the Egyptian Libyan-Nubian Desert one, reflecting the very different climate (extremely arid), topography (low altitudes and few wades) and the importance of the Nile River as a physical barrier.

Gebel Elba sector is well-separated at the southeasternmost corner of Egypt between the Saharo-Arabian desert and the highlands of Sudan, adjacent to the Red Sea. According to our results, the main reasons for separation of Gebel Elba were aridity index and the exclusive presence of three indicator endemic species (*Biscutella didyma* var. *elbensis*; *Ifloga spicata* subsp. *elbaensis* and *Solanum nigrum* var. *elbaensis*). These taxa are highly specific for the fundamental conditions (orographic rainfall and granite mountains) and its geographic location (Abd El-Ghani & Abdel-Khalik, 2006; Abdelaal et al., 2018). All previous related studies (Hassib, 1951; Zahran & Willis, 2009) confirmed the consideration of Gebel Elba as one of the main biogeographical units of Egypt.

Finally, the Egyptian Red Sea coast and its Suez Gulf sector were delimited as a distinct sector on the basis of climatic factors (Bio8 and continentality) and the presence of two endemic species (*Lotus nubicus* and *Tephrosia purpurea* subsp. *apollinea*, **see Appendix B**). This sector has been differently interpreted by El-Hadidi, (1980), who considered it as subarea within the Egyptian Arabian Desert division, and by Abd El-Ghani, Salama, & El-Tayeh (2013), who, in accordance to our results, considered it as an independent area.

Our results showed that the coastal Mediterranean and mountainous sectors and subsectors host higher endemic species richness as compared with inland and low-lands. Such finding was already recorded by Lobo, Castro, & Moreno (2001) and Simón et al. (2002) in Europe, Fenu et al. (2014) in Mediterranean Basin and Abdelaal et al. (2018) in Egypt. The main reasons for endemic richness may be attributed to all factors related to the high altitudinal ranges, such as isolation, habitat diversity and low human pressure. South Sinai is the richest subsector followed by North Sinai, and Mariut coast.

Nearly all of the variables were significantly differed and varied among clusters. Specifically, the classification pattern was mainly influenced by climatic-related variables, soil organic carbon and elevation. In line with our results, previous studies (Hattab et al., 2015; Huang et al., 2016) also have reported the importance of environmental variables in shaping the patterns of species distribution. In this sense, the Mediterranean coast, the Nile region and the Egyptian Libyan-Nubian Desert sectors are shaped by mean temperature of the wettest quarter (Bio8), precipitation seasonality (Bio15) and aridity index, while the South Sinai- Egyptian Arabian Desert sector is shaped mainly by elevation. In general, our case study reveals that climate-related variables (precipitation seasonality, temperature, continentality and aridity index), elevation and finally soil organic carbon are the most important determinants for biogeographical regionalization of Egypt. This finding in a broad agreement with Djamali, Brewer, Breckle, & Jackson (2012)who highlighted the importance of both precipitation seasonality and continentality in differentiating phytogeographic subregions of the Irano-Turanian region. In contrast, all vegetation-related parameters played an insignificant role in our analysis. This may be attributed to a little variation occurred at the scale of the study area and also due to the fact that Egypt is an extremely arid region with very scanty vegetation (Zahran & Willis, 2009).

Prioritizing conservation efforts require detailed information about endemic-rich regions, diversity patterns and environmental drivers (Ficetola et al., 2017; Rondinini, Wilson, Boitani, Grantham, & Possingham, 2006). Our study provides valuable information regarding the biogeographical sectors and subsectors in Egypt and highlighted the richest sectors in endemic taxa and degree of protection. This information will guide to implement an effective conservation plan and to adopt appropriate conservation actions in the future. Although the Egyptian Mediterranean coast sector resulted particularly rich in endemic plants, the protection rate is insufficient. It suggests further efforts in the protection of this sector and in enhancing knowledge on the detailed distribution and conservation status of each species. Since endemic plants are often classified as threatened, mainly due to their limited geographic distribution and ecological amplitude, they constitute a first-step group for conservation. Nonetheless, correlation with such environmental diversity and other species' groups should be investigated to better address more effective conservation actions.

5. Conclusion

This is the first contribution towards delineating the biogeographical units in Egypt using advancement in quantitative approaches. Our results showed a distinctive biogeographical scheme including six sectors and nine subsectors, highlighting the importance of climatic-related variables, elevation and soil organic carbon in shaping the environmental clusters and endemism in Egypt. We also showed that the already established protected areas in Egypt are not sufficient for conserving the identified endemic-rich Mediterranean coast sector. Moreover, knowing which geographical units or environmental clusters are likely to contract or expand in the range under a changing climate or excessive human impacts will assist in predicting the future of the environmental clusters or ecoregions. Our regionalization method could be replicated for other species' groups, with the ultimate goal of integration all species of interest in a single biogeographical system. For this reason, we kindly invite other researchers to use our same environmental cluster output, which will be provided by contacting the first and/or corresponding author.

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CHAPTER III

Using MaxEnt modeling to predict the potential distribution of the endemic plant *Rosa arabica* Crép. in Egypt

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Abstract

Climate change poses negative impacts on plant species, particularly for those of restricted ecology and distribution range. *Rosa arabica* Crép., an exclusive endemic species to Saint Catherine Protectorate in Egypt, has severely declined and become critically endangered in the last years. In this paper, we applied the maximum-entropy algorithm (MaxEnt) to predict the current and future potential distribution of this species in order to provide a basis for its protection and conservation. In total, 32 field-based occurrence points and 22 environmental variables (19 bioclimatic and three topographic) were used to model the potential distribution area under current and two future representative concentration pathways (RCP2.6 and RCP8.5) for the years 2050 and 2070 Annual temperature, annual precipitation and elevation were the key factors for the distribution of *R. arabica*. The response curves showed that this species prefers habitats with an annual temperature of 8.05-15.4°C, annual precipitation of 36 to 120 mm and elevation range of 1571 to 2273 m a.s.l. Most of the potential current suitable habitats were located at the middle northern region of Saint Catherine. Prediction models under two future climate change scenarios displayed habitat range shifts through the disappearance of *R. arabica* in sites below 1500 m a.s.l., an altitudinal range contraction at 1500-2000 m and possible expansions towards higher elevation sites (2000-2500 m a.s.l.). Our findings can be used to define the high priority areas for reintroduction or for protection against the expected climate change impacts and future modifications.

Keywords: Environmental variables, global warming, habitat type, Saint Catherine, Sinai Peninsula.

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1. Introduction

The ecological niche of a species is the interaction of space and conditions where it is able to survive, persist and continuing its reproductive ability to remain in viable populations (Choudhury et al., 2016). Ecological niches play a central role in explanations of species origin, persistence, distribution and capacity of competition (Silvertown, 2004). Climate, soil features, topography, land-use and biological interactions have been recognized as the main drivers for distribution and ecological niche of species at various geographical scales (Woodward, 1987; Abolmaali et al., 2018). In particular, the climate warming may result in shifts in natural species range specifically for those of geographically limited and/or endemic species which are unable to adapt to unusual climatic conditions and thus become endangered or even extinct (Parmesan, 2006; Loarie et al., 2008; Cuena-Lombraña et al., 2018). Furthermore, human impacts cause additional habitat fragmentation and threaten plant diversity (Tilman and Lehman, 2001; Vásquez et al., 2015). The growing effect of such kind of impacts on plant species calls a request to realize areas where endangered species or species with narrow niche width exist or likely exist in order to enhance their conservation and restoration (Dubuis et al., 2011; Kaky and Gilbert, 2016).

Many endemic taxa are included in the IUCN Red List of the threatened species as they are in danger of global extinction because of their narrow geographic distribution and extremely habitat-restricted (Crisp et al., 2001; Orsenigo et al., 2018). Hence, protecting and conserving such species is important, through addressing the potential distribution of suitable habitats and finding the environmental factors which drive the presence and persistence under current and future conditions (Brooks et al., 2002; Primack, 2006; Attorre et al., 2018). The first step to initiate conservation processes for these taxa is to identify the current geographic distribution, population status and threats that expose them to the risk of extinction (Crisp et al., 2001).

To our knowledge, no previous studies have been done to address the ecological niche of *Rosa arabica* Crép. (*R. arabica* hereafter); accordingly, predicting its habitat suitability, in order to estimate its spatial geographic distribution, and exploring suitable persistence conditions are critical to conserving this plant species. Ecological niche models or species distribution models (SDMs) are aimed at predicting the suitable key sites for a target species in relation to environmental conditions where the species is present (Guisan and Zimmermann, 2000). Recently, SDMs are used to reintroduce, manage or rehabilitate numerous threatened species from being extinct in their historical native sites (e.g. Yang et al., 2013; Fois et al., 2016). Furthermore, SDMs can guide conservationist through predicting the impact of climate warming, land use change, exploring unsuitable areas as well as suitable areas with high presence for further surveys, reintroduction or natural preservation of such kind of endangered species (Thomas et al., 2004; Fois et al., 2016; Amici et al., 2017; Safaei et al., 2018). The main task of SDMs is to understand how the environment shapes the distribution of a species in its native area. To do so, we construct a SDM by collecting presence data and environmental features (climate and topography) stored in a geographic information system.

Numerical outputs of statistical SDMs have often been simplified to environmental suitability indexes, ranging from 0 (unsuitable) to 1 (optimal). Furthermore, it was proved that such index is often related not only to the probability of occurrence but also to other key parameters of populations, such as growth rate, surface area and number of vegetative and reproductive individuals (Csergő et al., 2017; Fois et al., 2018c).

Among SDMs, MaxEnt was chosen because of its numerous advantages including: (1) the input species data can be presence points only, (2) both categorical and continuous environmental layers can be applied, (3) its prediction is stable and reliable with a great accuracy even if low sample sizes are undertaken, thus can predict distribution of threatened species, (4) it creates a spatially explicit map for habitat suitability with an easy interpretation, (5) it enables replicated runs to test model robustness nonetheless threshold rule, (6) the importance of each environmental variable can be measured using jackknife test, (7) MaxEnt model (bioclimatic envelope model) can be used to project into the future under climate change to predict habitat losses and gains within species range and thus help in planning appropriate conservation measures (Phillips et al., 2006; Pearson et al., 2007; Elith et al., 2011; Fois et al., 2018b).

In this study, we addressed the following question: should future climate changes further reduce the suitable habitats for *R. arabica*? If so, this should be considered when planning to protect, restore or reintroduce this plant in its native environment in case of human threats (grazing and cutting) are controlled. Accordingly, we analyzed the potential distribution of *R. arabica* and the possible impact of climate warming. Hence, our objectives were: (1) to predict the current potential distribution, (2) to identify the key environmental factors that highly correlated with *R. arabica* distribution range, and (3) to forecast the impact of projected climate change under two global greenhouse emission hypotheses for the 21st century.

2. Materials and methods

2.1. Study area and target species

Our study was carried out in St. Catherine Protectorate, which is located in southern Sinai at the northeastern corner of Egypt with a total area of ca. 5196 km^2 **(Fig. 1a).** Saint Catherine is an igneous massif characterized by smooth faced-outcrops that formed mountain areas with an elevation range up to 2640 m a.s.l. (Moustafa and Klopatek, 1995). The location of St. Catherine supports the differentiation of distinctive environments (gorges, slopes, terraces, caves and ridges), each of them hosts a peculiar plant community (Moustafa et al., 2001; 2017). Saint Catherine is distinguished by a wide range of variation in air temperature and precipitation. It is categorized as the coolest region in Egypt and the only one that has snow (Moustafa et al., 2017). The average monthly temperatures range from 8.6°C in January to 25.5°C in August. The average annual rainfall (1970-2017) was scanty, irregular and reached c. 37.5 mm, but unpredictable one-day flash floods have occurred and reached c. 300 mm (years 2012-2014) (Moustafa et al., 2017; Omar et al., 2017).

According to Abdelaal et al. (2018), St. Catherine harbors 14 exclusive vascular plants, and it is therefore considered one of the most important Egypt’s protected landscape. The long-term drought, overgrazing and tourism activities are the main threatening factors for the plant diversity in St. Catherine (Moustafa et al., 2001; Zaghloul et al., 2006; Grainger and Gilbert, 2008). All of these threats will drive endemic and rare plant species to extinction risk.

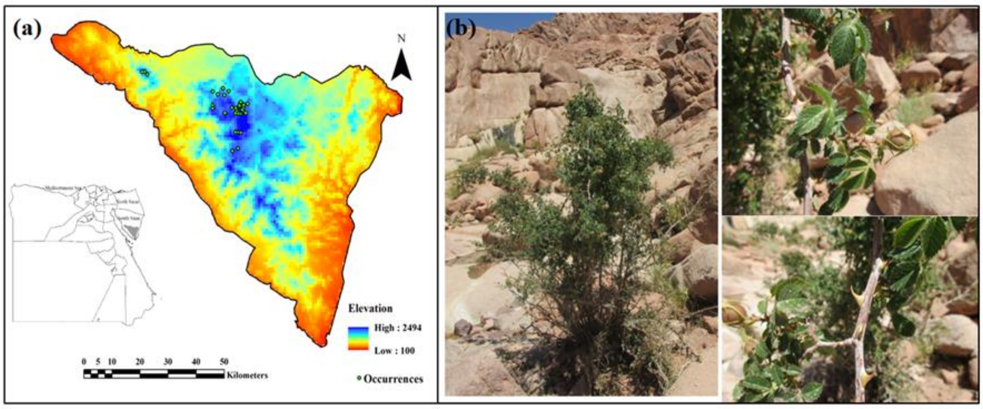

Fig. 1. (a) Map of Saint Catherine Protectorate with occurrence points of *Rosa arabica* and (b) *Rosa arabica* Crép.

R. arabica Crép. (Rosaceae) is a perennial prickly shrub 2-3 m tall **(Fig. 1b)**. It is an exclusive endemic species to St. Catherine Protectorate. It is only restricted to mountain wadis and gorges habitats near moist grounds at high elevations (Moustafa et al., 2001; 2017). During our filed surveys, *R. arabica* was recorded in nine localities within St. Catherine: Wadi Elarbain, Kahf Elgholah, Shaq Mousa, Gebel Ahmar, Farsh Elrumanna, Wadi Saqr, Wadi Tinia, Gebel Catherine, and Wadi Abu Twitta. The population size of *R. arabica* was of 81 individuals distributed in the above-mentioned nine localities. The highest number of mature individuals was recorded in Wadi Abu Twitta (14 individuals). These results are almost completely in accordance with Omar (2017), who recorded 90 mature individuals in 14 localities in 2015, reporting a continuous declining in number and extent of occurrence of *R. arabica* in the last 10 years. For a long-term monitoring of *R. arabica*, three permanent fenced enclosures (Kahf Elgholah, Shaq Mousa and Monastery garden in Wadi Elarbain) were made in 1998 (Moustafa et al., 2017).

