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Variation in Plant Community Composition and Biomass to Macro and Micronutrients and Salinity across Egypt's Five Major Coastal Lakes

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Abstract: To better assess the relationship between excess nutrient runoff and plant species diversity in the Egyptian northern coastal lakes, the relationships between aboveground biomass, species diversity, and both micro and macronutrient concentrations in sediment, water, and plant materials were investigated. A total of 38 sampling sites were established for the five Egyptian northern lakes (8 for Bardawil, 10 for Manzala, 8 for Burullus, and 6 for each of Edku and Mariut). Sediment, water, and plant materials were collected and analyzed for both micro and macronutrients including nitrogen (N), phosphorus (P), sulfur (S), magnesium (Mg), calcium (Ca), potassium (K), iron (Fe), boron (B), sodium (Na), and aluminum (Al). Based on the Sørensen similarity index, Burullus and Mariut lakes were very similar (0.70) in their vegetation composition, while Bardawil Lake had no similarity with the rest of the lakes. In sediment, Mariut Lake had the highest total P concentrations (1.3 g kg^{-1}), while Bardawil Lake had the lowest (0.3 g kg^{-1}). Bardawil, a hypersaline lake, had the highest concentrations for both Na and B (9.6 and 0.1 g kg^{-1}, respectively). Among the deltaic lakes, Mariut Lake water bodies had the lowest plant species richness. The current study indicated that the excessive agricultural and industrial nutrient runoff had a greater impact on the nutrient distribution pattern and negatively impacted plant species diversity at the Egyptian coastal lakes. An integrated management plan, including establishing more pretreatment facilities for runoff and wastewater, should be implemented to reduce the nutrient loads from the main industrial and agricultural runoff sources. Moreover, periodic monitoring and assessment for nutrient runoff reaching the lakes are necessary to help reduce eutrophication levels.

Keywords: plant species diversity; wetlands; *Eichhornia crassipes*; agricultural runoff; vegetation analyses; eutrophication

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1. Introduction

Mediterranean coastal lakes have a vital role in maintaining water quality and supporting biological diversity of native species by providing resting, feeding, and nesting habitats [1–6]. At the north coast of Egypt, there are coastal wetlands (Figure 1) that are of great socioeconomic and environmental importance to Egypt, in particular, and to North Africa. Those coastal wetlands provide a wide variety of ecosystem services and goods including fish production [1,7,8]. Coastal lake restorations had been proposed for several decades for improving water quality to mitigate the severe impact of industrial and agricultural runoff before the water reached the main streams. However, a tremendous amount of runoff water with insufficient pretreatment had reached urban lake sediments, impacting sediment biota including dwelling organisms [9].

