TÜBİTAK

Turkish Journal of Botany

http://journals.tubitak.gov.tr/botany/

Research Article

Turk J Bot
(2016) 40: 59-73
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doi:10.3906/bot-1403-108

Characteristics of desert vegetation along four transects in the arid environment of southern Egypt

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Received: 01.04.2014 • **Accepted/Published Online:** 23.12.2014 • **Final Version:** 01.01.2016

Abstract: The floristic diversity and vegetation–environment relations in the southern part of the Eastern Desert, between 26°45′N and 24°1′N and between 32°45′E and 35°00′E and covering a total area of about 54,500 km^2, were investigated. For this purpose, 142 georeferenced stands distributed in four transects were selected: 22 from Qena-Safaga road (T1), 28 from Idfu-Marsa Alam road (T2), 46 from Aswan-Kharit-Gimal (T3), and 46 from Red Sea Coastal Plain (T4). Altogether, 94 species belonging to 33 families were recorded, and the species richness (SR) varied from one transect to another: 46, 35, 52, and 46 in T1, T2, T3, and T4, respectively. Soil samples were collected from each stand, and the soil texture, soil moisture content, organic matter (OM), electric conductivity (EC), total soluble salts (TSS), pH, and major ions (Na^+, K^+, Ca^{+2}, Mg^{+2}, Cl^-, SO_4^{-2}, and HCO_3^-) were determined. The soil–vegetation relationships were assessed by both detrended correspondence analysis and canonical correspondence analysis. Both species diversity measurements (SR and H') exhibited significant differences among the separated vegetation groups within each transect. Classification of the vegetation resulted in 6, 7, 4, and 6 vegetation groups for T1, T2, T3, and T4, respectively. Canonical correspondence analysis showed well the relative positions of species and sites along the most important ecological gradients. The segregation of these groups along the first two axes of the biplot demonstrated that soil texture, moisture content, salinity, sulfates, and organic matter contents were highly correlated with the distribution of species.

Key words: Species diversity, detrended correspondence analysis, canonical correspondence analysis, Egypt, plant communities, vegetation–environment relationships

1. Introduction

According to Zahran and Willis (2009), the inland part of the Eastern Desert of Egypt can be divided into four main geomorphological and ecological regions, from north to south: 1) the Cairo-Suez Desert, 2) the Limestone Desert, 3) the Sandstone Desert, and 4) the Nubian Desert. From a phytogeographical point of view, El-Hadidi (1980) divided the Eastern Desert of Egypt into two main subterritories: 1) the Galalah Desert, including Cairo-Suez and the northern limestone plateau (c. 27°N), and 2) the Arabian Desert, including the southern limestone plateau and the Nubian Sandstone. The dissection of the Eastern Desert by dense networks of wadis indicates that Egypt must have witnessed some periods of pluviation. The range of the Red Sea coastal mountains divides the Eastern Desert into two main ecological units: the Red Sea coastal land and the inland desert (Zahran and Willis, 2009). The Red Sea coastal land in Egypt extends from Suez to Mersa Halaib at the Sudano-Egyptian border. The land adjacent to the Red Sea is generally mountainous, flanked on the western side by the range of coastal mountains. The inland part of the Eastern Desert lies between the range of the Red Sea coastal land in the east and the Nile Valley in the west. It is a rocky plateau dissected by a number of wadis. Each wadi has a main channel with numerous tributaries.

Approximately half of the estimated 3000 plant species reported from the arid zones of North Africa are found in the Sahara (Le Houerou, 1986). Throughout this region annual plants provide additional variety to the vegetation. In Egypt, the desert vegetation is by far the most important and characteristic type of natural plant life. It covers about 95% of the total area of the country and is mainly formed of xerophytic shrubs and subshrubs. From the early beginnings of the last century different ecological aspects and vegetation of the Eastern Desert were studied by different scholars (see Abd El-Ghani et al., 2013 for literature).

The correlation of soils and vegetation was also among the major themes in the arid regions of the Middle East (e.g., Olsvig-Whittaker et al., 1983; Salama et al., 2012).

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These investigations included large areas and therefore they reported striking gradients referring to soil conditions and vegetation.

Modern synecological research has preferred a more objective methodology for use at the local and sometimes regional scale, seeking to reduce the complexity of a field dataset either by classification and/or ordination of floristic data and then relating results to environmental data, or by deriving vegetation–habitat relationships from a single analysis of a combined floristic and environmental variable set (Ter Braak, 1987). There have been great advances in numerical techniques in the last decade and the aim here is to examine their potential for summarizing Egyptian desert vegetation in relation to important habitat factors.

The relation between different edaphic factors such as soil texture pH, EC, and soil macronutrients and the vegetation composition and plant distribution were also studied by many other authors (Fossati et al., 1998; Galal and Fahmy, 2012).

The present work aimed to 1) identify habitat types and associated plant communities, 2) identify the dominant plant communities through detailed phytosociological study, and 3) analyze the vegetation and species diversity in relation to the prevailing environmental conditions using multivariate analysis techniques.

2. Materials and methods

2.1. Study area

The study area covered nearly the southern quarter of the Eastern Desert (about 54,500 km^2) between 26°45′N and 24°1′N and between 32°45′E and 35°00′E (Figure 1). According to Zahran and Willis (2009), this area comprises three desert types: 1) the limestone desert (Assiut-Qena Desert), 2) the sandstone desert (Idfu-Kom Ombo Desert), and 3) the Red Sea coastal plain. Detailed studies on the geology, geomorphology, topography, and lithology have been documented by Zahran and Willis (2009).

Available climatic records over the period 2003–2012 from four meteorological stations (Qena, Safaga, Aswan, and Marsa Alam) demonstrated that the average monthly temperature ranged between 14.9 °C in January (minimum) and 33.6 °C (maximum) in July. Rainfall occurs only in winter and is due to random cloudbursts, a general feature in arid deserts: rain may occur once every several years. Annual average rainfall records (over 30 years) showed notable decrease along north-south direction. Averages of relative humidity reached a maximum of 51.5% and 52.7% (in December), while the minimum was 25.6% and 32.4% (in June) for Mersa Alam and Safaga, respectively.

2.2. Data collection and vegetation analysis

Between 2011 and 2013, vegetation sampling was performed in the study area using 4 transects representing the 3 desert types. One hundred and forty-two georeferenced (using GPS model Garmin eTrex HC) randomly selected stands (20 × 30 m) were used along the four transects to represent apparent variations in the physiognomy of vegetation and in the physiographic features. The sandstone desert included T1, which comprised the Aswan-Berenice road (300 km; 24°05′N to 24°00′N and 32°55′E to 35°24′E), Wadi Kharit (250 km, 24°26′N to 24°12′N and 33°11′E to 34°40′E), W. Natash (100 km, 24°21′N to 24°40′N and 33°24′E to 34°30′E), and W. Gimal (65 km, 24°34′N to 24°40′N and 34°35′E to 35°05′E), and T2, which comprised the Idfu-Marsa Alam road (100 km, 25°55′N and 32°55′E to 34°55′E). In the limestone desert, T3 included the Qena-Safaga road (155 km, 26°12′N to 26°46′N and 32°44′E to 33°56′E), and along the Red Sea coastal plain T4, which extends for about 240 km between 24°39′N and 26°36′N and 32°05′E and 34°00′E. Taxonomic nomenclature was according to Täckholm (1974) and Boulos (1999–2005). Voucher specimens of each species were collected and identified at the herbaria of Assiut University (ASTU) and Cairo University (CAI), where they were deposited.

A floristic presence/absence data matrix of 142 stands and 94 species was subjected to classification by cluster analysis with the Community Analysis Package version 1.2 (Henderson and Seaby, 1999) using a squared Euclidean distance dissimilarity matrix with minimum variance (also called Ward's method) as the agglomeration criterion. The resulting vegetation groups (plant communities) were named after the dominant species that had the highest presence percentages in the stands of the group. In this study, the default option of the computer program CANOCO software version 3.12 (Ter Braak, 1990) was used for detrended correspondence analysis (DCA) and canonical correspondence analysis (CCA) ordinations.