R. arabica is a medicinal plant rich in active phenolic metabolites in addition to its high pastoral importance (Souleman and El-Mousallamy, 2000; Moustafa et al., 2017). Its flower and fruits can be used to treat the pain of woman's during the menstrual period and also in the ethnoveterinary use. Its edible fruits are used by local Bedouins as well as cutting off its branches for grafting the garden roses (Abd El-Ghani and Fahmy, 1994; Omar, 2017). *R. arabica* is listed as one of the most rare and threatened species in Egypt (Abd El-Ghani and Fahmy, 1994; Moustafa et al., 2017) and also assessed as a critically endangered (CR) taxon with an Extent Of Occurrence (EOO) of 40 km^2 and an Area Of Occupancy (AOO) of 36 km^2 (Omar et al., 2017).

2.2. Data sources and variables selection

The current distribution data of *R. arabica* in the study area was collected from fieldwork after revision of literature (Täckholm, 1974; Danin et al., 1985; Abd El-Ghani and Fahmy, 1994; Moustafa et al., 1995; Ayyad et al., 2000; Moustafa et al., 2001, 2017; Omar et al., 2017). We dealt with the autocorrelation issues by eliminating redundant presences in each 1 × 1 km grid on the scale of the bioclimatic variables used (de Luis et al., 2018). Furthermore, records were screened in ArcGIS 10.4.1 for spatial autocorrelation using average nearest neighbour analyses to remove spatially correlated data points (Bosso et al., 2016; Smeraldo et al. 2018). After this selection, 32 occurrence points of *R. arabica* were used to generate SDMs **(Fig. 1a)**.

Twenty-two variables were retrieved as predictors to model the potential environmental niche of *R. arabica* based on its current presence dataset. In particular, 19 bioclimatic layers and one topographic variable (elevation) were obtained from WorldClim database (http://www.worldclim.org/, Hijmans et al., 2005) at a spatial resolution of 30 arc-second (ca. 1 × 1 km). From elevation data, slope and aspect were extracted using ArcGIS 10.4.1. The overall environmental variables are summarized in **Table 1**. In order to eliminate multicollinearity and select the most fitting predictors that show more contribution power to the model, Variance Inflation Factors (VIFs) of 22 environmental variables were tested. VIFs are based on correlation coefficients (R^2) that created from regression among all predictors and was implemented through the 'sdm' package in the R-environment (version 3.1.1). Consequently, 14 variables with VIFs >5 were excluded (Chatterjee and Hadi, 2006) and only eight variables were kept to establish the distribution model of R. arabica under the current conditions (~1960-1990). The selected variables include annual mean temperature (Bio1), mean diurnal range (Bio2), isothermality (Bio3), mean temperature of driest quarter (Bio9), annual precipitation (Bio12), precipitation of driest month (Bio14), precipitation seasonality (coefficient of variation, Bio15) and elevation (Elev). Similarly, all of these non-linear variables with an exception of elevation were used for *R. arabica* modeling under future global warming scenarios. In the 5th report of the Intergovernmental Panel on Climate Change (IPCC2014), four representative concentration pathways (RCPs) were set using the total radioactive forcing of values 2.6, 4.5, 6 and 8.5 watt/m2. Two of these scenarios, RCP2.6 (minimum emission hypothesis) and RCP8.5 (maximum emission hypothesis) were chosen in our study. One global climate model CCSM4 was obtained from WorldClim database under both scenarios over the periods 2050 (average for 2041-2060) and 2070 (average of 2061-2080). CCSM4 is one of the most efficient global climate projection that predicts the influence of future climatic changes on the distribution of plant species and was already successfully tested in similar environments (Al-Qaddi et al., 2017; Sanjerehei and Rundel, 2017).

Table 1. Environmental variables used for modeling the potential distribution of *R. arabica* in the present study. Problems related to collinearity were avoided by removing variables with variance inflation factor (VIF) values >5. The highlighted variables were selected through multi-collinearity test and were used in modeling.

Variable	Code/Unit	Source	VIF
Annual mean temperature	**Bio1 (°C)**	**WorldClim**	**2.05**
Mean diurnal range (max. temp – min. temp)	**Bio2 (°C)**	**WorldClim**	**3.68**
Isothermality (Bio2/Bio7) × 100	**Bio3**	**WorldClim**	**2.95**
Temperature seasonality (SD ×100)	Bio4 (°C)	WorldClim	14.71
Max temperature of warmest month	Bio5 (°C)	WorldClim	11.10
Min temperature of coldest month	Bio6 (°C)	WorldClim	8.56
Temperature annual range (Bio5-Bio6)	Bio7 (°C)	WorldClim	12.90
Mean temperature of wettest quarter	Bio8 (°C)	WorldClim	24.08
Mean temperature of driest quarter	**Bio9 (°C)**	**WorldClim**	**4.20**
Mean temperature of warmest quarter	Bio10 (°C)	WorldClim	14.55
Mean temperature of coldest quarter	Bio11 (°C)	WorldClim	18.21
Annual precipitation	**Bio12 (mm)**	**WorldClim**	**3.06**
Precipitation of wettest month	Bio13 (mm)	WorldClim	16.81
Precipitation of driest month	**Bio14 (mm)**	**WorldClim**	**3.29**
Precipitation seasonality (Coefficient of variation)	**Bio15**	**WorldClim**	**3.35**
Precipitation of wettest quarter	Bio16 (mm)	WorldClim	23.73
Precipitation of driest quarter	Bio17 (mm)	WorldClim	9.67
Precipitation of warmest quarter	Bio18 (mm)	WorldClim	11.14
Precipitation of coldest quarter	Bio19 (mm)	WorldClim	9.55
Elevation	**Elev (m)**	**WorldClim**	**3.56**
Slope	SL (%)	Derived from Elev	9.17
Aspect	AS (degrees)	Derived from Elev	10.80

2.3. MaxEnt model

In our study, all models were run using the MaxEnt algorithm (version 3.3.3 k; Phillips et al., 2006) with default settings. We employed 10 replicates and average of probability maps for habitat suitability (Hoveka et al., 2016). It is better to use MaxEnt model particularly when the data points include presence-only with a limited number of records (Vasconcelos et al., 2012; Bosso et al., 2013; Fois et al., 2015, 2018b). The training and test data points were 80% and 20%, respectively. The relative importance of each environmental predictor for the models of *R. arabica* was assessed using percent contribution of Jackknife test (Phillips et al., 2006), which is the best index for small sample sizes (Pearson et al., 2007). To determine the accuracy of the resulting models, we computed the Area Under the Curve (AUC) of the Receiver Operating characteristic Curve (ROC). AUC score is the dominant tool to measure the model performance, mainly due to its independence by threshold choices (Bosso et al., 2013; Yi et al., 2016; Fois et al., 2018b). The higher the value of AUC (closer to 1), the better the performance of the model (Fielding and Bell, 1997; Phillips et al., 2006). The generated AUC graph is obtained by plotting the true positive predictions (sensitivity) against the false positive predictions (1-specificity) (Fielding and Bell, 1997). In addition, the minimum difference between training and testing AUC data (AUC_{Diff}) was also considered and the smaller difference indicates the lesser overfitting present in the model (Warren and Seifert, 2011; Fois et al., 2018b).

The logistic output of MaxEnt application is a map, indexing the environmental suitability of R. arabica with values ranging from 0 (unsuitable) to 1 (optimal). For further analysis, the MaxEnt results were imported into ArcGIS 10.4.1, and four classes of potential habitats were grouped as follows: unsuitable (≤0.10), low potential (0.11-0.30), moderate potential (0.31-0.70) and high potential (≥0.71) (Yang et al., 2013; Choudhury et al., 2016; Qin et al., 2017). Changes in the predicted ecological extent of *R. arabica* between the current and future climatic scenarios in correspondence of classes were computed as follows: MaxEnt ASCII output projections were converted to raster layers with float data-type using ArcGIS 10.4.1, then the number of cells (pixels) among projected climatic extent was calculated using zonal statistics in spatial analyst tools in ArcGIS 10.4.1. The differences in the mean number of cells among four classes of potential habitats were converted to surface area (km^2) (Fielding and Bell, 1997). Finally, the predictive maps of MaxEnt for the current and future scenarios were related with elevation classes.

3. Results

3.1. Potential habitat suitability of *R. arabica* over current conditions

Our models showed high levels of predictive performances with values of AUC (training, 0.985 ± 0.001; test, 0.968± 0.009) and AUC$_{\text{Diff}}$ (0.010 ± 0.007). The results of variables’ contribution using Jackknife test in distribution modeling of *R. arabica* are showed in **Table (2)**. Environmental predictors that exhibited the highest mean contributions were annual precipitation (Bio12), elevation (Elev) and annual mean temperature (Bio1). Bio12, Bio1, Bio9, Elev and Bio2 provided high gains (>2) to the model when used individually, indicating that these variables have the most useful information by themselves than the rest of variables. Considering permutation importance, Bio1, Bio12 and Elev were the main environmental variables which have influenced the potential distribution of *R. arabica* **(Table 2)**.

Table 2. Estimates of average contribution and permutation importance of the environmental variables used in MaxEnt modelling of *R. arabica*.

Variable	Percent contribution	Permutation importance
Bio1	2.01	68.27
Bio2	1.06	1.34
Bio3	0.29	0.53
Bio9	0.12	0.34
Bio12	84.45	20.30
Bio14	0.05	0.01
Bio15	0.25	0.46
Elev	11.78	8.74

The response curves of eight variables to *R. arabica* habitat suitability are shown in **Figure 2**. While considering probabilities of temperature variables, the mean annual temperature range (Bio1) of *R. arabica* was 8.05-15.4°C, whereas the mean diurnal temperature (Bio2) ranged from 11.7◦C to 12.2◦C. In addition, the range of isothermality (Bio3) varied from 42 to 44.2, whereas the mean temperature of driest quarter (Bio9, three driest months) varied from 15.3 to 20°C. On the other hand, the range of annual precipitation

(Bio12) was 36 to 120 mm per year while the suitable habitat occurs also when the precipitation seasonality of 58 to 97.5 with a peak for *R. arabica* at 72.5 mm. Furthermore, there is a positive relationship between habitat suitability of *R. arabica* and precipitation of the driest month. The suitable elevation range of *R. arabica* was 1571 to 2273 m with an optimal elevation at 2200 m. Indeed, the highest suitability under which presence of *R. arabica* occurs resulted at an annual temperature of 10.9°C, 87.50 mm annual precipitation, and an elevation of 2200 m a.s.l. In contrary, areas with an elevation higher than 2300 m a.s.l. or lower than 1500 m a.s.l, and with an annual temperature higher than 20°C were the less suitable habitats for *R. arabica*.

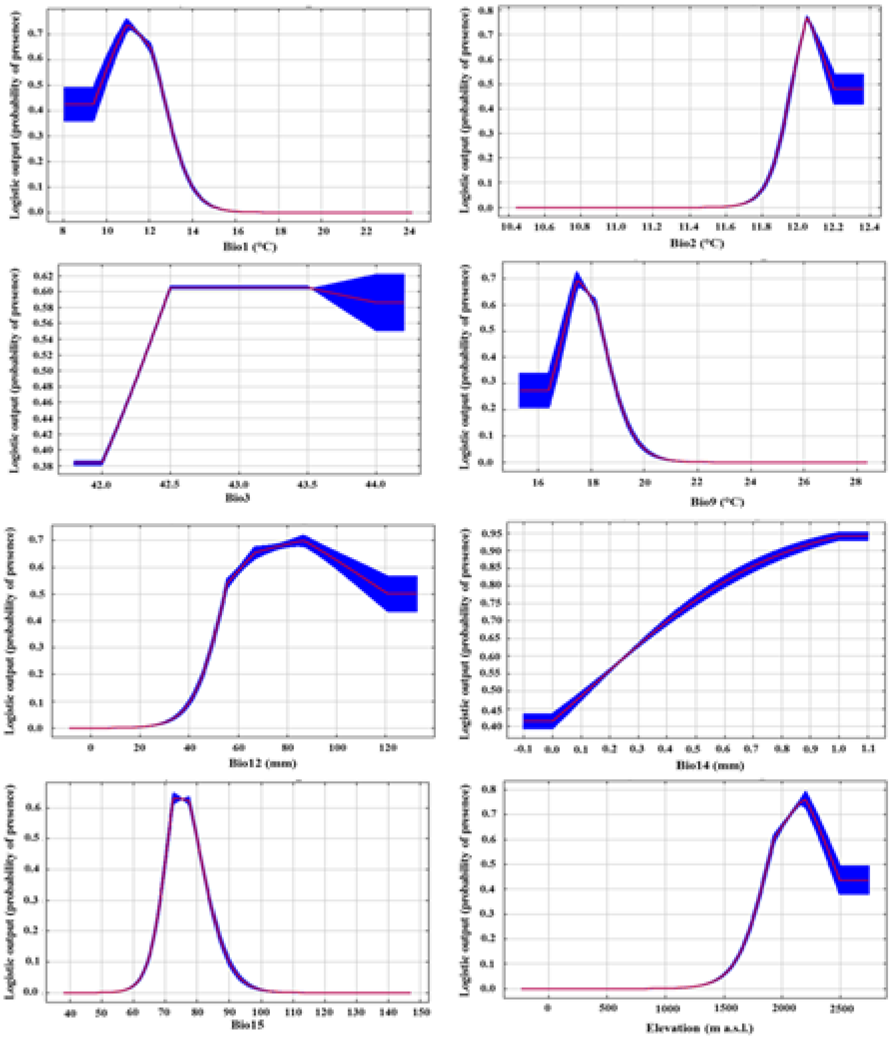

Fig. 2. Response curves of eight environmental predictors used in the ecological niche model for *R. arabica*. For abbreviations, see Table 1.

The potential distribution map of *R. arabica* in St. Catherine is displayed in **Figure 3**. Out of 5196 km^2 of the total area, 4627 km^2 (≤0.10) was unsuitable for *R. arabica*; the remaining 596 km^2 was divided into 282 km^2 with a low potential distribution, 247 km^2 with a moderate potential and only 40 km^2 with the highest probability of suitable ecological conditions. The majority of probably suitable habitats (≥0.71) was located in the middle northern part of St. Catherine area.

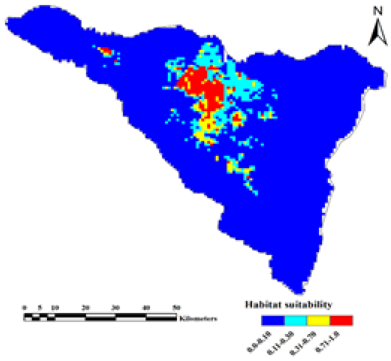

Fig. 3. Map for potential current habitat suitability of *R. arabica* according to occurrence records in St. Catherine. Habitat suitability classes include: unsuitable (0-10), low potential (0.11-0.30), moderate potential (0.31-0.70) and high potential (0.71-1.0).