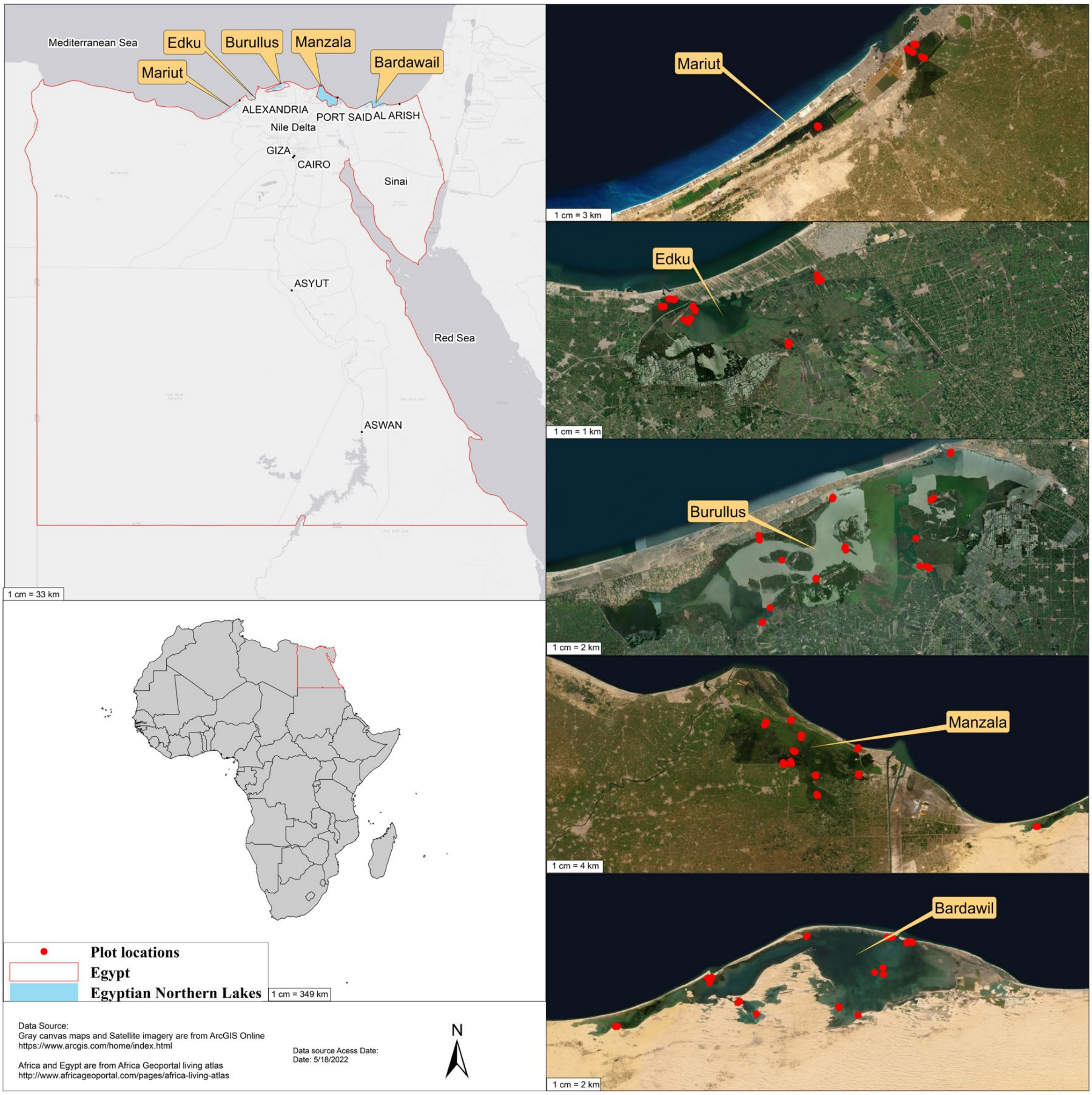

Figure 1. Study sites map showing the five Egyptian northern lakes and the sampling plot locations (red dots on the map). Map produced in ArcGIS Desktop 10.4.

Along the Mediterranean coast of Egypt, there is a vast complex of naturally occurring lakes (Figure 1) that include deltaic and non-deltaic water bodies. Bardawil Lake at north Sinai is non-deltaic, while Burullus, Manzala, Edku, and Mariut are lakes associated with the Nile delta. The Egyptian northern lakes provide a wide variety of ecosystem services including fishing, and two lakes (Burullus and Bardawil) were recognized as important wetlands during the Ramsar convention [10]. Egyptian coastal lakes experience several major human impacts including habitat fragmentation, drying and conversion to agricultural lands, habitat loss, and pollution from tremendous amounts of industrial, agricultural, and municipal wastewater lacking sufficient treatment. For example, Burullus Lake receives 4 billion m^3 of drainage water annually from the Nile Delta agricultural lands [11]. The consequences of sediment and nutrient runoff include eutrophication and hypoxia (e.g., annual dissolved oxygen in Burullus Lake was 8.6 ± 2.3 mg L^{-1} [8]), which are considered serious threats to coastal and marine ecosystems [12,13].

In general, nutrient transport via riverine systems and agricultural channels are the main mechanisms by which nutrients enter coastal and marine ecosystems [14,15]. Both conservation practitioners and resource managers perceive the negative impact of excess nutrients on coastal ecosystems as a major threat at both local and global scales [16]. Excess nutrients can lead into increased phytoplankton abundance and can affect the marine vegetation communities [17]. In tidal freshwater marshes and swamps, for example, Baldwin 2013 [18] concluded that eutrophication can alter plant species composition.