Preliminary analyses were made by applying the default options of DCA in the CANOCO program to check the magnitude of change in species composition along the first ordination axis (i.e. gradient length in standard deviation units). DCA estimated the compositional gradient in the vegetation data of the present study to be equal to or larger than 5.0 SD units for all subset analysis, and thus CCA is the appropriate ordination method to perform direct gradient analysis (Ter Braak and Prentice, 1988).

The relationships between vegetation gradients and the studied environmental variables can be indicated on the ordination biplot produced by CCA. A Monte Carlo permutation test (499 permutations; Ter Braak, 1990) is used to test for significance of the eigenvalues of the first canonical axis. Intraset correlations from the CCAs are therefore used to assess the importance of the environmental variables.

The vegetation groups that resulted from cluster analysis were subjected to an ANOVA based on soil

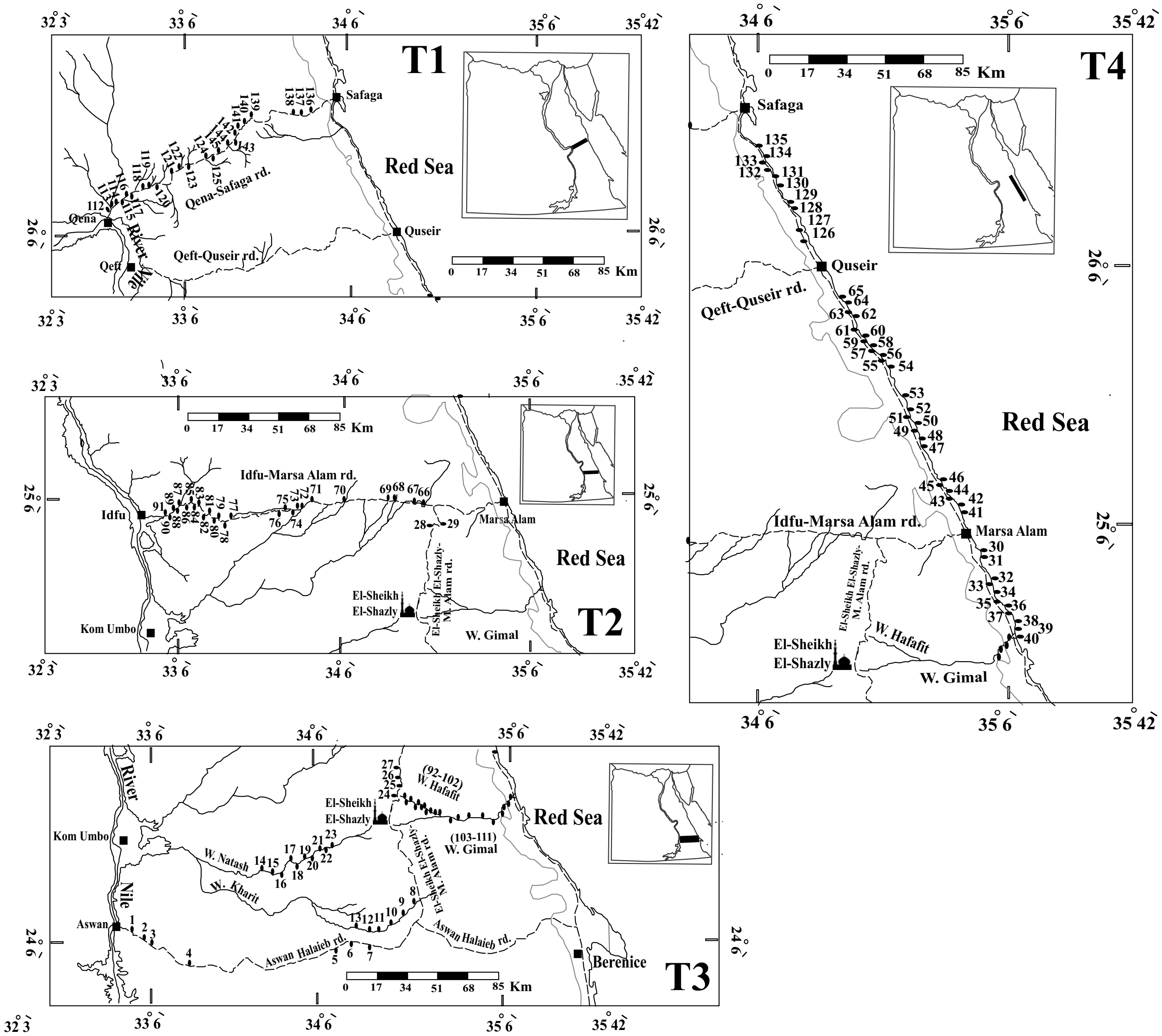

Figure 1. Location maps of transects showing the stand distribution of the vegetation groups in each transect.

variables to find out whether these were significant variations among vegetation clusters identified (Sokal and Rohlf, 1981) according to Ward's technique using SPSS version 16.0. Species diversity within each separated vegetation group (clusters) was assessed using two different indices expressing species richness and diversity. Species richness (alpha-diversity; SR) was calculated as the average number of species per stand, which measures the species turnover between different areas, determined according to Magurran (2003). The species diversity was calculated as the Shannon–Wiener index: $H' = -\sum_{i=1}^{s} P_i \mathrm{Log}_2 P_i$, where S is the total number of species and P_i is presence value of the species (Pielou, 1975) that reflects species distribution in the different habitats in the study area.

2.3. Soil sampling and analysis

Soil samples (0–50 cm depth) were collected at 3 random points from each stand as a profile (composite samples). These samples were then air-dried, thoroughly mixed, and passed through a 2-mm sieve to get rid of gravel and rocks. The soil texture was determined using the sieve method; the amount of each fraction (sand, silt, and clay) was expressed as percentage of the original weight used (Jackson, 1967). Soil moisture content was estimated by drying at 105 °C, and then the percentage of soil moisture was calculated based on dry weight of the soil (Kapur and Govil, 2000). The soil portion of less than 2 mm in size was kept for chemical analysis according to Jackson (1967). Soil–water extracts (1:5) were prepared for determination of electrical conductivity (EC) using a conductivity meter (model 4310 JEN WAY), and pH using a glass electrode pH-meter (model Hanna pH 211). Organic matter (OM) was determined using Walkley and Black rapid titration (Black, 1979). Sodium and potassium were determined by flamephotometer (Model Carl-Zeiss DR LANGE M7D). Calcium and magnesium were estimated by titration against ethylenediamine dihydrogen tetraacetic acid (EDTA) using ammonium purpurate and eriochrome black T as indicators (Jackson, 1967). Chlorides were determined by direct titration against $AgNO_3$ using potassium chromate as an indicator, and bicarbonates by direct titration against HCl using methyl orange as indicator. Sulfates were determined by a turbidimetric technique with barium chloride and acidic sodium chloride solution using a spectrophotometer (Model 1200) according to Bardsley and Lancaster (1965).

3. Results

A comparative summarized analysis between the vegetation structure and species composition (in terms of P%) of each transect is shown in Table 1. Altogether, 94 species (67 perennials and 27 annuals) constituted the floristic composition, representing 76 genera and 32 families. The total number of recorded species was 46, 35, 52, and 46 for T1, T2, T3, and T4, respectively. Shrubs predominated (37 species, 39.4%), followed by annual herbs (32 species, 34%), trees (13 species, 13.8%), and perennial herbs (12 species, 12.8%). Trees and perennial herbs were the least represented (2–7 species) among the 4 studied transect, while annual herbs and shrubs were the most (14–24 species). Six shrubs and 3 annual herbs were the ubiquitous species with wide ecological distribution ranges recorded in all transects (Table 1). Forty-seven species (8 trees, 18 shrubs, 8 perennial herbs, and 13

Table 1. Species composition of the 4 transects, together with their presence values (P%). T1 = Qena-Safaga transect; T2 = Idfu-Marsa Alam transect; T3 = Aswan-Kharit-Gimal transect, and T4 = Red Sea transect.