3.2. Distribution of suitable habitats of *R. arabica* under future global warming scenarios

The projected climate map under CCSM4 model for both 2050 and 2070 resulted in a progressive reduction of the extent of suitable habitat for *R. arabica*, as compared with the potential current distribution **(Fig. 4 and Table 3)**. At both minimum and maximum emissions scenarios (RCP2.6 and RCP8.5, respectively), the habitat suitability decreased with climate warming. By 2050, the potential unsuitable areas for *R. arabica* (≤0.10) within St. Catherine would increase by 0.26% and 0.37% due to rising of global warming from 2.6 watts/km^2 to 8.5 watts/km^2. A similar pattern is also confirmed in 2070 by gain percentages of 0.45% and 1.19%, respectively. By focusing on the moderate potential occurrence (0.31-0.70), there are gains in the areas suitable for *R. arabica* at both climatic future scenarios. In contrast, at high potential distribution class (≥0.71) and by 2050, the habitat suitability will decrease by 47.5% and 60% for RCP2.6 and RCP8.5, respectively. For 2070, the climate change may lead to losses of 60% and 72.5% in *R. arabica* current habitat under RCP2.6 and RCP8.5, respectively. Compared with the current potential distribution, a gradual range contraction is observed in the northwestern and southern parts of St. Catherine under predicted climate change.

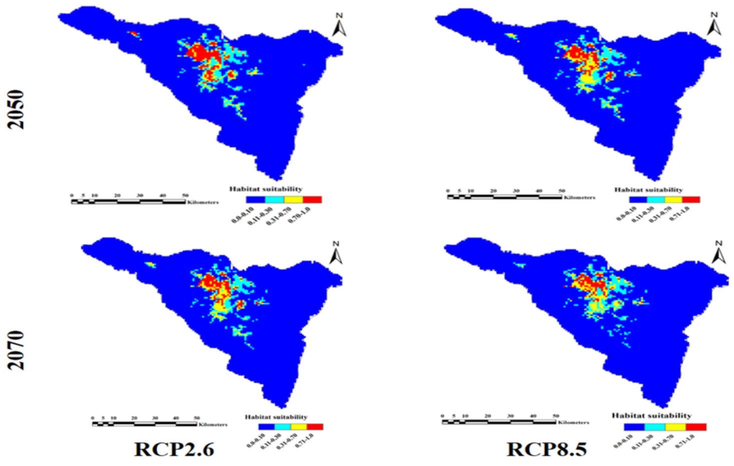

Fig. 4. Ecological niche modeling of *R. arabica* based on predicted climate change for 2050 and 2070 at two global warming scenarios RCP2.6 and RCP8.5. Habitat suitability classes include: unsuitable (0-10), low potential (0.11-0.30), moderate potential (0.31-0.70) and high potential (0.71-1.0).

Table 3. Predicted range changes (km^2) for *R. arabica* distribution for 2050 and 2070 at two global warming scenarios RCP2.6 and RCP8.5 as compared with the potential current distribution. In brackets (+) gain and (-) loss range areas (in km^2).

Predicted class	Current	Future scenarios			
		2050		2070	
		RCP2.6	RCP8.5	RCP2.6	RCP8.5
0.0-0.10 Unsuitable	4627	4639 (+12)	4644 (+17)	4648 (+21)	4682 (+55)
0.11-0.30 Low potential	282	276 (-12)	246 (-36)	232 (-50)	208 (-74)
0.31-0.70 Moderate potential	247	262 (+16)	290 (+43)	302 (+55)	295 (+48)
0.71-1.0 High potential	40	19 (-21)	16 (-24)	14 (-26)	11 (-29)

Comparing predictive maps with elevation classes indicated that *R. arabica* would disappear in sites located below 1500 m a.s.l., contract between 1500-2000 m a.s.l. and expand its range towards sites located between 2000-2500 m a.s.l. during future projections **(Fig. 5)**.

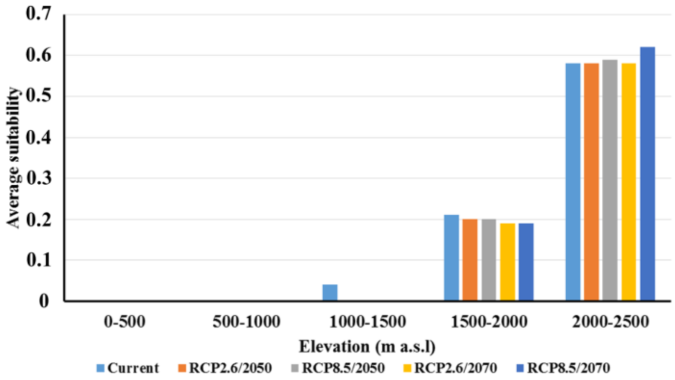

Fig. 5. Average habitat suitability of *R. arabica* in relation to elevation range classes under current and future climate change scenarios.

4. Discussion

Our results showed that, under the current climatic condition, the environmental suitability of *R. arabica* lies within the middle northern boundaries of St. Catherine. This finding fits with our field observations and the known distribution reported in literature (Täckholm, 1974; Danin et al., 1985; Abd El-Ghani and Fahmy, 1994; Moustafa et al., 1995; Ayyad et al., 2000; Moustafa et al., 2001, 2017; Omar et al., 2017), and suggests that the current distribution represents its climate optimum at sites with high altitude and near fresh water springs.

Models' results also displayed some topographic-climatically suitable sites within St. Catherine such as Gebel Musa, Mountain Tarboush, Wadi Jibal, Mountain Serbal, Zaater, Elmaeen, Sad Abu Hebeik and Kharazet Elshak where no historic or literature data provide an evidence for the occurrence of this plant before, except for the last four sites where *R. arabica* has been recorded by St. Catherine rangers in 2015

(Omar et al., 2017) and subsequently not found during our field surveys. Such possible local extinctions (Zaater, Sad Abu Hebeik, Kharazet Elshak, Elmaeen,) are at the altitudes of 2100, 2000, 1940, 1795 m a.s.l., respectively. These recent local extinctions occurred in suitable sites where the plant was previously present with very small population size, therefore, reasons may be attributed to stochastic events or human disturbances (overgrazing and excessive collection). Nonetheless, further surveys efforts are encouraged in such sites for the search of new *R. arabica* populations or to investigate which factors have contributed to preventing the colonization of this species in all suitable places.

All of the current and predicted sites fulfill the *R. arabica* requirements where high elevation (1500-2273 m a.s.l.), cold temperature (8.05-15.4°C) and annual precipitation range of 36-120 mm. Consequently, warm sites with elevation less than 1500 m a.s.l are less suitable for *R. arabica*. These results are in line with Moustafa and Kamel (1995) who reported that *R. arabica* mainly occurs in moist gorges habitats with a narrow elevation range from 2000 to 2400 m at mountain peaks.

In addition, MaxEnt outputs under current conditions indicated that *R. arabica* distribution range was more influenced by annual temperature, annual precipitation and elevation. This is consistent with factors affecting the suitable habitats of several medicinal and endangered mountain plant species such as *Myristica dactyloides* (Remya et al., 2015), *Fritillaria cirrhosa* (Zhao et al., 2017), *Quercus coccifera* (Al-Qaddi et al., 2017), *Gentiana lutea* (Cuena Lombraña et al., 2018), *Artemisia* spp. (Sanjerehei and Rundel, 2017) and *Daphne mucronata* (Abolmaali et al., 2018), where climatic factors and elevation resulted the most crucial drivers in plant species' distribution. Also in Egypt, the importance of climatic factors and elevation was confirmed for the spatial distribution of medicinal plants (Kaky and Gilbert, 2016), and for the distribution of *Hypericum sinaicum* and *Nepeta septemcrenata* in St. Catherine Protectorate (Khafagi et al., 2011, 2012). More in general, the distribution of endemic taxa within St. Catherine is largely driven by rainfalls and elevation (Moustafa et al., 2001).

MaxEnt predictions for the years 2050 and 2070 disclosed that the geographic distribution of *R. arabica* would shrink under the future conditions. The projected models showed habitat range shifts through the disappearance of this species in sites below 1500 m a.s.l., range contraction at 1500-2000 m a.s.l. and range expansions towards optimum habitats at higher elevation sites (2000-2500 m a.s.l.). The reason of range shift is that the climatic envelope (precipitation and temperature) of this plant will become less suitable for survival at sites below 2000 m a.s.l. Such phenomenon of habitat range shifts under climate change was also reported for other mountain plant species in northern Africa (Al-Qaddi et al., 2017), Middle East (Khanum et al., 2013; Abolmaali et al., 2018) and in the Mediterranean mountains (Fois et al., 2016; López-Tirado et al., 2018). Nonetheless, low survival and germination rates at high temperatures were observed after ex situ experiments (El-Demerdash, 2007) and further studies should consider these limitations at the time of estimating the future conservation status of this plant.

Plants differ in their responses against future climate change which depend mainly on their physiological or phenological characteristics (Zhao et al., 2017). Particularly, plants with wide ecological niches will be more able to adapt to climate change than species with narrow ecological niches (Khanum et al., 2013; Abolmaali et al., 2018). For instance, significant improvement in habitat suitability with global warming for *Homonoia riparia* in China (Yi et al., 2016) and for *Ruscus aculeatus* in Sardinia (Fois et al., 2018a). In contrast, a considerable reduction in suitable habitats for many other species, such as *Myristica dactyloides* in India (Remya et al., 2015), *Fritillaria cirrhosa* in China (Zhao et al., 2017), *Artemisia aucheri*, *A. sieberi* and *Daphne mucronata* in Iran (Sanjerehei and Rundel, 2017; Abolmaali et al., 2018) was predicted for future climate change. In both cases, range shifts, more than retractions, were the crucial information to be considered when efficient conservation measures are planned (Koch et al., 2017; Fois et al., 2018a).

In the case of *R. arabica*, a species with a narrow geographical niche and dispersal ability may particularly reduce the ability of this plant to face global climate change consequences, especially if human-induced habitat fragmentation increases barriers to dispersal.

5. Conclusion

This study indicated that the geographic distribution of *R. arabica* might undergo habitat range shifts through the disappearance of this species in sites below 1500 m a.s.l., range contraction between 1500-2000 m a.s.l. and range expansions towards optimum habitats at sites with higher elevation (2000-2500 m a.s.l.). Moreover, as a high-altitude plant sensitive to high temperature, *R. arabica* cannot withstand the future global warming. In order to reduce the risk of extinction in the wild, ex situ and in situ conservation measures for *R. arabica* are urgent. Specifically, reinforcements of the existing populations, as well as programs of assisted migrations should be planned in the wild. These activities should be accompanied by an increase of public awareness and policy activities with the aim of reducing impacts related to human activities.

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CHAPTER IV

Using MaxEnt-mediated field surveys to predict unknown populations of rare critically endangered plants: An example of *Primula boveana* Decne. ex Duby in Egypt

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Abstract

Endemic species play a key role in conservation ecology. However, knowledge of the real distribution and ecology is still scarce for many endemics particularly in arid mountain areas. *Primula boveana* Decne. ex Duby is one of the rarest and critically endangered plants worldwide, with a narrow- range and low population size surviving exclusively in St. Catherine Protectorate mountains in South Sinai of Egypt. This study aimed to predict the current potential distribution of *P. boveana* and use model results to guide in field surveys to identify the unknown new populations or historical extinct localities. MaxEnt program was used to predict the potential habitat suitability by relating eight field occurrence-points with different predictors singly or in joint (climate, topography and edaphic). Unfortunately, the edaphic variables when used solely or jointly did not provide accurate prediction and negatively affect the performance of other models., contrary to climatic predictors that performed better. The key environmental factors that highly correlated with *P. boveana* distribution range were elevation, the mean temperature seasonality (Bio4), mean temperature of wettest quarter (Bio8), the range of precipitation of driest month (Bio14) and soil pH. The majority of suitable habitats of *P. boveana* was located in the high elevated middle northern part of the St. Catherine area. The highest potential habitat suitability occurs at an elevation of 2300 m a.s.l. a maximum of warmest month of 24 °C and an optimum precipitation seasonality of 72 and not less than 50. After a set of field trips to all predicted potential distribution sites, especially within habitats of *P. boveana* at high elevated sites near water springs unfortunately we did not find any new populations but we discovered five extinct localities where *P. boveana* were completely disappeared. It is recommended to initiate in-situ conservation through restoration or establishment of suitable managed fenced enclosures together with *ex-situ* conservation through germplasm, artificial propagation or artificial irrigation specifically in the dry season. Species distribution models cannot replace field surveys that proposed to collect distribution data, but can be a valuable tool to improve data investigation and to help identify potential knowledge gaps of any target species with isolated distribution or low-presence data and can guide fieldwork plan or possible potential areas for introduction or translocation.

Keywords: *Ex-situ* conservation, habitat suitability, population size, Saint Catherine, Sinai Peninsula, threatened species.

This research under preparation

1. Introduction

Knowledge about the current and potential distribution of restricted-range endemic vascular taxa is limited with extensive gaps in our knowledge, particularly in arid environments. Species distribution models (SDMs) offer a potentially very powerful tool for filling these gaps by correlate a set of data on species occurrence to environmental variables thought to be important in determining the geographic distribution of such species by prediction where a species is currently found and/or will be found throughout an area of interest (Elith and Leathwick 2009). The use of species distribution models has increased rapidly in the last two decades and become in recent years one of the most widely used tools in ecology and conservation (Guisan and Thuiller 2005, Phillips et al. 2006). SDMs applications include the study of ecological niche patterns, prediction of future distribution as a result of climate change and land-use, identification of suitable areas for conservation concern, assess fundamental ecological and evolutionary issues (Smeraldo et al., 2018, Fois et al. 2015, 2018a). Among these applications, the use of SDMs predictive maps for guiding field surveys is increasingly applied. This approach is particularly used for searching for new populations/locations of poorly known species or endangered species in order to better assess their distribution and conservation (Fois et al. 2015, McCune et al. 2016, Yi et al. 2016, Rus et al. 2017, Wang et al. 2019).

Moreover, the main task of SDMs is to understand how the environment shapes the distribution of a species in its native area. To do so, we construct SDMs by collecting presence data and environmental features (climate, topography and edaphic) stored in a geographic information system. Numerical outputs of statistical SDMs have often been simplified to environmental suitability indexes, ranging from 0 (unsuitable) to 1 (optimal) (Phillips et al. 2006). Furthermore, it was proved that such index is often related not only to the probability of occurrence but also to other key parameters of populations, such as growth rate, surface area and the number of vegetative and reproductive individuals (Csergő et al. 2017; Fois et al. 2018b).

Among SDMs, MaxEnt was chosen because of its numerous advantages including the input species data can be presence points only, both categorical and continuous environmental layers can be applied, its prediction is stable and reliable with a great accuracy even if low sample sizes are undertaken, thus can predict distribution of threatened species, it creates a spatially explicit map for habitat suitability with an easy interpretation, it enables replicated runs to test model robustness nonetheless threshold rule, the importance of each environmental variable can be measured using jackknife test, thus it helps in planning appropriate conservation measures (Phillips et al. 2006; Pearson et al. 2007; Elith et al. 2011; Fois et al. 2018b, Abdelaal et al. 2019).

Modelling species with presence-only data has been particularly used for species with small distributional range and where knowledge is scarce (Pearson et al. 2007). However, the lack of a surveyed locality still affects the model performance and validation can be problematic (Pearson et al. 2007, Wisz et al. 2008, Chen and Lei 2012, Fois et al. 2016). SDMs have been used for population discoveries of either rare or endangered wild plants (e.g. Jarvis et al. 2005, Williams et al. 2009, Gogol-Prokurat 2011, Fois et al 2015, McCune et al. 2016, Yi et al. 2016, Wang et al. 2019). SDMs can be used to identify potentially suitable habitat for rare and endangered species, which can aid in the location of new populations and identify areas for monitoring or reintroduction of a species. These models use known location occurrences and spatial environmental layers to infer the ecological requirements of a species (Fois et al. 2016, Li and Ding 2016, Mitchell et al. 2017).