Plant growth is limited by macro and micronutrients [19]. Macronutrients include nitrogen (N), phosphorus (P), sulfur (S), magnesium (Mg), calcium (Ca), and potassium (K). Micronutrients include iron (Fe), manganese (Mn), Copper (Cu), Zinc, (Zn), nickel (Ni), molybdenum (Mo), boron (B), chloride (Cl), sodium (Na), silicon (Si), cobalt (Co), selenium (Se), and aluminum (Al). Wetland plant species diversity may decrease when the nutrient availability exceeds a certain threshold [20]. The relationships between nutrient supply, plant species richness, and productivity are complex and vary among different wetland ecosystems. Many research studies showed that soil nutrients have a critical role in limiting both plant species diversity and productivity in wetlands and other ecosystems [18,20–24].

To better understand the consequences of excess agricultural and industrial runoff on plant species diversity in coastal Egyptian lakes, it is critical to assess the relationship between nutrient concentrations and plant species diversity [25,26]. Many research studies have been conducted to study the vegetation composition at the Egyptian Northern lakes [27–29]; however, fewer studies have investigated the impact of excess nutrient runoff on plant species diversity at the Egyptian northern lakes. The main objectives of the current study were to investigate the effects of nutrients (both macro and micro) in sediment, water, and plant materials on plant species diversity and aboveground biomass. We hypothesized that high concentrations of nutrients in water column, sediment, and plant materials of coastal lakes would exist near the main sources of agricultural canals at the southern parts of the deltaic lakes. We also hypothesized that plant species diversity would be negatively related to nutrient concentrations in sediment, particularly total N and P.

2. Materials and Methods

2.1. Study Area

Study sites were located at the coastal lakes complex at the northern part of Egypt along its Mediterranean coast (Figure 1), where five natural lakes exist (from east to west: Bardawil, Manzala, Burullus, Edku, and Mariut). Field visits and sampling collection were conducted during years of 2012 and 2013. A total of 38 sampling sites (Figure 1) were established for the five lakes (8 for Bardawil, 10 for Manzala, 8 for Burullus, and 6 for each of Edku and Mariut). Bardawil Lake is located on the Sinai coast and there is a smooth coastal sand barrier between the lake and the Mediterranean Sea, while the southern shore appears irregular due to the effect of pre-lake topography similar to the North Sinai Mediterranean Sea [30,31]. Manzala, Burullus, and Edku lakes are located on the coast of the Nile River delta. Manzala appears as a rectangle in parallel to the Mediterranean Sea with maximum dimensions of 49 km North-West to South-East and 29 km South-West to North-East [32,33]. It is separated from the Mediterranean Sea by small sand ridges and connected with the Mediterranean Sea by two connections in the eastern part called El-Gamil 1 and El-Gamil 2 [34]. Mariut, Edku, Burullus, and Manzala are brackish water bodies (salinity, expressed here as Electrical Conductivity EC, 2.9 to 12.2 mS cm^{-1}) and Bardawil is hypersaline (salinity 48.1 mS cm^{-1}) [9]. For more detailed study site descriptions, see Keshta et al. 2020 [9] and Eid et al. 2017 [35].

2.2. Vegetation and Aboveground Biomass

At each sampling site, three randomly selected plots (1 m^2) were established and all plant species (Table S1) were identified according to Boulos 2009 [36]—life forms were according to the Raunkiaer system [37]. The aboveground biomass of each species was sampled during the growing season (July–September) using the three randomly distributed floating quadrats (Photo S1) (total biomass was determined for floating plants, *Eichhornia crassipes* (C. Mart.) Solms, *Lemna gibba* L., *Azolla filiculoides* Lam., and *Pistia stratiotes* L.). Within each quadrat, all plant individuals were cut off at a sediment level and separated by species. Total fresh weight (kg m^{-2}) for each species was immediately determined in the field using a digital electrical balance, and then samples were brought in plastic bags to the laboratory, where they were oven-dried at 60 °C to constant weight in order to give the dry weights (kg m^{-2}) and then the moisture content.