Species	P% for each transect			
	T1	T2	T3	T4
Species present in all transects				
Shrubs				
Aerva javanica (Burm. F.) Juss ex Schult.	18.2	25	8.7	4.3
Caroxylon imbricatum (Forssk.) Akhani & E. H. Roalson	45.5	67.9	2.2	2.2
Leptadenia pyrotechnica (Forssk.) Decne.	18.2	7.1	6.5	2.2
Lotus hebranicus Hochst. ex Brand	13.6	14.3	17.4	13
Zilla spinosa (L.) Prantl.	81.8	96.4	73.9	15.2
Zygophyllum coccineum L.	59.1	3.6	8.7	30.4
Annual plants				
Astragalus vogelii (Webb.) Bornm.	9.1	21.4	13	6.5
Polycarpaea repens (Forssk.) Asch. & Schweinf.	4.5	3.6	4.3	6.5
Tetraena simplex (L.) Beier & Thulin	9.1	28.6	8.7	2.2
Species present in three transects				
Trees				
Acacia tortilis (Forssk.) Hayne subsp. *raddiana* (Savi) Brenen	0	46.4	65.2	17.4
Calotropis procera (Aiton) W. T. Aiton	4.5	7.1	6.5	0
Tamarix aphylla (L.) H. Karst.	0	10.7	26.1	17.4
T. nilotica (Ehreub.) Bunge	18.2	0	4.3	30.4
Shrubs				
Cleome droserifolia (Forssk.) Delile	4.5	0	4.3	6.5
Fagonia thebaica Boiss.	18.2	46.4	0	2.2
Ochradenus baccatus Delile	18.2	0	2.2	6.5
Panicum turgidum Forssk.	0	3.6	15.2	8.7
Pergularia tomentosa L.	13.6	10.7	2.2	0
Pulicaria undulata (L.) C. A. Mey	0	39.3	10.9	2.2

Table 1. (Continued).

Suaeda monoica Forssk. ex J. F. Gmel.	0	7.1	2.2	6.5
Perennial plants				
Citrullus colocynthis (L.) Schrad.	22.7	35.7	32.6	0
Monsonia heliotropioides (Cav.) Boiss.	0	3.6	10.9	2.2
Phragmites australis (Cav.) Trin. ex Steud.	18.2	3.6	0	13.0
Annual plants				
Cotula cinerea Delile	9.1	3.6	19.6	0
Eremobium aegyptiacum (Spreng.) Asch. & Schweinf. ex Boiss.	4.5	10.7	2.2	0
Forsskaolea tenacissima L.	18.2	3.6	6.5	0
Morettia philaeana (Delile) DC.	31.8	60.7	39.1	0
Schouwia purpurea (Forssk.) Schweinf.	9.1	35.7	8.7	0
Trichodesma africanum (L.) R. Br.	22.7	25.0	4.3	0
Species present in two transects				
Trees				
Phoenix dactylifera L.	22.7	0	0	2.2
Shrubs				
Convolvulus hystrix Vahl	0	0	2.2	8.7
Fagonia indica Burm. F.	0	0	6.5	2.2
Farsetia stylosa R. Br.	0	10.7	17.4	0
Heliotropium bacciferum Forssk.	0	7.1	0	2.2
Pulicaria incisa (Lam.) DC.	27.3	0	4.3	0
Senna italica Mill	0	3.6	17.4	0
Perennial plants				
Cynodon dactylon (L.) Pers.	13.6	0	0	4.3
Annual plants				
Arnebia hispidissima (Lehm.) DC.	4.5	0	0	4.3
Asphodelus tenuifolius Cav.	0	7.1	15.2	0
Cistanche phelypaea (L.) Cout.	4.5	3.6	0	0
Cleome amblyocarpa Barratte & Murb.	0	3.6	10.9	0
Euphorbia granulata Forssk.	0	3.6	4.3	0
Launaea nudicaulis (L.) Hook. F.	0	0	13	8.7
Malva parviflora L.	0	0	2.2	10.9
Reseda pruinosa Delile	0	0	2.2	2.2
Tribulus megistopterus Kralik	4.5	0	2.2	0
T. pentandrus Forssk.	0	14.3	10.9	0
Species present in one transect				
Trees				
Acacia nilotica (L.) Delile	4.5	0	0	0
Avicennia marina (Forssk.) Vierh.	0	0	0	8.7
Balanites aegyptiaca (L.) Delile	0	0	28.3	0
Capparis decidua (Forssk.) Edgew.	0	0	2.2	0
Hyphaene thebaica (L.) Mart.	0	0	0	2.2
Moringa peregrina (Forssk.) Fiori	4.5	0	0	0
Ricinus communis L.	9.1	0	0	0

Table 1. (Continued).

Ziziphus spina-christi (L.) Desf.	18.2	0	0	0
Shrubs				
Artemisia judaica L.	9.1	0	0	0
Arthrocnemum macrostachyum (Moric.) K. Koch	0	0	0	13.0
Atriplex leucoclada Boiss.	4.5	0	0	0
Capparis spinosa L.	0	0	0	2.2
Caroxylon villosum Schult.	4.5	0	0	0
Chrozophora oblongifolia (Delile) Spreng.	4.5	0	0	0
Cornulaca monacantha Delile	0	0	0	6.5
Crotalaria aegyptiaca Benth.	0	0	0	10.9
Fagonia bruguieri DC.	4.5	0	0	0
F. mollis Delile	9.1	0	0	0
Iphiona mucronata (Forssk.) Asch. & Schweinf.	0	7.1	0	0
Limonium axillare (Forssk.) Kuntze	0	0	0	21.7
Nitraria retusa (Forssk.) Asch.	0	0	0	26.1
Oxystelma esculentum (L.F.) R. Br.	0	0	2.2	0
Salvadora persica L.	0	0	8.7	0
Senna holosericea (Freseu) Greuter	0	0	4.3	0
Taverniera aegyptiaca Boiss.	0	0	0	2.2
Zygophyllum album L.	0	0	0	26.1
Perennial plants				
Aeluropus littoralis (Gouan) Parl.	0	0	0	6.5
Cyperus rotundus L.	0	0	0	2.2
Dichanthum annulatum (Forssk.) Stapf	4.5	0	0	0
Imperata cylindrica (L.) Raeusch	9.1	0	0	0
Juncus rigidus Desf.	0	0	0	2.2
Leptochloa fusca (L.) Kunth	0	0	0	2.2
Stipagrostis plumosa (L.) Munro ex T. Anderson	4.5	0	0	0
Typha domingensis (Pers.) Poir. ex Steud.	4.5	0	0	0
Annual plants				
Astragalus eremophilus Boiss.	0	0	30.4	0
Chenopodium album L.	4.5	0	0	0
Ch. murale L.	0	0	0	2.2
Echium horridum Batt.	4.5	0	0	0
Filago desertorum Pomel	4.5	0	0	0
Glinus lotoides L.	0	0	2.2	0
Hippocrepis constricta Knuze	0	0	6.5	0
Launaea amal-aminae N. Kilian	0	0	4.3	0
L. capitata (Spreng.) Dandy	0	0	2.2	0
Lupinus digitatus Forssk.	0	0	6.5	0
Oligomeris linifolia (Vahl.) ex Hornew J. F. Macbr.	0	0	0	2.2
Polycarpaea robbairea (Kuntze) Greuter and Burdet	0	0	6.5	0
Sonchus oleraceus L.	0	0	0	2.2

annual herbs) representing 50% of the total species were recorded in a single transect (17 in T1, 1 in T2, 12 in T3, 17 in T4). Chorological and life form analyses were presented in an earlier work carried out by the same authors in this area (Salama et al., 2014).

3.1. Classification of vegetation

Cluster analysis of species composition in each of the studied 4 transects is shown in Figure 2. The yielded groups were named after the dominant species that had the highest presence values (P%). Detailed floristic data of the species composition of each vegetation group in a certain transect are not given here and can be requested from the first author. The resulting vegetation groups of each transect were plotted along the first and second axes of DCA, as shown in Figure 3.