Choosing a precis environmental variable for SDMs depends on the modelling targets and its biological significance to the target species (Austin 2007). Different species may have particular constraints related to their dependency on environmental factors and no single variable is expected to be equally meaningful for all species. Climate, topography, edaphic factors, land-use and biological interactions have been recognized as the main drivers for the distribution and ecological niche of species at various geographical scales (Abolmaali et al. 2018). In particular, climate warming may result in shifts in natural species range specifically for those of geographically limited and/or endemic species that are unable to adapt to unusual climatic conditions and thus become endangered or even extinct (Loarie et al. 2008). Soil-related variables are also considered important in the distribution of plant species as it is the main source of nutrients (Velazco et al. 2017). On the other hand, human impacts cause additional habitat fragmentation and threaten plant diversity (Vasquez et al. 2015). All of these factors call a request to realize areas where endangered species or species with narrow niche width exist or likely exist in order to enhance their conservation and restoration (Dubuis et al. 2011, Kaky and Gilbert 2016).

Many endemic taxa are included in the IUCN Red List of the threatened species as they are in danger of global extinction because of their narrow geographic distribution and extremely habitat-restricted (Crisp et al., 2001; Orsenigo et al., 2018). Hence, the first step to initiate conservation strategy for these taxa is to identify the current geographic distribution, population status and threats that expose them to the risk of extinction (Crisp et al., 2001). *P. boveana* Decne. ex Duby (*P. boveana* hereafter) deserves special attention because it was assessed globally as a critically endangered (CR) taxon according to the IUCN methodology, with an Extent Of Occurrence (EOO) of 13 km^2 and an Area Of Occupancy (AOO) less than 6 km^2 (Omar 2014a). To our knowledge, no previous studies have been done to address the geographic distribution and niche of *P. boveana*; accordingly, predicting its habitat suitability and new locations/populations are critical to conserve or reintroduce this plant species. In this study, we addressed the following question: Which Maxent models or combination of models would be most helpful for guiding field surveys to investigate new or historical populations/locations of *P. boveana*? Hence, our objectives were: (1) to predict the current potential distribution of *P. boveana* using distinct different predictors singly or in joint (climate, topography and edaphic), (2) to address the key environmental factors that highly correlated with *P. boveana* distribution range and (3) to use models results to guide in field surveys to identify the new unknown populations or historical extinct localities.

2. Materials and methods

2.1. Study area and target species

Our study was carried out in St. Catherine Protectorate (SKP), which is located in southern Sinai at the northeastern corner of Egypt with a total area of ca. 5196 km^2 (Fig. 1a). The St. Catherine is one of Egypt's largest protected areas and includes the country's highest mountains. Saint is an igneous massif characterized by smooth faced-outcrops that formed mountain areas with an elevation range up to 2640 m a.s.l (Moustafa and Klopatek 1995). The location of St. Catherine supports surprising biodiversity and a high proportion of plant endemics and rare plants distributed in distinctive environments (gorges, slopes, terraces, caves and ridges). The soil of St. Catherine is formed mainly from mountains weathering, thus it is mainly granitic in origin. The soil layer is shallow where the bedrock is close to the surface. St. Catherine is distinguished by a wide range of variations in temperature and precipitation. It is categorized as the coolest region in Egypt and the only one that has snow (Moustafa et al. 2017). Annual rainfall is less than 50 mm. However, rainfall is not annual, rather two to three consecutive years without rainfall is common. Rain takes the form of sporadic flash floods or limited local showers, thus highly spatial heterogeneity in received moisture is also common. The average monthly temperatures range from 8.6°C in January to 25.5°C in August (Moustafa et al. 2017). According to Abdelaal et al. (2018), St. Catherine harbors 14 exclusive vascular plants, and it is therefore considered one of the most important of Egypt's protected landscapes. The long-term drought, overgrazing and tourism activities are the main threatening factors for the plant diversity in St. Catherine (Moustafa et al. 2001a, Grainger and Gilbert 2008). All of these threats will drive endemic and rare plant species to extinction risk.

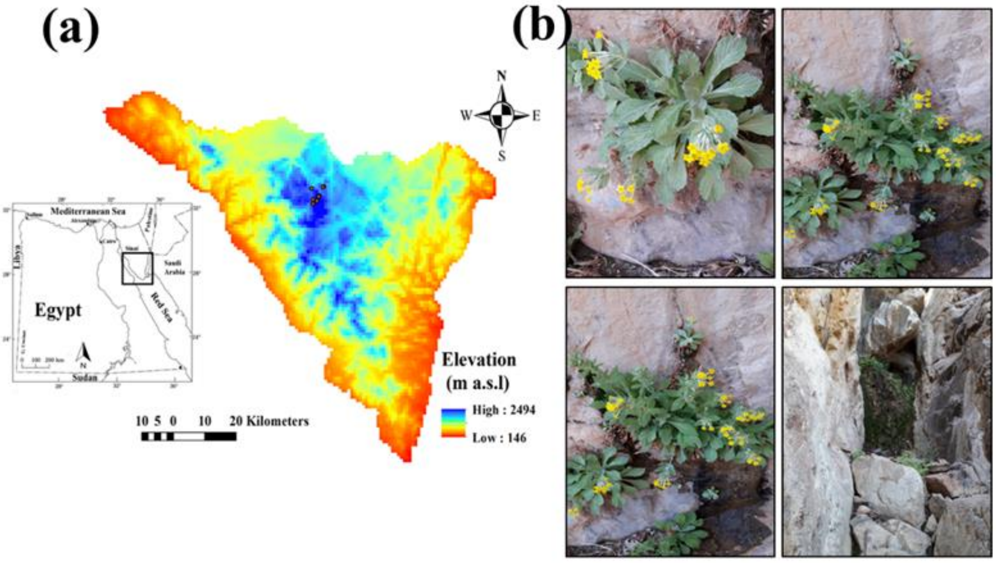

Fig. 1. **(a)** Map of Saint Catherine Protectorate with known occurrence points of *Primula boveana* and **(b)** *P. boveana* and its habitat.

The Sinai primrose, *Primula boveana* Decne. ex Duby (Primulaceae) is the only species from the genus *Primula* in Egyptian flora (Figure 1b). *P. boveana* is a glabrous rhizomatous perennial herb with up to 40 cm height with erect unbranched stem, sessile leaves and capsule-type fruit with dust seeds (Boulos 2000). It has been reported as one of the rarest and critically endangered plant species worldwide (Richards 2003, Omar 2014 a, b). It is endemic to the St. Catherine Protectorate in southern Sinai of Egypt. This species is restricted to montane wadis fed by melted snow and distributed in the moist ground in the vicinity of wells and sheltered mountain areas.

In this study, the occurrence points of *P. boveana*, population size and threats were obtained from field data collected by the first author in St. Catherine Protectorate during 2016-2017, after consulting the published literature (Al Wadi 1993, Moustafa et al. 2001b, Richards 2003, Mansour et al. 2013, Jiménez et al. 2014, Omar 2014 a, b, Zaghloul et al. 2015) and online databases. *P. boveana* distributed in six localities within St. Catherine: Wadi Shaq Mousa (WSM), Wadi Garagenia (WG), Ain Shennarah (AS), Kahf El-Ghoula (KG) and Gebal Alahmar (GA) and Sad Abu Hebeik (SH) (Table 1). Six populations and nine subpopulations (three each in WSM and WG, and one for each other localities) were recorded during the field survey. The population size of *P. boveana* was of 815 individuals including 134 mature individuals, distributed in the above-mentioned localities. The highest number of mature individuals was recorded in WSM (78 individuals) and WG (36 individuals). The vegetative growth of *P. boveana* proliferates over the four season with maximum activity in September, flowering through April to May while fruiting lasts from April (early Spring) until July (early Summer) (Moustafa et al. 2001b). For the long-term conservation of *P. boveana*, two managed enclosures (Kahf El-Ghoula and Gebal Alahmar) were established (Moustafa et al. 2001b).

A narrow elevation range was recorded for *P. boveana* ranging from 1825 to 2225 m a.s.l. It was observed that, the population size is positively affected by elevation (Table 1). This species is restricted to cliff, cave and steep slopes habitats that face northeast and east aspect with slope degree of 90°. This species is severely threatened by drought, temperature extremes and human activities (collection for medical or genetic scientific researches). Occasionally, it is threatening by overgrazing, tourist activities and ants attack. Due to its extreme aridity and reproductive biology, this species is considered as a priority target for conservation at a national level in Egypt (Radford et al. 2011).

All *P. boveana* occurrence records were checked for accuracy in ArcGIS environment before use. The autocorrelation issues were avoided by eliminating redundant presences in each 1x1 km grid on the scale of the environmental variables used. Furthermore, records were screened in ArcGIS 10.4.1 for spatial autocorrelation using the average nearest neighbor analyses to remove spatially correlated data points (Bosso et al. 2016; Smeraldo et al. 2018). After this selection, eight occurrence points of *P. boveana* were used to generate SDMs (Fig.1a).

Table 1. The known current locations (2016-2017), populations size, topography, habitat and threats of *P. boveana* in Egypt.

Locality (Population)	Subpopulation		Topography			Habitat	Threats
	Total individuals	Mature Individuals	Elevation (m a.s.l.)	Slope	Aspect (direction, degree		
Wadi Shaq Mousa	420	55	2060	90	NE	cliff	Droughts, temp. extremes, storms and floods, tourism and recreation areas
	78	15	2019	90	NE	cliff	
	62	8	1965	90	NE	cliff	
Wadi Garagniah	75	11	2113	90	NE	cliff	Droughts, temp. extremes, tourism and recreation areas, gathering terrestrial plants
	92	23	2225	90	NE	slope	
	10	2	1890	90	NE	cliff	
Ain Shennarah	54	14	2026	90	NE	cliff	Droughts, temp. extremes
Kahf El-Ghoula	5	0	1839	90	E	cave	Droughts, temp. extremes
Gebal Alahmar	12	5	2033	90	E	gorge	Droughts, temp. extremes
Sad Abu Hebeik	7	1	1825	90	NE	cliff	Droughts, temp. extremes

2.2 Environmental variables

We used three sets of environmental variables for predicting potential current suitable geographical distribution of *P. boveana*: bioclimatic variables (19), topography (3) and edaphic factors (8) **(Table 1)**. We employed the 19 bioclimatic variables for the current period (1950 to 2000) from the WorldClim version2 database (http://www.worldclim.org) (Fick and Hijmans 2017) at a spatial resolution of 30 arc-seconds (~1 km^2), these data have been widely used in creating species distribution models. Elevation was downloaded from the DIVA-GIS online database (https://www.diva-gis.org/gdata) at 30 seconds resolution, while slope and aspect were generated from the same elevation data by planar algorithm method in ArcGIS environment. Edaphic factors related to physical and chemical soil properties were obtained from the SoilGrids database v 0.5.3, available from ISRIC-World Soil Information (Hengl et al. 2014), we selected and downloaded all available layers at 1 km^2 resolution in October 2018 (Table 2). The SoilGrids database has an automated updating system that progressively increases its accuracy when new input data becomes available in the international soil profile databases. To eliminate multicollinearity and select the most fitting predictors that show more contribution power to the model, Variance Inflation Factors (VIFs) of 30 environmental variables were tested. VIFs are based on correlation coefficients (R^2) that created from regression among all predictors and was implemented through the 'sdm' package in the R-environment (version 3.1.1). Consequently, 14 variables with VIFs< 5 were kept (Chatterjee and Hadi 2006) to establish the distribution model of *P. boveana* under the current conditions (Table 2). The selected non-linear variables include seven bioclimatic (Bio4, Bio5, Bio8, Bio9, Bio14, Bio15 and Bio17), three topographic (elevation, slope and aspect) and four edaphic factors (mean of soil bulk density, mean of clay content, mean of silt content and pH in H_2O) (Table 2).

To predict the potential occurrence of new populations of *P. boveana*, we build seven MaxEnt models, depending on the selected type of environmental variables. We used climate variables only (hereafter called C. model), topography only (T. model), edaphic only (E. model), and both climatic and topographic (CT. model), climatic-edaphic variables (CE. model), topographic- edaphic variables (TE. model), and climatic-topographic and edaphic variables (CTE. Model). Note that all of these predictors were continuous variables.

3.3. MaxEnt modeling procedures

MaxEnt software (version 3.4.1, Phillips et al. 2006) (https://biodiversityinformatics.amnh.org/open source/maxent/) was utilized to predict the suitable habitat distribution of *P. boveana* in Egypt. We employed 10 replicates, a random test percentage and an average of probability maps for habitat suitability was chosen for each replicate (Hoveka et al. 2016, Abdelaal et al. 2019). MaxEnt uses presence-only and small sample size data to model habitat suitability as a function of environmental variables, and it is consistently among the highest performing SDM methods (Vasconcelos et al. 2012; Bosso et al. 2013; Fois et al. 2015, 2018b). Response curves indicate the relationships between climatic, topographic and edaphic variables, and the

Table 2. List of environmental variables used for this study with type, unit, Variance Inflation Factors (VIFs), source and resolution. Problems related to multicollinearity were avoided by removing variables with VIF values ≥5. The highlighted variables were selected through multicollinearity test and were used in modelling.

Type	Code/ Unit	Environmental variables	VIF	Source and resolution
Bioclimatic	Bio1 (℃)	Annual mean temperature	8.10	WorldClim version2
	Bio2 (℃)	Mean diurnal range (max. temp – min. temp)	7.39	30 seconds resolution (~1 km^2).
	Bio3 (℃)	Isothermality (Bio2/Bio7) × 100	8.63	
	Bio4	**Temperature seasonality (SD ×100)**	**2.02**	
	Bio5 (℃)	**Max temperature of warmest month**	**3.45**	
	Bio6 (℃)	Min temperature of coldest month	9.80	
	Bio7 (℃)	Temperature annual range (Bio5-Bio6)	10.73	
	Bio8 (℃)	**Mean temperature of wettest quarter**	**3.18**	
	Bio9 (℃)	**Mean temperature of driest quarter**	**3.56**	
	Bio10 (℃)	Mean temperature of warmest quarter	6.55	
	Bio11 (℃)	Mean temperature of coldest quarter	16.12	
	Bio12 (mm)	Annual precipitation	7.34	
	Bio13 (mm)	Precipitation of wettest month	9.19	
	Bio14 (mm)	**Precipitation of driest month**	**2.30**	
	Bio15	**Precipitation seasonality (Coefficient of variation)**	**4.11**	
	Bio16 (mm)	Precipitation of wettest quarter	15.16	
	Bio17 (mm)	**Precipitation of driest quarter**	**4.23**	
	Bio18 (mm)	Precipitation of warmest quarter	11.34	
	Bio19 (mm)	Precipitation of coldest quarter	8.14	
Topographic	**Elev (m. a.s.l)**	**Elevation**	**1.39**	DIVA-GIS (1×1 km)
	Slope (%)	**Slope**	**1.58**	Derived from Elev.
	Aspect (degree)	**Aspect**	**1.17**	Derived from Elev.
Edaphic*	**BD (g/cm^3)**	**Mean of bulk density**	**3.18**	SoilGrids (1 km)
	CF (%)	Mean of coarse fragments volumetric	9.12	
	Clay (%)	**Mean of clay content**	**3.88**	
	Silt (%)	**Mean of silt content**	**4.10**	
	Sand	Mean of sand content	10.56	
	CEC (cmolc/kg)	Mean of cation exchange capacity	6.27	
	OC (g/kg)	Mean of soil organic carbon content	5.50	
	pH	**Mean of soil pH in H_2O**	**2.11**	

*Edaphic data are mean of four soil depths interval (0.00, 0.05, 0.15 and 0.30 m).

predicted probability of the presence of *P. boveana* was determined by MaxEnt. The percent contribution and permutation importance of environmental variables were calculated for each model type, and jackknife procedures were executed in MaxEnt. These analysis methods are useful to measure the importance of the environmental variables. To make the results of the MaxEnt model more reliable and stable, cross-validation was performed in this study. The remaining model values were set to default values.

To determine the accuracy of the resulting models, we computed the Area Under the Curve (AUC) of the Receiver Operating Characteristic Curve (ROC). AUC score is the dominant tool to measure the model performance, mainly due to its independence by threshold choices that can evaluate a model's ability to discriminate presence from absence (or background) (Bosso et al. 2013, Yi et al. 2016, Fois et al. 2018b). The higher the value of AUC (closer to 1), the better the performance of the model (Fielding and Bell, 1997; Phillips et al. 2006). The generated AUC graph is obtained by plotting the true positive predictions (sensitivity) against the false-positive predictions (1-specificity) (Fielding and Bell 1997). Besides, the minimum difference between training and testing AUC data (AUC$_{\text{Diff}}$) was also considered and the smaller difference indicates the lesser overfitting present in the model (Warren and Seifert 2011, Fois et al. 2018b). The logistic output of MaxEnt application is a map, indexing the habitat suitability of *P. boveana* with values ranging from 0 (unsuitable) to 1 (optimal) (Phillips and Dudík 2008). For further analysis, the MaxEnt results were imported into ArcGIS 10.4.1, and four arbitrary categories of habitat suitability for *P. boveana* were defined as classes as follows: unsuitable (< 0.20), low suitability (0.20- 0.40), moderate suitability (0.40- 0.60) and high suitability (> 0.60) (Yang et al. 2013, Choudhury et al. 2016, Qin et al. 2017). Differences in the predicted current ecological extent of *P. boveana* between the different MaxEnt models in correspondence of four classes were computed as follows: MaxEnt ASCII output projections were converted to raster layers with float data-type using ArcGIS 10.4.1, then the number of cells (pixels) among MaxEnt models extent was calculated using zonal statistics in spatial analyst tools in ArcGIS 10.4.1. The differences in the mean number of cells among four classes of potential habitats in terms of different predictors in MaxEnt models were converted to surface area (km^2) (Fielding and Bell 1997).

2.4. Field validation and areas of population survey

To survey for new populations, we carried out the MaxEnt model using the highest contributed and important variables (elevation, Bio4, Bio8, Bio14 and soil pH), then we selected the cumulative output, with values of probabilities between 0 and 100%. Two thresholds are considered to generate binary maps of presence/absence. The first threshold is the maximum training sensitivity plus the specificity (Liu et al. 2005). The second is the Lowest Presence Threshold (LPT). The LPT is a conservative method used to identify both predicted minimum area and unknown distribution areas (Pearson et al. 2007, Fois et al. 2015, Rus et al. 2018). The resulted two maps are superimposed to produce a map of potential areas for field surveys. We made a set of field trips to the potential highly suitable sites (≥ 60%) to search for new populations of *P. boveana*.

4. Results

4.2. Models performance and contributions of variables

The use of different predictors (climatic, topographic and edaphic) solely or together significantly affected model performance as measured by the AUC index. All models showed high levels of predictive performances with values of AUC> 0.90 (Table 3). According to AUC, C. model performed better (training 0.985± 0.001; test 0.982± 0.002; AUC$_{\text{Diff0,}}$.003± 0.00) than other models. Models with topography-only, topography-edaphic and climatic-topography-edaphic predictors performed equally well for *P. boveana*. As expected, the response of MaxEnt to different predictors varied individually for each model type. For instance, as compared with the C. model, the use of topographic-only predictors (T. model) or edaphic-only predictors (E. model) or both (CT. model, TE. model and CTE. model) notably decreased model performance for *P. boveana*. The results of variables' contribution using Jackknife test in different MaxEnt models of *P. boveana* are shown in Table (3). Regarding contribution percent, for the C. model, the predictors that exhibited the highest mean contribution were temperature seasonality (Bio4), mean temperature of wettest quarter (Bio8) and precipitation of driest month (Bio14). For T. model, elevation was the highest contribution predictor with 89.33 %. Soil pH, soil texture (clay content) and mean soil bulk density were the most influential factors, collectively represented by a contribution of 91.59 %. For the CT. model, the predictors that showed high contribution percent were elevation, Bio8, Bio14. In the CE model, Bio14, Bio15 and Bio8 were the highest contribution predictors while the edaphic factors were represented by a negligible percentage. As expected, elevation was the most important predictor in TE. model. Finally, for the CTE. model, elevation, Bio8 and Bio14 were the highest predictors. The values of permutation importance are more similar to contribution percent (See Table 3).

Table (3). Models performance, estimates of average percent contribution and permutation importance of the different predictors used in MaxEnt models of *P. boveana*. The highlighted variables were selected as the main predictors in each model-type.

	C. model	T. model	E. model	CT. model	CE model	TE. model	CTE. model
Model performance							
AUC training	0.985±0.001	0.977±0.003	0.904±0.020	0.979±0.010	0.974±0.003	0.977±0.016	0.977±0.010
AUC test	0.982±0.002	0.969±0.044	0.876±0.162	0.973±0.035	0.972±0.037	0.973±0.035	0.973±0.035
AUC $_{Diff}$	0.003±0.00	0.008±0.00	0.028±0.00	0.006±0.00	0.002±0.00	0.004±0.00	0.004±0.00
Average percent contribution							
Bio4	**55.45**			2.82	2.33		2.40
Bio5	0.92			8.82	2.83		8.30
Bio8	**21.43**			**12.84**	**12.21**		**12.00**
Bio9	2.74			6.06	8.11		6.20
Bio14	**17.60**			**10.19**	**53.29**		**10.10**
Bio15	0.03			5.86	**13.13**		6.30
Bio17	1.83			2.83	4.32		2.10
Elev.		**89.33**		**50.11**		**94.24**	**48.20**
Slope		6.29		0.38		1.00	0.30
Aspect		4.38		0.11		1.10	0.20
BD			**13.23**		0.37	0.34	0.40
Clay			**25**		1.10	1.00	1.50
Silt			8.14		2.18	2.14	2.10
pH			**53.36**		0.12	0.17	0.10
Average permutation importance							
Bio4	**31.04**			4.63	2.06		2.40
Bio5	0.28			3.84	2.98		0.60
Bio8	**46.10**			11.64	0.59		6.00
Bio9	0.02			1.57	6.82		0.80
Bio14	**21.10**			**25.41**	**49.88**		10.90
Bio15	0.26			10.88	**27.95**		7.30
Bio17	1.20			2.65	3.99		2.80
Elev.		**89.28**		**38.61**		**93.20**	**46.15**
Slope		6.02		0.77		2.00	0.25
Aspect		4.70		0.01		1.29	0.20
BD			5.90		0.11	0.07	1.50
Clay			**16.53**		0.0	0.30	0.20
Silt			**18.60**		5.15	3.12	2.50
pH			**58.97**		0.46	0.01	**18.30**

From both contribution percent and permutation importance in all models, the key environmental factors that highly correlated with *P. boveana* distribution range were elevation, Bio4, Bio8, Bio14 and soil pH.

4.3. Predictive potential habitat suitability of *P. boveana*

The response curves of 14 variables to *P. boveana* habitat suitability regardless of model types or contribution and permutation importance are shown in Figure 2. Response curves show the quantitative relationship between environmental variables and the logistic probability of presence (also known as habitat suitability), and they deepen the understanding of the ecological niche of the species. Notably, all predictors in all models are at the same scale and range values. According to the response curves of topography variables, the suitable elevation range is 1600- 2300 m. a.s.l., slopes of all sampled points were c. 90° while aspects fluctuated from 3 to 350 degree with northeast (NE) and east (E) aspects. While considering probabilities of temperature variables, the mean temperature seasonality (SD ×100) (Bio4) of *P. boveana* was 530- 580, whereas the mean maximum temperature of warmest month (Bio5) ranged from 25 to 30 ℃. In addition, the range of mean temperature of wettest quarter (Bio8) varied from 5 to 12 ℃, whereas the mean temperature of driest quarter (Bio9) varied from 17 to 23 ℃. On the other hand, the range of precipitation of driest month (Bio14) was from 0 to 1 mm while the suitable habitat occurs also when the precipitation seasonality of 55 to 73. Furthermore, there is a positive relationship between habitat suitability of *P. boveana* and precipitation of the driest quarter (0- 5.5 mm). Regarding probabilities of the edaphic predictors, the soil bulk density was varied from 1.35 to 1.50 g/cm3, whereas the soil texture, clay and silt contents varied from 15 to 32% and from 9 to 37%, respectively. While considering the only chemical properties of soil, pH varied from 7.4 to 8.1.

The potential distribution maps of *P. boveana* show the range of all theoretical possibilities in which the species could occur and not as predicting actual limits to the range of a species (Figure 3). Before to refining models outputs, we rejected three models that contain edaphic variables (E. model, CE. model and TE. model) as it creates overestimating distribution with inaccurate localities (Figure 3, Table 4). We kept the CTE. model as it releases acceptable prediction classes similar to CT. model with no role of incorporation of edaphic variables. For C. model, out of 5196 km^2 of the total area, 4822 km^2 (< 0.20) was unsuitable for *P. boveana*, the remaining 374 km^2 was divided into 201 km^2 with low habitat suitability, 103 km^2 with moderate suitability and only 70 km^2 with the highest probability of suitable ecological conditions. For other prediction classes in different models, see Table 4. The other four models (C. model, T. model, CT. model and CTE model) showed that, the majority of suitable habitats of *P. boveana* was located in the high elevated middle northern part of St. Catherine area. Indeed, the highest suitability under which the presence of *P. boveana* occurs resulted in at elevation of 2300 m a.s.l. with a slope of 90°, NE slope, a maximum of warmest month of 24 ℃ and not more than 25 ℃ and with an optimum precipitation seasonality of ≈ 72 and not less than ≈ 50.

4.4. Potential distribution areas for populations survey

The four accepted models (C. model, T. model, CT. model and CTE. model) showed high AUCs values, thus the choice of the best-fitted model was difficult because of the problems of small size data training. Thus, we preferred to do another MaxEnt model using only the highly contributed variables (elevation, Bio4, Bio8, Bio14 and soil pH) at two thresholds maximum training sensitivity plus the specificity and LPT. Potential areas to survey for new populations of *P. boveana* are shown in Figure 4. With 60% of the probability of presence, the potential survey areas are reduced to 52 grid cells (52 km^2, > 60%). After several field surveys especially inside specific habitats of *P. boveana* (cliffs, caves and steep slopes) at high elevated sites near water springs and in cracks of granite supplied with water, unfortunately we did not find any new populations but we discovered five extinct localities Gebal Catherine, Gebal Mousa, Gebal Safsafa, Gebel Umm Shaumer and Elgalt Elazrak.

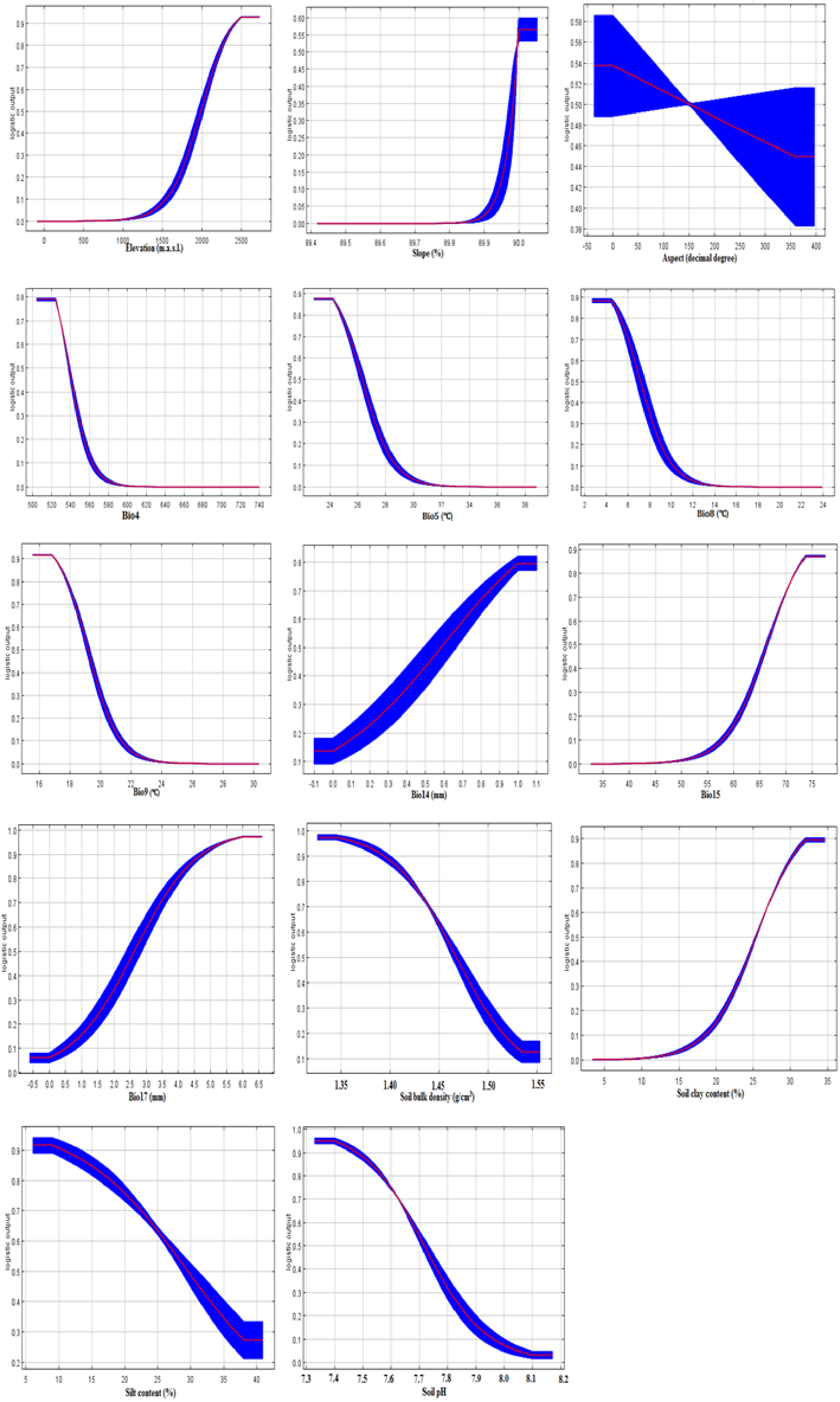

Fig. 2. Response curves of 14 environmental predictors in *P. boveana* habitat distribution model. See Table 2 for acronyms.