3.1.1. Qena-Safaga transect (T1)

Classification of the presence/absence dataset of 46 species recorded in 22 stands along Qena-Safaga transect (T1) yielded 6 vegetation groups at level 3 of the hierarchy. Inspection of the location map (Figure 1), on which the stands representing each of these vegetation groups were located, revealed that most stands of groups A, D2, and E were located in the proximity of Qena Province (c. 26°06′N). Stands of groups B, C, and D1 tended to be closer to the Red Sea coast, and especially D1 stands (c. 26°45′N). *Zilla spinosa* was recorded with variable presence values in the six groups.

Group A, *Zilla spinosa-Caroxylon imbricatum-Ziziphus spina-christi*, comprised 16 species recorded from 3 stands. *Phoenix dactylifera* represented the codominant species in this community with P = 67%. Group B, *Zilla spinosa*, comprised 17 species from 4 stands. *Pulicaria incisa*, *Fagonia thebaica*, *Lotus hebranicus*, and *Artemisia judaica* were the codominants with presence values ranging between 50% and 75%. Group C, *Zygophyllum coccineum-Aerva javanica*, comprised 13 species recorded from 2 stands. This community had four characteristic species (P = 100%): *Zygophyllum coccineum*, *Aerva javanica*, *Zilla spinosa*, and *Forsskaolea tenacissima*. The codominant species (P = 50% for each) included *Ochradenus baccatus*, *Pergularia tomentosa*, *Citrullus colocynthis*, and *Leptadenia pyrotechnica*. Group D1, *Zilla spinosa-Zygophyllum coccineum* (8 species from 7 stands), included *Caroxylon imbricatum* and *Leptadenia pyrotechnica* as codominant species with P = 29%. Group D2, *Zygophyllum coccineum-Tamarix nilotica*, included 10 species from 3 stands. The two codominant species *Morettia philaeana* and *Phragmites australis* had the same presence value as *Zygophyllum coccineum* and *Tamarix nilotica* (P = 67%). Group E, *Caroxylon imbricatum-Morettia philaeana-Trichodesma africanum-Citrullus colocynthis*, was the most diversified (32 species recorded in 3 stands). Codominant associated species (P = 67%) were *Zilla spinosa*, *Zygophyllum coccineum*, *Phragmites australis*, *Tamarix nilotica*, *Pulicaria incisa*, and *Astragalus vogelii.*

3.1.2. Idfu-Marsa Alam transect (T2)

Classification of vegetation dataset (35 species × 28 stands) along the Idfu-Marsa Alam road (T2) yielded 7 vegetation

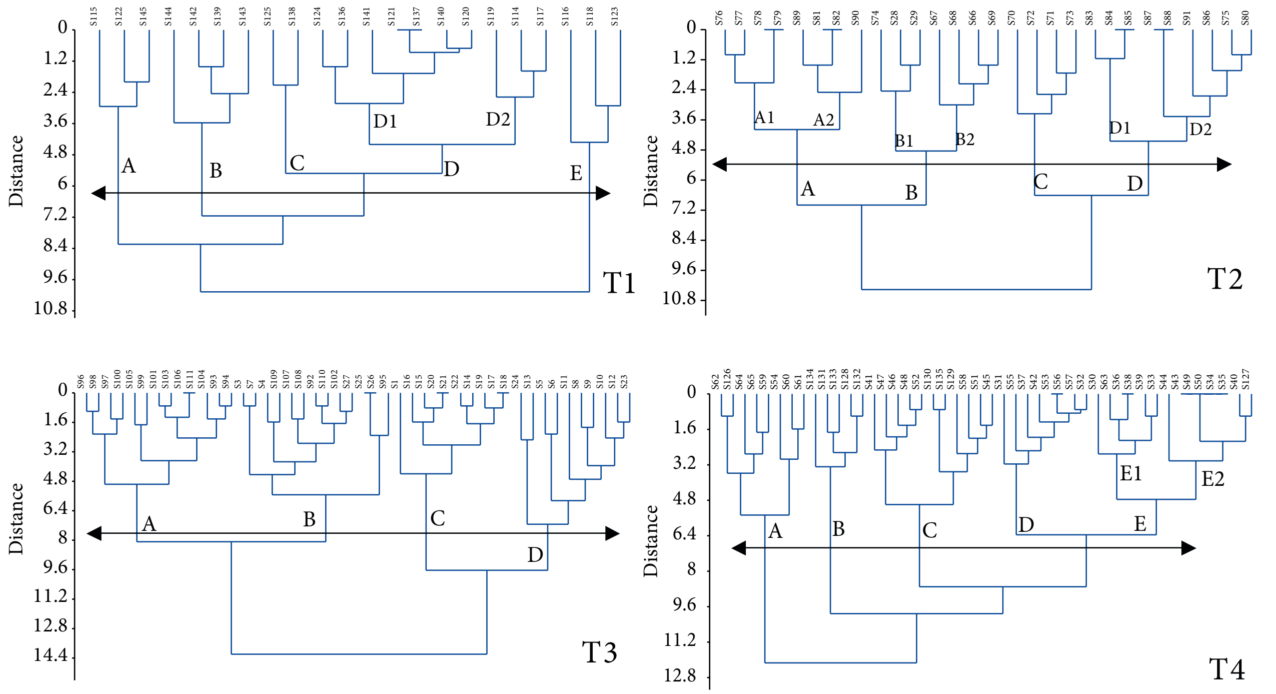

Figure 2. Dendrograms showing cluster analysis of the studied stands in each transect.

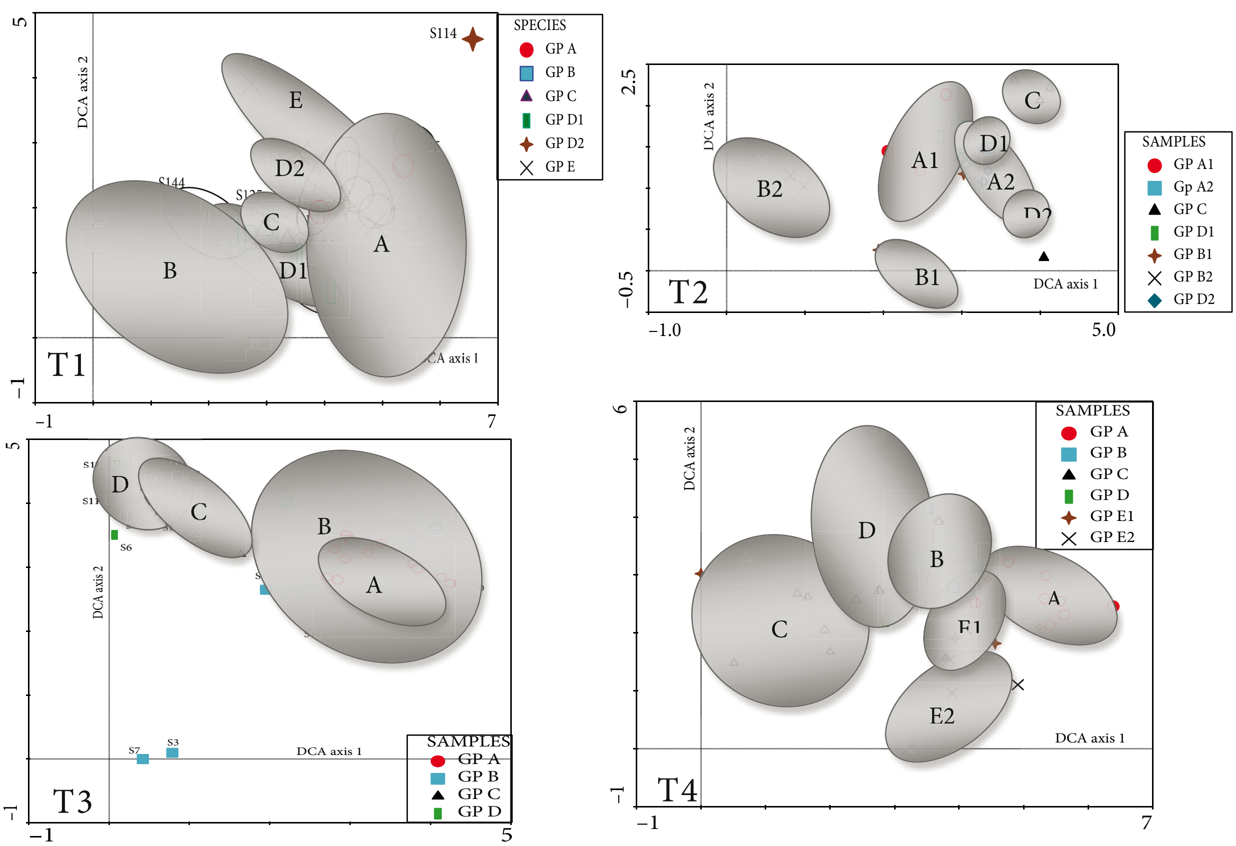

Figure 3. DCA diagram showing the distribution of the studied stands in each transect within their vegetation groups.