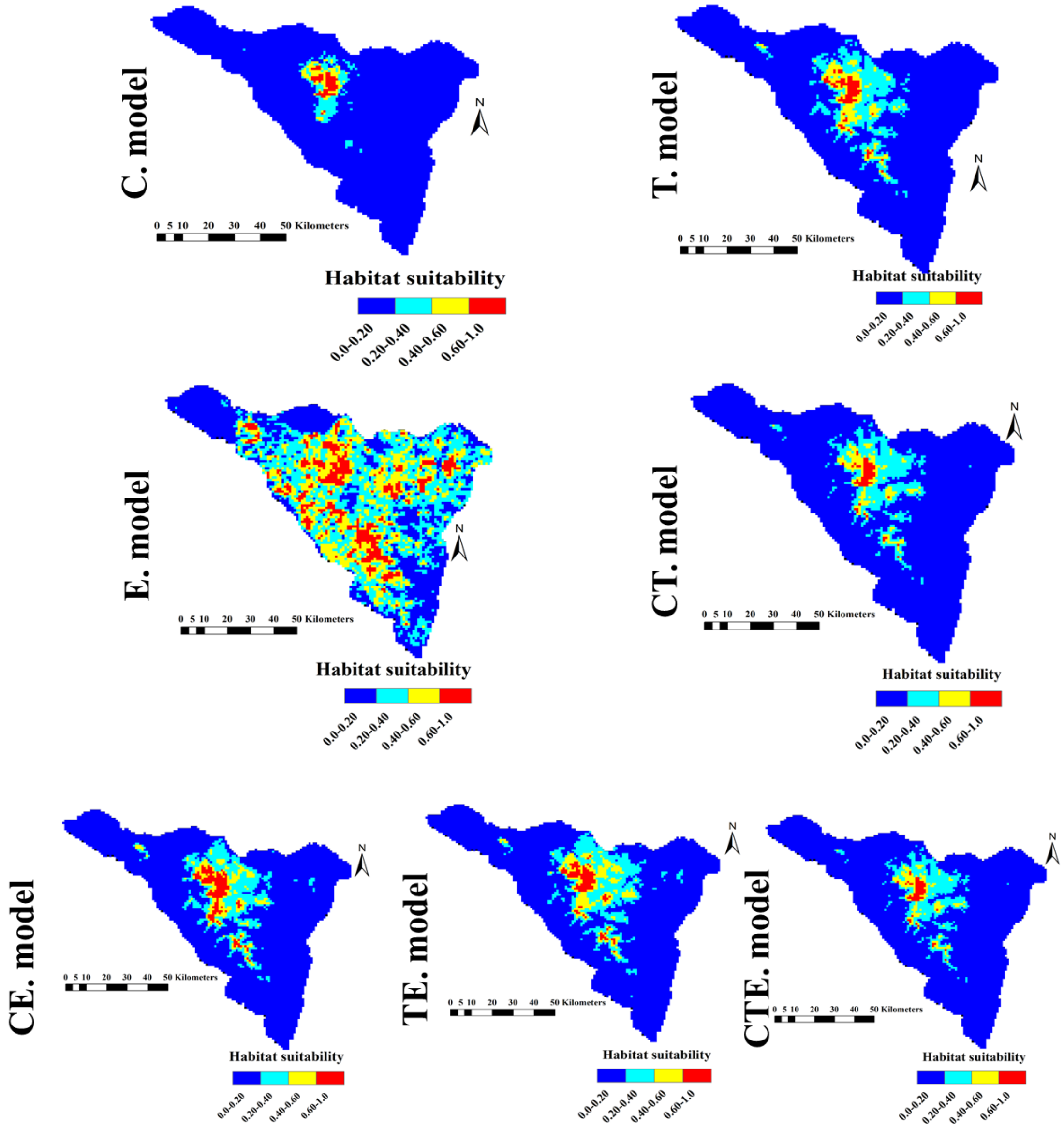

Fig.3. Map for potential current habitat suitability of *P. boveana* using different predictors in St. Catherine area. Habitat suitability classes include: unsuitable (0- 0.20), low suitability (0.20- 0.40), moderate suitability (0.40- 0.60) and high suitability (0.60- 1.0).

Table (4). Predicted current distribution areas (km^2) for *P. boveana* over different predictors.

Predicted class	C. model	T. model	E. model	CT. model	CE. model	TE. model	CTE. model
< 0.20 Unsuitable	4822	4158	1804	4303	4000	2697	4303
0.20- 0.40 Low suitability	201	698	1980	632	722	813	632
0.40- 0.60 Moderate suitability	103	262	1090	192	296	332	192
> 0.60 High suitability	70	78	322	69	178	159	69

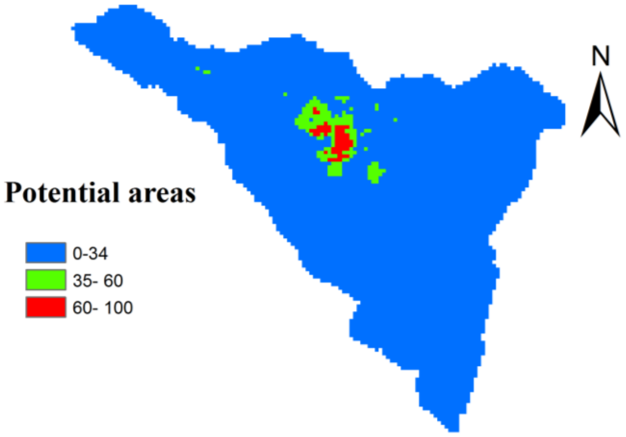

Fig. 4. Potential areas probabilities for the survey of new or historic populations of *P. boveana*. Cumulative percentage according to lowest presence threshold (LPT) and restrictive threshold of 60% of probability of presence. 0-30% absent, 30- 60% low potential and > 60% suitable.

5. Discussion

One of the most useful of species distribution models is to predict the potential areas of occurrence for rare and threatened species (Pearson et al. 2007). However, a thorough assessment of model fit and an understanding of the limitations of these models are necessary to prevent misapplication of model results and avoid errors during habitat prioritization and conservation design (Gogol-Prokurat 2011).

AUC values in our models (> 0.90) are among the highest reported models (e.g. Russo et al. 2015, Smeraldo et al. 2018, Morán-Ordóñez et al. 2018, Rus et al. 2018, Abdelaal et al. 2019) and demonstrate a high predictive capacity of habitat suitability (Elith et al. 2010). Some of the limitations of the species distribution models are the choice of algorithms and predictor variables. In our study, we applied Maxent models and also we took advantage of using regional edaphic data as predictors in species distribution modeling, in addition to climatic and topographic variables. Unfortunately, the edaphic variables when used solely or jointly did not provide accurate prediction and affect negatively the performance of other models. The rejection of edaphic data in our models owing to either these variables are calculated not measured, the used variables are not allowed better capturing of target plant requirements, low-resolution variables (1 km^2) or *P. boveana* is not strongly affected by soil factors. This is contrary to Velazco et al. (2017) who recommend to include edaphic data in species distribution models of plants. Moreover, in the mountain environment, Buri et al. (2017) suggest that very high-resolution soil predictors improve the predictive power of plant SDMs.

Our results showed that, the environmental suitability of *P. boveana* lies within the middle northern boundaries of St. Catherine areas. The results of this study can be applied in the management and conservation of this critically endangered endemic plant. One possibility is to survey and locate unknown populations. For this purpose, LPT has been used as a threshold in several previous works (e.g. Fois et al.

2015, Rus et al. 2017). The potential areas to survey for new populations of *P. boveana* according to this threshold are reduced so the effort would be feasible in the practice. On the other hand, with a more restrictive threshold that ensures a high probability of presence, in our case 60 %, we obtain a selection of potential distribution areas whose survey is feasible. After several field surveys during the flowering seasons (April- July, 2018) especially inside specific habitats of *P. boveana* (cliffs, caves and slopes) at high elevated sites near water springs and cracks of granite supplied with water, unfortunately we did not find any new populations but we discovered five extinct localities Gebal Catherine (2113 m a.s.l.), Gebal Mousa (2285 m a.s.l.), Gebal Safsafa (2166 m a.s.l.), Gebel Umm Shaumer (2090 m a.s.l.) and Elgalt Elazrak (2150 m a.s.l.) where *P. boveana* were disappeared. This finding fits with the known current and historic distributions reported in historic and literature data (Al Wadi 1993, Moustafa et al. 2001b, Richards 2003, Mansour et al. 2013, Jiménez et al. 2014, Omar 2014 a, b, Zaghloul et al. 2015). Danin (1976) stated that *P. boveana* has fare been found in Gebal Catherine, Gebal Mousa, Gebal Safsafa, Gebel Umm Shaumer while St. Catherine rangers reported its presence in both Gebal Catherine and Elgalt Elazrak between 2007 and 2012, but completely disappear. These sites are also suitable for reintroduction or translocation if necessary. Such local extinction in the suitable sites where the plant was previously present is attributed to habitat destruction by human activities (Moustafa et al. 2001b). Nonetheless, further annual survey efforts are encouraged in such sites or similar sites for the search of new *P. boveana* populations or to investigate which factors have contributed to preventing the colonization and recovery of this species in all suitable historic places. Our results encourage to apply SDMs for several threatened and poorly investigated plants spread through the St. Catherine area.

All of the current and predicted sites fulfill the *P. boveana* requirements where high elevation (1600-2300 m a.s.l.), slope of 90, NE aspects, a maximum of warmest month of 24 ℃ and not greater than 25 ℃, and with an optimum precipitation seasonality of ~ 72 and not less than ~ 50. Consequently, warm sites with elevation < 1600 m a.s.l. are less suitable for *P. boveana*. These results are in complete accordance with Moustafa et al. (2001b), Zaghloul et al. (2016) and Omar (2014 a) who reported that *P. boveana* mainly occurs in moist shaded north-facing rock crevices with a narrow elevation range from 1800- 2210 m a.s.l.

In addition, MaxEnt outputs models indicated that *P. boveana* distribution range was more influenced by elevation, Bio4, Bio8, Bio14 and soil pH. To provide an adequate interpretation of models, it is crucial to relate these variables with the ecology and biology of the target species. Our results are congruent with other studies that dealt with rare, endangered and medicinal mountain plants, where they addressed the crucial role of temperature, precipitation and elevation in plant distribution. For instance, *Myristica dactyloides* (Remya et al. 2015), *Fritillaria cirrhosa* (Zhao et al., 2018) and *Daphne mucronata* (Abolmaali et al. 2018). Specifically, in our study area, the importance of climatic factors and elevation was confirmed for the spatial distribution of *Rosa arabica* (Abdelaal et al. 2019), *Hypericum sinaicum* and *Nepeta septemcrenata* (Khafagi et al. 2011, 2012). In general, the distribution of endemic taxa within St. Catherine is mainly determined by rainfalls and elevation (Moustafa et al. 2001a).

All previous published literature confirms that, there is a continuous decline in habitat quality for *P. boveana* with evidence of decline in number and size of its population with time (Al Wadi 1993, Moustafa et al. 2001b, Mansour et al. 2013, Jiménez et al. 2014, Omar 2014 a, b, Zaghloul et al. 2015). The population size has fluctuated as follows: 2000 individuals in 1991 (Al Wadi 1993), 336 individuals in 2007, 268 individuals in 2011, 115 individuals in 2013 (Jiménez et al. 2014), 1010 individuals in 2014 (Omar 2014 a, b) and 815 individuals in the current study. The alarming decrease in *P. boveana* populations apparently relates to the growing aridification, human activities, rare gene flow among fragmented populations, high level of inbreeding which frequently cause a drop in fitness as well as its limited seed dispersal, habitat fragmentation and an increase in temperature (Jiménez et al. 2014). All of these threats force this rare endemic species toward extinction. Moreover, habitat decline due to global warming is a common threat for the survival not only of *P. boveana*, but also of other species endemic to the Sinai mountains (Hoyle and James 2005). Both temperature and aridification are predicted to increase in the Mediterranean region in the next decades (Alpert et al. 2008). This also reported by predictive models that forecasted an extreme extirpation risk for species that survive in mountains arid areas (McCain and Colwell 2011). Fewer annual precipitation would inevitably reduce the water flows to which *P. boveana* is closely linked, therefore reducing the number and size of habitats suitable for this species. Moreover, rising human stresses on the environment would exacerbate the problem of water availability which affects plant survival, with an increase in temperatures that could disrupt the pollination process (Root et al. 2003). Lastly, the reduction of genetic variation and gene flow between populations might eventually reduce selfing insufficient to compensate for the negative consequences of aridification.

6. Conclusion

SDMs cannot displace field surveys that proposed to collect an extra distribution data, but can be a valuable tool for data investigation to help identify potential knowledge gaps of any target species with isolated distribution and can direct fieldwork plan, creating potential restoration or management areas if needed and detecting possible potential areas of natural plant development. To improve the predictive ability of the model, we should annually update the presence data by visiting all suitable sites and habitats. There is an acceptable demand for such iterative efforts in the arid mountains area. This iterative approach will aid to get a model closer to reality and predict suitable areas with more accuracy for the rare and threatened species. To overcome the predicted fluctuation or extinction in population size of *P. boveana*, it is recommended to initiate *in-situ* conservation through restoration or establishment of suitable managed fenced enclosures together with *ex-situ* conservation through germplasm, artificial propagation or artificial irrigation specifically in the dry season.

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Summary

Though Egypt has the lowest number of endemic taxa, when compared with the other Mediterranean and neighbouring countries, there is a paucity of information about an exact number of endemic taxa, their distribution patterns and conservation status assessment. Therefore, the present study aimed to answer the following questions: (1) What is the exact number of endemic vascular taxa in the Egyptian flora? The answer to this question release the 2nd question (2) Could we categorize and mapping the occurrence of these endemic taxa into meaningful and interpretable hierarchical homogeneous biogeographical units to better understand the drivers for the spatial distribution of these taxa and conservational purposes? Regarding rare endemic taxa, 3) What is the current and potential distribution of endemic taxa (e.g. *Rosa arabica*) under current conditions and future global warming scenarios? 4) Could species distribution models (e.g. MaxEnt) help to guide for discovery new or historic localities/population for these rare species?

My Ph.D. thesis includes four chapters addressed the answer of the previously-mentioned questions. In general, the thesis includes methodological, empirical and theoretical contributions that aim to enhance the understanding of distribution patterns of endemic vascular plants in Egypt and their primary drivers.

In Chapter I. The checklist of the endemic vascular flora of Egypt was prepared from literature reviews, online global databases, field trips and local and international herbaria consultation. This list of species was further analysed according to their distribution and habitats among the administrative regions of Egypt. The Egyptian endemic flora includes 48 taxa (35 species, seven subspecies and six varieties) belonging to 42 genera and 18 families. No genera are exclusively endemic to Egypt. After deep investigations in this study, we excluded 57 doubtful endemic taxa that are recorded before in previous checklists. This exclusion is due to either updated taxonomy or geographic distribution information or synonymised nomenclatures. Indeed, the low rate of endemism in Egypt is a result of either hot-dry climate or topography or political barrier. The majority of endemic taxa are confined to the mountains of the Sinai Peninsula. The present endemic plant distribution analysis highlights areas of particular conservation concern among administrative regions, which may be of help for conservation programs.

In chapter II. Depending on the findings of Chapter I, we tried to classify Egypt into distinct biogeographical sectors and subsectors and to investigate the drivers of endemic plant species distribution. In this study we took the advanatage of availability of quantative environmental layers (climatic, topographic, soil, habitat heterogeneity). Fifteen environmental clusters were defined and then classified based on the presence of endemic taxa to finally produce six biogeographical sectors

and nine subsectors. Climatic-related variables, elevation and soil organic carbon are the most important determinants for environmental clustering of Egypt. In addition, the highest endemic richness sectors were the Egyptian Mediterranean coast followed by South Sinai- Egyptian Arabian Desert, Nile region, wherease the richest subsectors were South Sinai, North Sinai and Mariut coast. This research showed that the already established protected areas in Egypt are not sufficient for conserving the identified endemic-rich Mediterranean coast sector. Our regionalization method could be replicated for other species' groups, with the ultimate goal of integration all species of interest in a single biogeographical system. The presented regionalization will help to identify weaknesses in current protection actions and to understand biogeographical processes.

Chapter III. In this study, we tried to address the potential distribution of *Rosa arabica*, one of the rare and critically endangered in Egypt and the possible impact of climate change. Depending on 32 field-based occurrence points and 22 environmental variables and by applying MaxEnt model, we found that, Annual temperature, annual precipitation and elevation were the key drivers for the distribution of *R. arabica*. This species was located at the middle northern region of St. Catherine where cold moist and high elevated sites. Prediction models under future climate change scenarios displayed habitat range shifts through the disappearance of *R. arabica* in sites below 1500 m a.s.1., an altitudinal range contraction at 1500-2000 m and possible expansions towards higher elevation sites (2000- 2500 m a.s.1.). The findings of this study can be used to define the high priority areas for reintroduction or for protection against the expected climate change impacts and future modifications.

In chapter IV- This research aimed to predict the current potential distribution of *Primula boveana* Decne. ex Duby, one of the rarest and critically endangered plants worldwide, and use model results to guide in field surveys to identify the unknown new populations or historical extinct localities. Unfortunately, the edaphic variables when used solely or jointly did not provide accurate prediction and negatively affect the performance of other models. The majority of suitable habitats of *P. boveana* was located in the high elevated middle northern part of the St. Catherine area. After a set of field trips to all predicted potential distribution sites, especially within habitats of *P. boveana* at high elevated sites near water springs unfortunately we did not find any new populations but we discovered five extinct localities where *P. boveana* were completely disappeared. Species distribution models cannot replace field surveys that proposed to collect distribution data, but can be a valuable tool to improve data investigation.

This work represents only a step further towards a more comprehensive analysis on the distribution pattern of endemic vascular plants in Egypt. Many other researches based on the database and occurrences of endemic plant species are currently in progress. For instance, the use of species distribution models could guide field surveys on new plant species occurrences, as demonstrated with the study case of Primula boveana. Additionally, using SDMs together with current and future environmental drivers related with actual taxa presence, the distribution of other some interesting species from a conservational and ecological point of view will be conducted. On the other hand, conservation status assessments of endemic vascular plants may be integrated by the analyses of the potential reductions under future climate changes. Moreover, we will define the most important areas for the phytodiversity conservation in Egypt through the identification of macro, micro- and nano-hotspots as well as the impact of climate change on species richness.

Such preliminary results, as well as the entire thesis, will represent a tool for providing a framework for research, protection and policy implementations for these endemic taxa and threatened habitats.

Supplementary Materials

Supplementary Materials for Chapter II

Appendix A. Environmental datasets used in the analysis.

Attribute	Code/unit	Source	Resolution
Climate dataset			
Annual mean temperature	Bio1 (°C)	WorldClim	10 arc-min
Mean diurnal range (max. temp – min. temp)	Bio2 (°C)	WorldClim	
Isothermality (Bio2/Bio7) × 100	Bio3	WorldClim	
Temperature seasonality (SD ×100)	Bio4 (°C)	WorldClim	
Max temperature of warmest month	Bio5 (°C)	WorldClim	
Min temperature of coldest month	Bio6 (°C)	WorldClim	
Temperature annual range (Bio5-Bio6)	Bio7 (°C)	WorldClim	
Mean temperature of wettest quarter	Bio8 (°C)	WorldClim	
Mean temperature of driest quarter	Bio9 (°C)	WorldClim	
Mean temperature of warmest quarter	Bio10 (°C)	WorldClim	
Mean temperature of coldest quarter	Bio11 (°C)	WorldClim	
Annual precipitation	Bio12 (mm)	WorldClim	
Precipitation of wettest month	Bio13 (mm)	WorldClim	
Precipitation of driest month	Bio14 (mm)	WorldClim	
Precipitation seasonality (Coefficient of variation)	Bio15	WorldClim	
Precipitation of wettest quarter	Bio16 (mm)	WorldClim	
Precipitation of driest quarter	Bio17 (mm)	WorldClim	
Precipitation of warmest quarter	Bio18 (mm)	WorldClim	
Precipitation of coldest quarter	Bio19 (mm)	WorldClim	
Aridity index (the degree of water deficit below water need)	AridityIndex	ENVIREM	20 km
Climatic moisture index (a metric of relative wetness and aridity)	ClimMoisIndex	ENVIREM	
Continentality (average temp. of warmest month - average temp. of coldest month)	Continentality (°C)	ENVIREM	
Emberger's pluviothermic quotient (a metric designed to differentiate among Mediterranean type climates)	Emberger Q	ENVIREM	
Potential evapotranspiration	PETseasonality (mm/ month)	ENVIREM	
Topography dataset			

Elevation	Elev (m a.s.l.)	WorldClim	10 arc-min
Slope	Slope (%)	Derived from Elev	
Aspect	Aspect (degree)	Derived from Elev	
Soil dataset			5×5 arc-min
pH	pH	IGBP-DIS	
organic carbon	OC (mg/m^2)	IGBP-DIS	
Habitat heterogeneity dataset (based on Enhanced Vegetation Index, EVI)			12.5 arc-min (25 km)
Coefficient of variation of EVI	CV-EVI	EarthEnv	
Evenness of EVI	Evenness-EVI	EarthEnv	
Range of EVI	Range-EVI	EarthEnv	
Shannon diversity of EVI	Shannon-EVI	EarthEnv	

Appendix B. List of endemic vascular plants within the phytogeographical sectors and subsectors of Egypt. Shared values of each species are reported per subsector and, within brackets, per each sector. Significant indicator species (p< 0.05) are in bold. Shared and indicator values and their significance were calculated using the R package 'labsdv' (Roberts, 2016).

Sector	**1. Egyptian Libyan-Nubian Desert**	**2. Nile region**		**3. Egyptian Mediterranean coast**		**4. South Sinai-Egyptian Arabian Desert**		**5. Gebel Elba**	**6. Egyptian Red Sea coast**
Species Subsector	**1. Egyptian Libyan-Nubian Desert**	**2.1. Nile Delta and Valley**	**2.2. Nile Fayoum**	**3.1. Mariut coast**	**3.2. North Sinai**	**4.1. South Sinai**	**4.2. Egyptian Arabian Desert**	**5. Gebel Elba**	**6. Egyptian Red Sea coast**
Allium barthianum Asch. & Schweinf.	0	0	0	1(1)	0	0	0	0	0
Allium crameri Asch. & Boiss.	0	0	0	0	0.5(0.5)	0	0.5(0.5)	0	0
Allium mareoticum Bornm. & Gauba	0	0	0	**1(1)**	0	0	0	0	0
Allium sinaiticum Boiss.	0	0	0	0	0.5(0.5)	0.5(0.5)	0	0	0
Allium stamineum subsp. *decaisnei* (C.PresI) Kolllmann	0	0	0	0	1(1)	0	0	0	0
Allium tel-avivense Eig	0	0	0	**0.3(0.5)**	0	**0.3(0.5)**	**0.3(0.5)**	0	0
Anabasis syriaca Iljin var. *syriaca*	0	0	0	0	1(1)	0	0	0	0
Anarrhinum forskaohlii (J.F.Gmel.) Cufod. subsp. *pubescens* (Fresen.) D.A.Sutton	0	0	0	0	0	1(1)	0	0	0
Anthemis indurata Delile	0	0	0	**1(1)**	0	0	0	0	0
Anthemis microsperma Boiss. & Kotschy	0	0	0	**0.5(1)**	**0.5(1)**	0	0	0	0
Astragalus amalecitanus Boiss.	0	0	0	0	1(1)	0	0	0	0
Astragalus camelorum Barbey	0	0	0	0	0	1(1)	0	0	0
Astragalus fresenii Decne.	0	0	0	0	0	1(1)	0	0	0
Atractylis boulosii Täckh.	0	0	0	0	0	1(1)	0	0	0
Atractylis carduus (Forssk.) C.Chr. var. *marmarica* Täckh. &Boulos	0	0	0	1(1)	0	0	0	0	0
Atriplex nilotica Sukhor.	0	**0.5(1)**	**0.5(1)**	0	0	0	0	0	0

Ballota kaiseri Täckh.	0	0	0	0	0	1(1)	0	0	0
Bellevalia desertorum Eig & Feinbrun	0	0	0	0	0	1(1)	0	0	0
Bellevalia eigii Feinbrun	0	0	0	0.5(1)	0.5(1)	0	0	0	0
Bellevalia flexuosa Boiss. var. *galalensis* Täckh. & Drar	0	0	0	0	0	0	1(1)	0	0
Bellevalia salah-eidii Täckh. & Boulos	0	0	0	0.5(1)	0.5(1)	0	0	0	0
Bellevalia sessiliflora (Viv.) Kunth	0	0	0	**0.5(1)**	**0.5(1)**	0	0	0	0
Bellevalia zoharyi Feinbrun	0	0	0	0	0	1(1)	0	0	0
Biarum olivieri Blume	0	0	0	0.5(1)	0.5(1)	0	0	0	0
Biscutella didyma L. var. *elbensis* (Chrtek) El-Naggar	0	0	0	0	0	0	0	1(1)	0
Brassica deserti Danin & Hedge	0	0	0	0	1(1)	0	0	0	0
Bromus aegyptiacus Tausch	0	0.5(0.5)	0	0	0.5(0.5)	0	0	0	0
Bufonia multiceps Decne.	0	0	0	0	0	1(1)	0	0	0
Bupleurum nanum Poir.	0	0	0	1(1)	0	0	0	0	0
Carduncellus mareoticus Delile	0	0	0	**1(1)**	0	0	0	0	0
Carthamus glaucus M.Bieb. subsp. *alexandrinum* (Boiss. & Helder.) Hanelt	0	0	0	**1(1)**	0	0	0	0	0
Centaurea glomerata Vahl	0	0	0	1(1)	0	0	0	0	0
Centaurea scoparia Sieber ex Spreng.	0	0	0	0	0	**0.5(1)**	**0.5(1)**	0	0
Centaurium malzacianum Maire	0	0	0	0	0	1(1)	0	0	0
Colchicum cornigerum (Schweinf.) Täckh. & Drar	0	0	0	0	0.5(0.5)	0.5(0.5)	0.5(0.5)	0	0
Convolvulus schimperi Boiss.	0	0	0	0	0	1(1)	0	0	0
Convolvulus spicatus Peter ex Hallier f.	0	0	0	0	1(1)	0	0	0	0
Crepis libyca (Pamp.) Babc.	0	0	0	1(1)	0	0	0	0	0
Delphinium bovei Decne.	0	0	0	0	1(1)	0	0	0	0
Dianthus guessfeldtianus Muschl.	0	0	0	0	0	0	1(1)	0	0
Ducrosia ismaelis Asch.	1(1)	0	0	0	0	0	0	0	0
Ebenus armitagei Schweinf. & Taub.	0	0	0	**1(1)**	0	0	0	0	0
Echinops glaberrimus DC.	0	0	0	0	0	**0.5(1)**	**0.5(1)**	0	0
Echinops hussonii Boiss.	0	0	0	0	0	**0.5(1)**	**0.5(1)**	0	0
Echinops taekholmiana Amin	0	1(1)	0	0	0	0	0	0	0

Enarthrocarpus pterocarpus (Pers.) DC.	0	0	0	**1(1)**	0	0	0	0	0
Euphorbia bivonae Steud. var. *sinaica* Hadidi	0	0	0	0	1(1)	0	0	0	0
Euphorbia obovata Decne.	0	0	0	0	0	1(1)	0	0	0
Fagonia mollis Delile var. *hispida* Zohary	0	0	0	0	0	1(1)	0	0	0
Ferula marmarica Asch. & Taub.	0	0	0	**1(1)**	0	0	0	0	0
Galium sinaicum (Delile ex Decne.) Boiss.	0	0	0	0	0	**0.5(1)**	**0.5(1)**	0	0
Glinus runkewitzii Täckh. & Boulos	0	1(1)	0	0	0	0	0	0	0
Haloxylon negevensis (Iljin & Zohary) L.Boulos	0	0	0	0	1(1)	0	0	0	0
Haplophyllum poorei C.C.Towns.	0	0	0	0	0	1(1)	0	0	0
Helianthemum sancti-antonii Schweinf.	0	0	0	0	0	**0.5(1)**	**0.5(1)**	0	0
Helianthemum schweinfurthii Grosser	0	0	0	0	0	0	1(1)	0	0
Helianthemum sphaerocalyx Gauba & Janch.	0	0	0	1(1)	0	0	0	0	0
Herniaria cyrenaica F.Herm.	0	0	0	**1(1)**	0	0	0	0	0
Hyoscyamus boveanus (Dunal) Asch. & Schweinf.	0	0.2(0.3)	0	0.2(0.3)	0.2(0.3)	0.2(0.3)	0.2(0.3)	0	0
Hypecoum aegyptiacum (Forssk.) Asch. & Schweinf.	0	0	0	**0.5(1)**	**0.5(1)**	0	0	0	0
Hypecoum aequilobum Viv.	0	0	0	**0.5(1)**	**0.5(1)**	0	0	0	0
Ifloga spicata (Forssk.) Sch.Bip. subsp. *elbaensis* Chrtek	0	0	0	0	0	0	0	1(1)	0
Indigofera lotononoides Baker f.	1(1)	0	0	0	0	0	0	0	0
Iphiona mucronata (Forssk) Asch. & Schweinf.	0	0	0	0	0	**0.5(1)**	**0.5(1)**	0	0
Iris mariae Barbey	0	0	0	0	1(1)	0	0	0	0
Isatis microcarpa J.Gay ex Boiss.	0	0	0	0	0.3(0.5)	0.3(0.5)	0.3(0.5)	0	0
Kickxia floribunda (Boiss.) Täckh. & Boulos	0	0	0	0.5(1)	0.5(1)	0	0	0	0
Kickxia macilenta (Decne.) Danin	0	0	0	0	0	1(1)	0	0	0
Leopoldia eburnea Eig & Feinbrun	0	0	0	0	0	1(1)	0	0	0
Leopoldia longipes (Boiss.) Losinsk. subsp. *negevensis* Feinbrun & Danin	0	0	0	0	1(1)	0	0	0	0
Limonium sinuatum (L.) Mill. subsp. *romanum* Täckh. & Boulos	0	0	0	1(1)	0	0	0	0	0
Linaria joppensis Bornm.	0	0	0	0.5(1)	0.5(1)	0	0	0	0
Lotus hebranicus Hochst. ex Brand	0	0	0	0	0	**0.5(1)**	**0.5(1)**	0	0