groups (Figure 2). These 7 plant communities were represented on the T2 location map, illustrating that most stands of groups A2 and D2 were close to Idfu city on the River Nile, followed by A1 and D1 towards the east. The stands of vegetation group C were positioned at the center of this transect. Finally, most of groups B1 and B2 were located in the Red Sea Mountains region (Figure 1). *Zilla spinosa* was the only ubiquitous species that was recorded in the 7 groups with variable presence values. Trees of *Acacia tortilis* subsp. *raddiana* and the shrub *Caroxylon imbricatum* were represented in 6 groups.

Group A1, *Zilla spinosa-Caroxylon imbricatum-Morettia philaeana*, comprised 8 species recorded from 4 stands. *Acacia tortilis* subsp. *raddiana*, *Citrullus colocynthis*, *Pulicaria undulata* subsp. *undulata*, and *Calotropis procera* were the codominant species (P = 50%–75%). Group A2, *Zilla spinosa-Caroxylon imbricatum*, was the least diversified (10 species from 4 stands) among the recognized groups. The codominant species with P = 50% was *Schouwia purpurea*. Group B1, *Zilla spinosa-Acacia tortilis* subsp. *raddiana*, comprised 13 species recorded from 3 stands. *Citrullus colocynthis* and *Pulicaria undulata* subsp. *undulata* shared the dominance (P = 100%) with *Zilla spinosa* and *Acacia tortilis* subsp. *raddiana*. The associated two codominant species (P = 66.7%) were *Lotus hebranicus* and *Asphodelus tenufolius*. Group B2, *Zilla spinosa-Aerva javanica-Pulicaria undulata* subsp. *undulata-Pergularia tomentosa* (11 species from 4 stands), had *Acacia tortilis* subsp. *raddiana*, *Heliotropium bacciferum*, and *Iphiona mucronata* (P = 50%) as the codominants. Group C, *Zilla spinosa-Astragalus vogelii* (16 from 4 stands), had associated codominants (P = 50%–75%) *Fagonia thebaica*, *Morettia philaeana*, *Trichodesma africanum*, *Tetraena simplex*, *Tribulus pentandrus*, *Lotus hebranicus*, and *Eremobium aegyptiacum*. Group D1, *Fagonia thebaica-Morettia philaeana* (9 species from 3 stands), included 7 species (*Zilla spinosa*, *Acacia tortilis* subsp. *raddiana*, *Caroxylon imbricatum*, *Fagonia thebaica*, *Morettia philaeana*, *Schouwia purpurea*, and *Farsetia stylosa*) represented with P = 100% in its stands. *Aerva javanica* was the codominant species (P = 66.7%). Group D2, *Zilla spinosa-Caroxylon imbricatum-Fagonia thebaica-Morettia philaeana*, was the most diversified vegetation group (15 species recorded in 6 stands). The codominants (P = 50-83.3%) were *Citrullus colocynthis, Schouwia purpurea*, *Trichodesma africanum*, *Tetraena simplex*, and *Pulicaria undulata* subsp. *undulata.*

3.1.3. Aswan-Kharit-Gimal transect (T3)

The floristic dataset (46 stands × 52 species) of this transect yielded 4 vegetation groups (communities) (Figure 2). Most the stands of groups A and B were sampled from the northeastern part of this transect, in Wadi Gimal and its tributary (Wadi Hafafit). Group C stands were represented in Wadi Natash (the tributary of Wadi Kharit). Stands of Wadi Kharit were confined to group D. This transect had three characteristic species (P = 100%): *Zilla spinosa*, *Morettia philaeana*, and *Balanites aegyptiaca*. About half of the recorded species of this transect had a degree of consistency to group D.

Group A, *Balanites aegyptiaca* (15 species from 13 stands), had *Zilla spinosa*, *Acacia tortilis* subsp. *raddiana*, and *Tamarix aphylla* as the associated codominant species (P = 38.5%–76.9%). Group B, *Acacia tortilis* subsp. *raddiana* (18 species, 13 stands), had *Zilla spinosa*, *Panicum turgidum*, and *Tamarix aphylla* as the codominants (P = 30.8%–38.5%). Group C, *Morettia philaeana*, had 18 species distributed among 10 stands, of which *Zilla spinosa*, *Acacia tortilis* subsp. *raddiana*, *Citrullus colocynthis*, and *Senna italica* were the codominant species (P = 70%–90%). Group D, *Zilla spinosa-Astragalus eremophilus-Cotula cinerea*, was the most diversified (31 species × 10 stands) among the separated vegetation groups. The codominant species (P = 60%–90%) included, among others, *Acacia tortilis* subsp. *raddiana*, *Citrullus colocynthis*, *Astragalus eremophilus*, and *Launaea nudicaulis*.

3.1.4. Red Sea coast transect (T4)

The classification of the Red Sea floristic dataset (46 species × 46 stands) resulted in 6 vegetation groups (Figure 2) represented on the location map (Figure 1). Notably, most of stands of group A were located to the south of Qusier city, while those of group B were located to the south of Safaga city (between 26°6′N and 26°5′N). To the north of Marsa Alam city and to the south of group A stands, the group C stands occurred. The stands of groups E1 and E2 were represented around Marsa Alam city, especially to the south of 26°06′N. Stands of group D were scattered in the areas of groups A and E1. Three species were recorded with variable presence values in most of the 6 groups: *Tamarix nilotica*, *Crotalaria aegyptiaca*, and *Zygophyllum coccineum*.

Group A, *Zilla spinosa-Zygophyllum coccineum* (22 species, 8 stands), had *Lotus hebranicus*, *Acacia tortilis* subsp. *raddiana*, *Malva parviflora*, *Convolvulus hystrix*, *Launaea nudicaulis*, and *Astragalus vogelii* represented as the codominants (P = 37.5%–62.5%). Group B, *Tamarix nilotica-Zygophyllum coccineum* (14 species, 5 stands), included *Nitraria retusa* and *Phragmites australis* as codominant species (P = 60%–80%). Group C, *Nitraria retusa-Tamarix aphylla* (16 species, 11 stands), had the halophyte *Arthrocnemum macrostachyum* as the codominant species (P = 36.4%). Group D, *Zygophyllum album* (11 species from 8 stands), had *Tamarix nilotica* as the only codominant with a low presence value (P = 25%). Group E1, *Tamarix nilotica*, was the least diversified (8 species, 6 stands) among the separated vegetation groups. *Acacia tortilis* subsp. *raddiana* was the only the codominant species with P = 50%. Group E2 was *Limonium axillare* (10 species, 8 stands). Notably, about 70% of the recorded species of this group (7 species) were sporadic species (P = 12.5%). *Tamarix nilotica* and *Zygophyllum coccineum* were codominants (P = 25% for each).

3.2. Soil characteristics and species diversity

The total number of recorded species (species richness) was 46, 35, 52, and 46 for T1, T2, T3, and T4, respectively. The significant differences (at $P < 0.05$ and $P < 0.01$) for the examined soil variables and species diversity indices [species richness (SR) and Shannon's diversity index (H')] among the 4 transects are demonstrated in Table 2. For T1, only soil water content (WC) showed clear significant differences between its vegetation groups. In the Idfu-Marsa Alam transect (T2), clay, pH, Cl^-, and HCO_3^- were significantly different. Magnesium and WC showed high significant differences between the Aswan-Kharit-Gimal (T3) groups. In the Red Sea coast transect (T4), fine sand, silt, K^+, Mg^{+2}, WC, and OM showed significant differences between vegetation groups at $P < 0.05$. Electrical conductivity, total soluble salts, Na^+ and Cl^- (the salinity factors), and Ca^{+2} showed high significant differences between groups at $P < 0.01$. Both species diversity measurements (SR and H') exhibited significant differences among the separated vegetation groups within each transect.