Lotus nubicus Hochst. ex Baker	0	0	0	0	0	0	0	1(1)	1(1)0
Lupinus digitatus Forssk.	0	**0.5(1)**	**0.5(1)**	0	0	0	0	0	0
Lupinus palaestinus Boiss.	0	0	0	0	1(1)	0	0	0	0
Lycium schweinfurthii Dammer var. *aschersohnii* (Dammer) Feinbrun	0	0	0	0.5(1)	0.5(1)	0	0	0	0
Medemia argun (Mart.) Württemb. ex H.Wendl.	1(1)	0	0	0	0	0	0	0	0
Melilotus serratifolius Täckh. & Boulos	**0.2(1)**	0	0	0	0	0	0	0	0
Micromeria serbaliana Danin & Hedge	0	0	0	0	0	1(1)	0	0	0
Micromeria sinaica Benth.	0	0	0	0	0	1(1)	0	0	0
Minuartia picta (Sibth. & Sm.) Bornm. var. *sinaica* (Boiss.) Bornm.	0	0	0	0	0.5(0.5)	0.5(0.5)	0	0	0
Muscari albiflorum (Täckh. & Boulos) Hosni	0	0	0.5(0.5)	0.5(0.5)	0	0	0	0	0
Muscari salah-eidii (Täckh. & Boulos) Hosni	0	0	0	0	1(1)	0	0	0	0
Nasturtiopsis integrifolia (Boulos) Abdel Kahlik & F.T.Bakker	0	0	0	0	1(1)	0	0	0	0
Nigella arvensis L. var. *beersherensis* Zoh.	0	0	0	0	0	1(1)	0	0	0
Nigella deserti Boiss.	0	0	0	0	1(1)	0	0	0	0
Nonea vivianii DC.	0	0	0	**0.5(1)**	**0.5(1)**	0	0	0	0
Origanum isthmicum Danin	0	0	0	0	1(1)	0	0	0	0
Origanum syriacum L. subsp. *sinaicum* (Boiss.) Greuter & Burdet	0	0	0	0	0	1(1)	0	0	0
Pancratium arabicum Sickenb.	0	0	0	**0.5(1)**	**0.3(1)**	0	0	0	0
Persicaria obtusifolia (Täckh &Boulos) Greuter & Burdet	0	0	1(1)	0	0	0	0	0	0
Petrorhagia arabica (Boiss.) P.W.Ball & Heywood	0	0	0	0	0	1(1)	0	0	0
Phagnalon sinaicum Bornm. & Kneuck.	0	0	0	0	0	1(1)	0	0	0
Phlomis aurea Decne.	0	0	0	0	0	1(1)	0	0	0
Picris sulphureae Delile	0	0	0	0	0	**0.5(1)**	**0.5(1)**	0	0
Pimpinella etabica Schweinf.	0	0	0	0	0	0	0	1(1)	0
Pistacia khinjuk Stocks var. *microphylla* Boiss.	0	0	0	0	0	0	1(1)	0	0
Plantago sinaica (Barnéoud) Decne.	0	0	0	0	0	1(1)	0	0	0
Podonosma galalense Schweinf. ex Boiss.	0	0	0	0	0	0	1(1)	0	0
Polygala negevensis Danin	0	0	0	0	0	1(1)	0	0	0

Primula boveana Decne. ex Duby	0	0	0	0	0	1(1)	0	0	0
Pseuderucaria clavata (Boiss. & Reut.) O.E.Schulz	0	0	0	0.5(0.5)	0	0	0.5(0.5)	0	0
Pterocephalus arabicus Boiss.	0	0	0	0	0	1(1)	0	0	0
Pterocephalus sanctus Decne.	0	0	0	0	0	1(1)	0	0	0
Pycnocycla tomentosa Decne.	0	0	0	0	0.5(0.5)	0.5(0.5)	0	0	0
Reaumuria negevensis Zohary & Danin	0	0	0	0	1(1)	0	0	0	0
Rosa arabica Crép	0	0	0	0	0	1(1)	0	0	0
Rumex aegyptiacus L.	0	**0.3(0.5)**	**0.3(0.5)**	**0.3(0.5)**	0	0	0	0	0
Salvia deserti Decne.	0	0	0	0	0	**0.5(1)**	**0.5(1)**	0	0
Scorzonera drarii Täckh.	0	0	0	0	1(1)	0	0	0	0
Senecio belbeysius Delile	0	**1(1)**	0	0	0	0	0	0	0
Silene apetala Willd var. *glabrata* E.Shamso	0	0	0	1(1)	0	0	0	0	0
Silene biappendiculata Ehrh. ex Rohrb.	0	0	0	**1(1)**	0	0	0	0	0
Silene leucophylla Boiss.	0	0	0	0	0	1(1)	0	0	0
Silene oreosinaica Chowdhuri	0	0	0	0	0	1(1)	0	0	0
Sinapis allionii Jacq.	0	0.5(0.5)	0	0.5(0.5)	0	0	0	0	0
Solanum nigrum L. var. *elbaensis* Täckh. & Boulos	0	0	0	0	0	0	0	1(1)	0
Solanum sinaicum Boiss.	0	0	0	0	0	1(1)	0	0	0
Sonchus macrocarpus Boulos & C.Jeffrey	0	0.5(0.5)	0	0.5(0.5)	0	0	0	0	0
Stipagrostis shawi (H.Scholz) H.Scholz	1(1)	0	0	0	0	0	0	0	0
Tanacetum sinaicum(Fresen.) Delile ex K.Bremer & Humphries	0	0	0	0	0	1(1)	0	0	0
Tephrosia kassasii Boulos	0	1(1)	0	0	0	0	0	0	0
Tephrosia purpurea (L.) Pers. subsp. *apollinea* (Delile) Hosni & El-Karmy	0	0.2(0.2)	0	0.2(0.2)	0	0	0.2(0.2)	0.2(0.2)	1(1)
Tetraena dumosum (Boiss.) Beier & Thulin	0.3(0.3)	0	0	0	0.3(0.3)	0.3(0.3)	0	0	0
Teucrium leucocladum subsp. *sinaicum* Danin	0	0	0	0	0	1(1)	0	0	0
Teuricum leucocladum Boiss. subsp. *leucocldum*	0	0	0	0	0.5(0.5)	0.5(0.5)	0	0	0
Thesium humile Vahl var. *maritima* (N.D.Simpson) sa'ad	0	0	0	**1(1)**	0	0	0	0	0
Thymus bovei Benth.	0	0	0	0	1(1)	0	0	0	0

Thymus decussatus Benth.	0	0	0	0	0	1(1)	0	0	0
Trifolium philistaeum Zohary	0	0	0	0	1(1)	0	0	0	0
Trigonella media Delile	0	0	1(1)	0	0	0	0	0	0
Valerianella petrovichii Asch.	0	0	0	01(1)	0	0	0	0	0
Verbascum fruticulosum Post	0	0	0	0	1(1)	0	0	0	0
Verbascum letourneuxii Asch.	0	0	0	**0.5(1)**	**0.5(1)**	0	0	0	0
Verbascum schimperianum Boiss.	0	0	0	0	0	1(1)	0	0	0
Veronica anagalloides Guss. subsp. *taeckholmiorum* Chrtek & Osb.-Kos.	0	**0.5(1)**	**0.5(1)**	0	0	0	0	0	0
Vicia sinaica Boulos	0	0	0	0	1(1)	0	0	0	0
Withania obtusifolia Täckh.	0	0	0	0	0.3(0.3)	0.3(0.3)	0	0.3(0.3)	0
Zygophyllum scabrum (Forssk.) Christenh. & Byng	0	0	0	0	0	0	1(1)	0	0

Reference

Roberts, D. W. (2016). labdsv: ordination and multivariate analysis for ecology. 2016. R Package Version, 1.8. Http://Cran.r-Project.Org/Web/Packages/Labdsv/Index.Html.

Appendix C. Characteristic features of the environmental clusters (size and average of variables± standard deviations). Different letters in the same row displayed significant differences at $p < 0.05$.

Variable	R^2	**Environmental cluster**														
		1	**3**	**5**	**9**	**13**	**14**	**15**	**8**	**11**	**12**	**6**	**10**	**7**	**2**	**4**
Size (Number of grid cells)*		240	336	279	231	174	144	241	157	98	95	77	270	131	98	39
Bio8 (°C)	0.88	12.9± 0.85^{b}	13.9± 6.63^{fg}	11.9± 2.20^{d}	12.1± 0.31^{bc}	14.6± 0.95^{cd}	14.2± 0.94^{bc}	17.2± 3.24^{e}	26.1± 0.60^{cd}	13.9± 1.43^{bc}	13.7± 0.90^{bc}	15.5± 1.80^{a}	14.9± 1.59^{a}	14.5± 2.22^{g}	21.1± 4.25^{f}	15.1± 2.20^{d}
Bio9 (°C)	0.78	21.1± 4.12^{d}	16.8± 1.58^{b}	24.5± 2.14^{a}	26.0± 2.89^{ab}	24.5± 0.94^{g}	25.2± 1.79^{fg}	18.2± 3.19^{c}	24.8± 0.75^{fg}	25.9± 1.06^{g}	16.4± 0.56^{fg}	23.5± 1.50^{ef}	24.6± 2.16^{fg}	18.8± 2.11^{d}	23.0± 5.06^{e}	22.4± 2.71^{de}
Bio15	0.80	51.1± 12.6^{b}	15.6± 1.46^{a}	10.3± 1.42^{a}	13.5± 1.88^{a}	98.7± 14.64^{e}	89.8± 15.18^{de}	17.5± 2.24^{a}	93.8± 6.19^{de}	85.1± 8.29^{de}	104.1 ± 6.25^{e}	77.7± 12.38^{cd}	72.6± 11.53^{cd}	68.3± 8.82^{c}	65.5± 4.32^{bc}	72.0± 13.07^{cd}
Aridity index	0.81	99.6± 0.89^{e}	100.0 ± 0.0^{f}	100.0 ± 0.0^{f}	100.0 ± 00.0^{f}	93.1± 3.98^{a}	98.5± 0.89^{c}	98.0± 0.0^{f}	92.6± 3.38^{a}	94.7± 2.93^{ab}	93.7± 1.74^{a}	97.8± 1.01^{bc}	99.2± 0.78^{d}	99.6± 0.49^{e}	99.6± 0.52^{de}	99.7± 0.47^{e}
Cont.(°C)	0.79	17.1± o.89de	17.3± 0.49^{ef}	17.9± 0.33^{g}	17.5± 0.53^{fg}	13.7± 0.78^{a}	15.5± 0.79^{c}	16.8± 0.73^{d}	13.5± 0.95^{a}	14.4± 0.64^{ab}	13.8± 0.46^{a}	15.4± 0.51^{bc}	15.6± 0.54^{c}	14.2± 1.26^{a}	13.8± 1.5^{a}	14.9± 0.42^{abc}
Elev. (m)	0.70	148.9 ± 6.5^{cd}	393.4 ± 214.8^{fg}	452.2 ± 212.7^{g}	280.6 ± 81.6^{e}	19.6± 8.3^{a}	80.3± 33.8^{b}	258.4 ± 118.9^{e}	159.8 ± 70.8^{cd}	182.5 ± 169.9^{d}	97.7± 23.1^{bc}	745.3 ± 350.8^{h}	461.7 ± 234.8^{g}	396.1 ± 152.2^{g}	342.3 ± 150.3^{ef}	173.0 ± 80.1^{cd}
OC (mg/m^2)	0.76	5.68± 0.39^{g}	5.29± 0.09^{d}	5.47± 0.09^{f}	5.70± 0.16^{g}	4.34± 0.69^{ab}	5.00± 0.39^{c}	5.37± 0.17^{e}	3.78± 0.66^{a}	4.48± 0.49^{b}	3.75± 0.32^{a}	4.45± 0.24^{ab}	5.01± 0.28^{c}	4.56± 0.35^{b}	4.10± 0.38^{ab}	4.36± 0.31^{ab}
CV-EVI	0.15	0.22± 0.16^{a}	0.11± o.08^{a}	0.16± 0.10^{a}	0.38± 0.17^{a}	1.00± 0.18^{a}	0.46± 0.16^{a}	0.15± 0.08^{a}	0.41± 0.18^{a}	0.57± 0.16^{a}	0.00± 0.0^{a}	0.20± 0.08^{a}	0.33± 0.11^{a}	0.09± 0.0^{a}	0.32± 0.12^{a}	0.38± 0.11^{a}
Evenness-EVI	0.15	0.18± 0.01^{a}	0.10± 0.0^{a}	0.12± 0.0^{a}	0.13± 0.0^{a}	1.00± 0.29^{a}	0.31± 0.01^{a}	0.20± 0.11^{a}	0.25± 0.10^{a}	0.35± 0.25^{a}	0.36± 0.10^{a}	0.00± 0.0^{a}	0.22± 0.08^{a}	0.10± 0.0^{a}	0.36± 0.10^{a}	0.37± 0.14^{a}
Range-EVI	0.18	0.10± 0.0^{a}	0.02± 0.0^{a}	0.04± 0.0^{a}	0.12± 0.02^{a}	1.00± 0.16^{a}	0.25± 0.09^{a}	0.03± 0.0^{a}	0.46± 0.13^{a}	0.30± 0.15^{a}	0.01± 0.0^{a}	0.39± 0.15^{a}	0.24± 0.09^{a}	0.00± 0.0	0.08± 0.0^{a}	0.17± 0.04^{a}
Shannon-EVI	0.19	0.09± 0.0^{a}	0.0± 0.0^{a}	0.02± 0.0^{a}	0.07± 0.0^{a}	1.00± 0.22^{a}	0.20± 0.03^{a}	0.04± 0.0^{a}	0.40± 0.10^{a}	0.26± 0.09^{a}	0.06± 0.0^{a}	0.35± 0.12^{a}	0.24± 0.01^{a}	0.01± 0.0^{a}	0.04± 0.0^{a}	0.16± 0.02^{a}
Phytogeographic sector		Egyptian Libyan-Nubian Desert				The Nile region			Egyptian Mediterranean coast			South Sinai-Egyptian Arabian Desert		Gebel Elba	Egyptian Red Sea coast	

The size of one grid cell= 400 km^2

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