3.3. Stands ordination

Application of DCA to the vegetation data of the Qena-Safaga transect (Figure 3) revealed the segregation of the 6 vegetation groups along DCA axis 1 (eigenvalue 0.568) and DCA axis 2 (eigenvalue 0.393). The cumulative percentage variance of species data of the first two DCA axes was 32.2%. Stands of groups A and D2 separated along the positive side of DCA axis 1, while those of groups B and E separated along the positive end. Meanwhile, groups C and D1 were transitional in their ordination between the other groups.

Idfu-Marsa Alam road (T2) vegetation groups were ordinated along DCA axis 1 (eigenvalue 0.626) and DCA axis 2 (eigenvalue 0.296). However, DCA axis 2 with its low gradient length (2.32 standard deviation units; SD) was less important than DCA axis 1 (Figure 3). The cumulative percentage variance of species data of DCA axis 1 was 16.1% and it was 23.7% for DCA axis 2. Stands of groups A2, C, D1, and D2 separated toward the positive side of DCA axis 1. However, those of group B2 separated along the DCA axis 2 positive end. Stands of groups A1

Table 2. ANOVA values of the soil variables in the vegetation groups for each transect. *P < 0.05, **P< 0.01. EC = Electric conductivity, TS = total soluble salts, CS = coarse sand, FS = fine sand, OM = organic matter, SR = species richness, and H'= Shannon–Wiener index. For transect abbreviations, see Table 1, and for units see Table 3.

Soil factors	T1	T2	T3	T4
Gravel	0.656	1.34	1.478	0.814
CS	1.646	1.552	0.498	1.698
FS	2.263	2.199	0.778	3.14*
Silt	1.52	2.326	0.534	0.565
Clay	0.605	3.034*	0.966	2.52*
pH	1.59	2.763*	0.144	2.53*
EC	1.459	1.917	1.104	5.57**
TSS	1.459	1.917	1.104	5.57**
Na	1.423	1.275	1.535	4.74**
K	1.619	2.341	1.74	2.52*
Ca	1.71	1.792	0.172	4.02**
Mg	1.04	1.735	18.54**	2.99*
Cl	1.491	2.756*	1.249	5.44**
HCO_3	0.705	5.321**	0.713	0.526
SO_4	1.954	2.086	2.541	2.349
WC	4.74**	1.03	15.18**	3.34*
OM	2.4	1.623	2.26	2.93*
SR	22.30**	2.946*	12.65**	7.46**
H'	10.94**	3.15*	12.88**	6.50**

and B1 were transitional in their composition between the other groups.

The 46 stands of the Aswan-Kharit-Gimal transect were plotted along the first two DCA axes and tended to cluster into 4 vegetation groups that resulted from the cluster analysis described previously. The sites were spread out 5 SD units along the first two axes with eigenvalues of 0.698 and 0.532, respectively. The first 2 axes explained 29.5% of the total variation in species data, which may be attributed to the many zero values in the vegetation data matrix. Stands of groups A and B were separated out along the positive end of DCA axis 1, while stands of groups C and D were on the positive end of axis 2 (Figure 3).

The scatter plot of DCA separated the T4 vegetation groups along the first two axes with eigenvalues of 0.777 and 0.624 for axis 1 and 2, respectively. The sites were spread out 6.38 SD units for the first axis, expressing the high floristic variations among the other communities. The second DCA axis had the lowest importance (5.43 SD units). Stands of groups A, E1, and E2 were separated along the positive end of DCA axis 1. On the other hand, stands of group C were separated on the positive end of DCA axis 2. However, the stands of groups B and D were transitional in their composition between the others (Figure 3). These two axes explained 24.1% of the total variation in species data, which may be attributed to the many zero values in the vegetation data matrix.

3.4. Soil–vegetation relationships

The relationship between the vegetation and soil variables was studied using CCA ordination (Figure 4; Table 3). For T1, stands of group A were highly correlated with clay and HCO_3^-, while those of group B showed a correlation with coarse sand and OM. Whereas stands of group C showed some correlation with Mg^{+2} and OM, stands of group D1 were affected by many soil factors such as OM, coarse sand, pH, Mg^{+2}, and EC. Stands of group D2 also correlated to the soil EC. Potassium and organic matter were the main soil factors affecting the soil of group E.

The CCA biplot of the second transect (T2; Figure 4) showed that the stands of group A1 were highly correlated with gravels, pH, WC, Cl^-, and Mg^{+2}, while stands of group A2 showed a high correlation with K^+, Ca^{+2}, OM, clay, and fine sand. Stands of group B1 exhibited some correlation with Mg^{+2} and gravels, while those of group B2 showed a weak correlation with most of the measured soil factors (e.g., WC, OM, SO_4^{-2}, Na^+, and fine sand). Members of

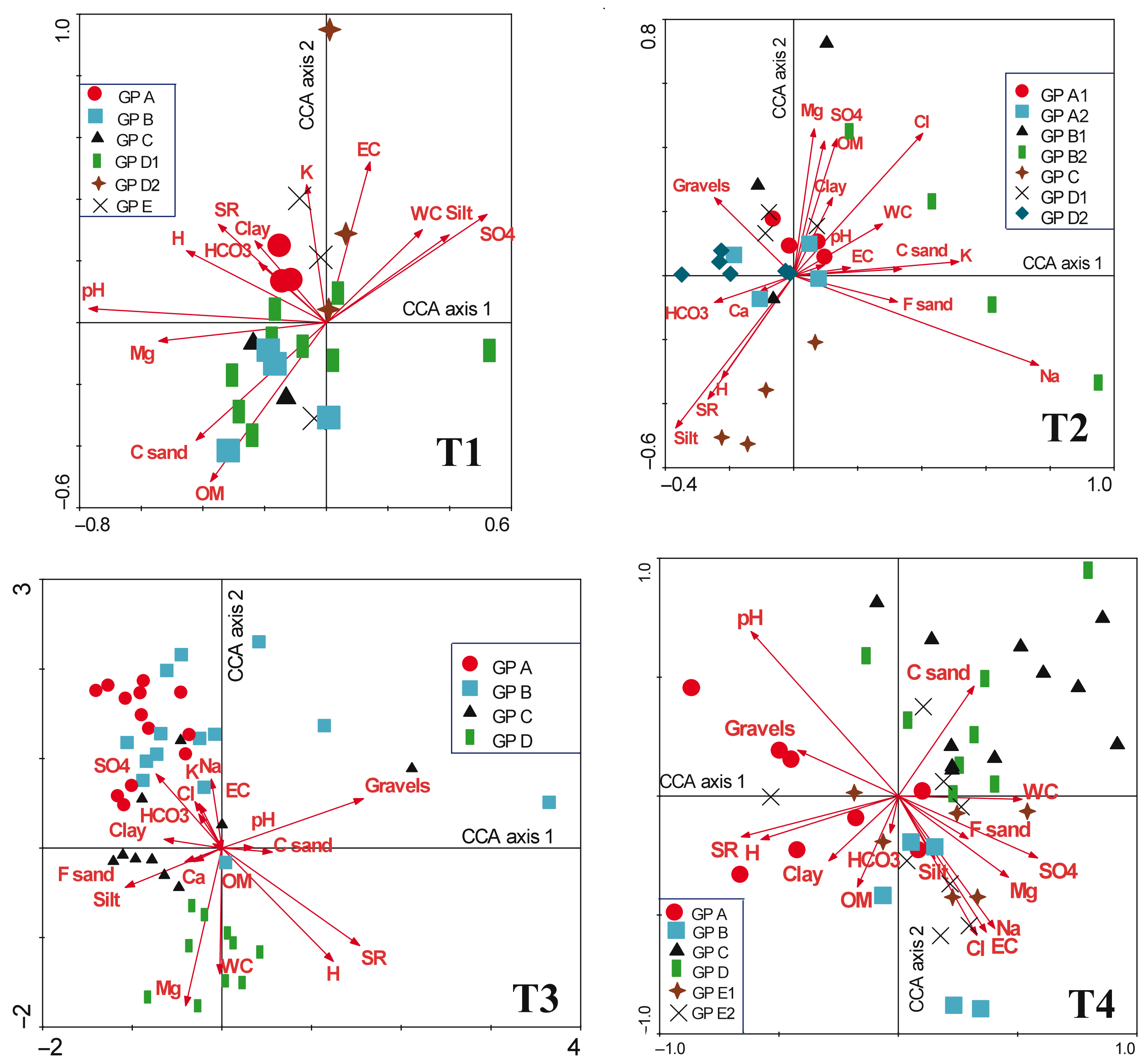

Figure 4. CCA biplot of axes 1 and 2 showing the distribution of the studied stands in each transect, together with their vegetation groups and soil variables.

group C were not affected by any soil factors except silt fraction. Stands of group D1 were correlated to gravels, clay, and OM. Gravels and HCO_3^- were the main soil factors affecting the vegetation of group D2.

The ordination of Aswan-Kharit-Gimal groups revealed that the stands of groups A and B were correlated with clay, Na^+, K^+, and all the measured anions (Cl^-, HCO_3^-, and SO_4^{-2}). On the other hand, stands of group C were highly associated with the fine sand, silt, and Ca^{+2} and somewhat to gravels and Na^+. Similar comments can be made for stands of group D that were related to WC and Mg^{+2} (Figure 4).

Red Sea dataset ordination (Figure 4) demonstrated that the stands of group A were highly correlated with gravels, clay, silt, and WC. Stands of group B were highly associated with Cl^-, OM, and HCO_3^-. Stands of groups C and D were related to WC and coarse sand. Generally, the two components of group E (E1 and E2) were associated with the salinity factors (EC, Na^+, and Cl^-).

The interset correlations of CCA analysis for the soil variables, together with eigenvalues and species–environment correlations in the studied 4 transects, are demonstrated in Table 3. For T1, CCA axis 1 was highly positively correlated with silt and highly negatively

Table 3. Interset correlation of CCA analysis for the soil variables, together with eigenvalues and species–environment correlations in the studied transects. NI = Not included due to high inflation factor. For transect abbreviations, see Table 1.

Transect	T1		T2		T3		T4	
Axes	1	2	1	2	1	2	1	2
Eigenvalues	0.563	0.457	0.55	0.4	0.593	0.565	0.674	0.508
Species– environment correlations	0.986	0.988	0.948	0.98	0.963	0.942	0.957	0.927
Gravels (%)	NI	NI	−0.233	0.239	0.727	0.246	−0.403	0.179
Coarse sand (%)	−0.412	−0.376	0.319	0.02	0.258	−0.02	0.304	0.428
Fine sand (%)	NI	NI	0.307	−0.081	−0.189	−0.069	0.279	−0.166
Silt (%)	0.393	0.281	−0.348	−0.466	−0.496	−0.196	0.147	−0.244
Clay (%)	−0.228	0.262	0.115	0.238	−0.296	0.043	−0.278	−0.252
WC (%)	0.307	0.297	0.263	0.159	−0.011	−0.627	0.495	−0.012
OM (%)	−0.37	−0.508	0.128	0.418	0.002	−0.009	−0.164	−0.354
pH	−0.759	0.045	0.091	0.032	0.162	0.003	−0.591	0.642
EC (mS cm^{-1})	0.14	0.514	0.168	0.024	−0.116	0.221	0.353	−0.531
Na (mg g^{-1} dry soil)	NI	NI	0.724	−0.274	−0.055	0.343	0.387	−0.515
K (mg g^{-1} dry soil)	−0.06	0.441	0.488	0.042	−0.138	0.231	NI	NI
Ca (mg g^{-1} dry soil)	NI	NI	−0.1	−0.051	−0.142	−0.069	NI	NI
Mg (mg g^{-1} dry soil)	−0.535	−0.059	0.061	0.449	−0.186	−0.786	0.441	−0.317
Cl (mg g^{-1} dry soil)	NI	NI	0.382	0.435	−0.119	0.169	0.314	−0.543
HCO_3 (mg g^{-1} dry soil)	−0.215	0.191	−0.233	−0.082	−0.045	0.022	−0.032	−0.143
SO_4 (μg g^{-1} dry soil)	0.514	0.346	0.091	0.411	−0.337	0.369	0.558	−0.241
Species richness (SR)	−0.345	0.315	−0.252	−0.377	0.708	−0.486	−0.629	−0.159
Shannon index (H')	−0.447	0.23	−0.212	−0.315	0.572	−0.565	−0.55	−0.169

correlated with pH. This axis can thus be interpreted as the silt–pH gradient. CCA axis 2 was highly positively correlated with EC and highly negatively with OM. Thus, this axis can be interpreted as the EC–OM gradient. CCA axis 1 for T2 was highly positively correlated with Na^+ and highly negatively correlated with silt, and this axis can be inferred as the Na^+–silt gradient. CCA axis 2 for the same transect was correlated highly positively with Mg and highly negatively with silt (Mg–silt gradient). CCA axis 1 for T3 can be interpreted as the gravels–silt gradient and CCA axis 2 can be interpreted as the SO_4–Mg gradient. For the Red Sea coast transect (T4), the interset correlations between the first two axes of the CCA biplot revealed that SO_4^{-2}, pH, and Cl^- were the main operating factors for the vegetation of this transect.

The species–environment correlations were high for the first two axes, explaining 51.5%, 49.9%, 51.5%, and 46.7% of the cumulative variance for T1, T2, T3, and T4, respectively. These results suggested an association between the vegetation and the measured soil parameters presented in the biplot. The species–environment correlations were high for the first two axes for all the studied transects (T1: 0.986 and 0.988; T2: 0.948 and 0.98; T3: 0.963 and 0.942, and T4: 0.957 and 0.927 for axis 1 and 2, respectively), indicating that the species data were related to the measured environmental variables. A test for significance with an unrestricted Monte Carlo permutation test (499 permutation) for the eigenvalue of axis 1 was found to be significant (P = 0.026, 0.038, 0.004, and 0.002 for T1, T2, T3, and T4, respectively), indicating that the observed patterns did not arise by chance.

4. Discussion

In extreme deserts, as in the study area, plant growth is triggered mainly by rain and thus is as scarce and unpredictable as the precipitation itself. Vegetation develops only in habitats receiving runoff water including wadis, depressions, and channels (contracted desert; Shmida, 1985). This highly dynamic vegetation is neither permanent nor seasonal, but is accidental (Bornkamm, 2001). The vegetation structure is relatively simple, in which the species have to withstand the harsh environmental conditions. This can be reflected by the presence of several highly adapted, drought-resistant species such as *Acacia* *tortilis* subsp. *raddiana*, *Capparis spinosa*, *Convolvulus hystrix*, *Fagonia bruguieri*, *Tamarix aphylla*, *Zygophyllum coccineum*, *Zilla spinosa*, and *Ziziphus spina-christi*. The floristic diversity of the study area included 94 species of the vascular plants belonging to 33 families distributed among four transects.

The studied vegetation was restricted to wadis, runnels, and depressions with deep fine sediments that received adequate water supply. Dataset classification of the recorded species in each of the four transects using the cluster analysis yielded separated vegetation groups at level 3 of the hierarchy. The cluster analysis of the Qena-Safaga transect (T1) yielded 6 vegetation groups recorded in 22 stands. Meanwhile, Idfu-Marsa Alam (T2) had 7 vegetation groups within 28 stands and there were 4 groups belonging to the southern transect (Aswan-Kharit-Gimal; T3) represented in 24 stands. The last transect, the Red Sea coast (T4), had 6 groups distributed among 46 stands. Most of the identified vegetation groups have very much in common with those recorded in some wadis of the Eastern Desert (Salama et al., 2012), the Western Desert (Abd El-Ghani, 2000), the south Sinai region (Moustafa and Zaghloul, 1996), and northwestern Negev, Israel (Tielbörger, 1997). The members of each pair of groups are, in some cases, linked together by having one of the dominant species in common, e.g., groups D1 and D2 in the Qena-Safaga transect (T1), most of the Idfu-Mersa Alam transect (T2) groups, and groups C and D in the Qusier-Safaga transect along the Red Sea coast (T4). Meanwhile, it can be noted that certain vegetation groups characterized one or more of the studied transects: e.g., group B2 in the eastern part of T2, group D of Wadi Kharit (T3), and group C in T4.

In terms of classification, 6 vegetation groups were identified in the Qena-Safaga transect (T1). Groups A, D2, and E were characterized by a high degree of salinity. Soils of these groups are subjected to human land reclamation and high evaporation. Usually the cyclic drought periods accelerate the salinization process, particularly when associated with human activity (Akhani, 2006). The presence of the halophytes *Phragmites australis* and *Tamarix nilotica* confirmed this salinization. The highest water content of group E clarified the high values of species indices of this group of flora (32 species in 3 stands). Restriction of *Imperata cylindrica* to the wet silty plains of group E was apparently due to the inability of the species to reach the capillary fringe of the groundwater, which is fairly close to the surface (Abd El-Ghani, 1992). The species is considered as a facultative halophyte mainly occurring on sandy soils with slight salt content. Thus, this habitat may represent a transitional habitat between moist and dry saline habitats (Abd El-Ghani, 2000).

In the present study, the vegetation–environment relationships were assessed by DCA and CCA. CCA showed well the relative positions of species and sites along the most important ecological gradients. It was clearly indicated that salinity, fine sediments, organic matter, and moisture content were the important factors controlling the distribution of the vegetation in the study area. This has been reported by other researchers including Jenny et al. (1990) in arid microhabitats of Wadi Araba in Jordan and Yibing et al. (2008) in the Gurbantunggut Desert of China.

In this investigation, groups B, C, and D1 were closer to the Red Sea Mountains region and they occurred on dry, fertile, nonsaline sandy soil. The CCA biplot revealed a relation of these groups of flora to the organic matter and coarse sand. The soil texture gradient that exists from sandy uplands to fine-textured flats in arid desert environments results in gradients of available soil moisture. Therefore, moisture content is probably one of the most effective physical factors leading to vegetation variations in the Qena-Safaga transect (T1).

The present study showed that the vegetation of Idfu-Marsa Alam road (T2) comprised 35 species in 28 stands and the cluster analysis technique classified them within 7 vegetation groups. These groups were arranged from east to west as follows: A2 mixed with D2, followed by D1, and then A1. The stands of group C were in the center of the road, followed by the stands of the Red Sea Mountains (B1 and B2). The highest salinity and fertility were represented in the soil of group A2 and it was characterized by the presence of some xerohalophytes (e.g., *Caroxylon imbricatum*, *Tamarix aphylla*, and *Phragmites australis*). Silt and clay dominated the soil structure of the highest diversified groups (C, D1, and D2). They had a similar floristic composition, which was dominated by *Zilla spinosa*, *Acacia tortilis* subsp. *raddiana*, *Caroxylon imbricatum*, *Fagonia thebaica*, *Morettia philaeana*, *Aerva javani*ca, *Citrullus colocynthis*, and *Schouwia purpurea*. In agreement with this, the CCA biplot showed a high correlation between group C flora and the silt fraction. These species are widely distributed in Egypt (Batanouny, 1979) and neighboring countries (Wojterski, 1985). The stands of group B2 showed a special position on DCA and CCA diagrams as it had a special floristic composition correlated with sulfate (SO_4^{-2}) and water contents. This group was characterized by *Heliotropium bacciferum*, *Iphiona mucronata*, and *Pergularia tomentosa* as codominant species. The interset correlations between CCA axis 1 and 2 and the soil fractions showed that the flora of this transect was clearly correlated with silt, water content, OM, Mg^{+2}, Na^+, K^+, SO_4^{-2}, and Cl^-. These results were also in line with those of Abbadi and El-Sheikh (2002) on Failaka Island of Kuwait and Li et al. (2008) in a coastal region of North China.

Vegetation groups A, B, C, and D of the Aswan-Kharit-Gimal transect (T3) were located in three main wadis in the southern part of the study area. Groups A and B (*Balanites aegyptiaca* and *Acacia tortilis* subsp. *raddiana*, respectively) were located in Wadi Gimal and Hafafit, inside the Red Sea Mountains. To the west of them, group D (*Zilla spinosa-Astragalus eremophilus-Cotula cinerea*) was located in Wadi Kharit. The Wadi Natash vegetation belonged to group C (*Morettia philaeana*). Vegetation group A grows on a dry-saline soil dominated by trees (e.g., *Balanites aegyptiaca*, *Tamarix aphylla*, and *Acacia tortilis* subsp. *raddiana*) and shrubs (e.g., *Zilla spinosa* and *Salvadora persica*) in the vegetation of the Wadi Gimal and Wadi Hafafit slopes. Trees and shrubs were the most important elements of this semidesert vegetation, and it is known that many community and ecosystem processes are regulated by them (Galal, 2011). *Salvadora persica* was obviously less tolerant to drought and was confined to localities where topographic and climatic conditions provide for an increased supply of moisture (Kassas and Girgis, 1970). The heavy disturbance of *S. persica* by humans who collect its roots for use as tooth brushes through the Arabian region may be a possible reason for its low occurrence and diversity (Shaltout et al., 2004). Group C xeropsammophytes (e.g., *Senna italica*, *Zilla spinosa*, *Morettia philaeana*, *Citrullus colocynthis*, *Astragalus eremophilus*, and *Tetraena simplex*) were found in dry nonsaline sandy stands with soils of higher fertility along Wadi Natash, where infiltration is higher and water accumulates in deeper layers. DCA and CCA showed a significant difference between this community's composition and the previously mentioned ones (groups A and B). Silty nonsaline soil of Wadi Kharit (group D) with the highest water content had the highest species diversity among the other groups (31 species × 10 stands). The highest water content in this wadi reflects the predominance of annual plants among the other functional groups (e.g., *Launaea nudicaulis*, *Asphodelus tenufolius*, *Astragalus vogelii*, *Cotula cinerea*, *Cleome amblyocarpa*, *Hippocrepis constricta*, *Launaea amal-aminae*, *Lupinus digitatus*, and *Schouwia purpurea*). The CCA biplot revealed a strong correlation between these species and the soil moisture content. Generally, the vegetation of this transect was highly affected by water content, gravels, clay, silt, Mg^{+2}, and SO_4^{-2}. Our results were partially in agreement with those of Li et al. (2004) in the Shapotou-Jingtai Region on the southeastern fringe of the Tengger Desert of China, and those of Abdel Khalik et al. (2013) in Wadi Al-Noman of Mecca in Saudi Arabia.

The Red Sea coast transect (T4) was characterized by many salt-tolerant, salt-excretive species and Red Sea elements (e.g., *Limonium axillare*, *Hyphaene thebaica*, *Avicennia marina*, *Phoenix dactylifera*, *Zygophyllum album*, *Arthrocnemum macrostachyum*, *Nitraria retusa*, *Tamarix nilotica*, *Suaeda monoica*, *Juncus rigidus*, and *Aeluropus littoralis*). These species were also recorded on the Red Sea coast in previous studies by Abd El-Ghani and Amer (2003). The salt-tolerant plant *Tamarix nilotica* dominated vegetation groups B, D, E1, and E2, forming hillocks of considerable sizes characterizing the T4 transect and vigorously growing southwards (Springuel et al., 1991). It represents the natural climax community type of the Red Sea coastal plain with deep deposits and an underground water reserve. According to Kassas and Girgis (1965), the growth of the desert scrub *Nitraria retusa* represents the highest tolerance to soil salinity conditions and a penultimate stage in the successional development. Meanwhile, the lower number of annual plants in T4 inhabiting the coastal plains of the Red Sea may be related to its high soil salinity. Such an effect of salinity stress on floristic diversity in the study area and related areas was reported by Moustafa and Klopatek (1995).

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