2.3. Sediment, Plant, and Water Analyses

Sediment was collected as a composite sample from the three quadrats within each sampling site. All sediment samples were collected to a depth of 25 cm, underneath the lake's bottom, with an approximate 0.031 m^2 surface area. Sediment samples were air-dried, ground, and passed through a 2 mm sieve to separate gravels and debris before macro and micronutrients analyses. Plant material was a composite sample from the aboveground biomass, except for floating plants (e.g., *E. crassipes*) where the sample represented the total plant tissues including roots. Plant material was oven-dried at 60 °C and ground. Total C and N in plant tissues were determined by the CHN method [38] using a LECO CHN-2000 analyzer (LECO Corporation, St. Joseph, MI, USA). For macro and micronutrient determination, sediment and plant materials (5–10 g) were digested according to microwave digestion—EPA3051 using concentrated nitric acid [39,40]; then, P, Ca, K, Mg, S, Al, Na, Fe, and B were determined by Inductively Coupled Plasma Atomic Absorption Spectrometry (ICP/AAS) analyses [41] in the Soil Testing Lab, University of Delaware, USA, with a detection limit of 0.0003 mg kg^{-1}. Quality assurance and quality controls guidelines listed in EPA-Method 200.7 [42] were followed for sample preparation and analyses. For assessing a threshold level, as an example, of total P content in sediment to be used as an indication of excess nutrient runoff, an average of P content was determined for those plots only where *Eichhornia crassipes* was recorded among the deltaic lakes (Manzala, Burullus, Mariut, and Edku).

For water sampling, three water samples were collected in 1 L polyethylene bottles. Each sample was taken as an integrated composite sample from the top down to 50 cm below the water surface. Water temperature (°C) was measured by using a thermometer in the field during the time of sample collection. Water bottles were brought to the laboratory and then samples were refrigerated in a deep freezer until analyses. Data for water salinity, pH, transparency, and lake depth were from Keshta et al. 2020 [9]. For water samples: Mg, K, Na, and Ca were determined by Atomic Absorption Spectroscopy, while total P and N were determined spectrophotometrically using the molybdenum blue and indo-phenol blue methods, respectively [43].

2.4. Data Analyses

Plant communities were analyzed using two-way indicator species analysis (TWINSPAN), as a classification technique, and Detrended Correspondence Analysis (DCA), as an ordination technique, was applied [44–46] to the matrix of 29 plant species recorded in the five Egyptian northern lakes. All vegetation composition analyses were performed in PC-ORD software. The relationship between plant species composition and water variables is indicated on the ordination diagram by applying principal component analysis (PCA) [47] using Canoco software. The Sørensen similarity index [48] was calculated to assess the similarity coefficients between Egyptian northern lakes based on plant species composition. One-way analysis of variance (1-way ANOVA) was used to test the main effects of lakes (Bardawil, Manzala, Burullus, Edku, and Mariut) on nutrient concentrations on sediment, plant materials, and water, followed by means separation using Tukey's Honestly Significant Difference (HSD) test. For meeting ANOVA assumptions, data were tested and found to be normally distributed and homogenous; thus, no data transformation was required. The data presented are means and standard errors (mean ± SE), unless otherwise noted. The Pearson simple linear correlation coefficient (r) was calculated for assessing the relationship between nutrients in sediment, water, and plant materials. All statistical analyses were performed using SAS 9.4 (SAS Institute, Cary, NC, USA).

3. Results

3.1. Vegetation Analyses

A total of 28 vascular plant species and one macro-algal species, *Enteromorpha compressa* L., were recorded in the five Egyptian northern lakes water bodies (Tables 1 and S1), where Manzala had the highest number of plant species (14), followed by Edku (13), Burullus (12), Mariut (8), and Bardawil (4 species plus *E. compressa*). Common species in all of the deltaic lakes (Burullus, Edku, Mariut, and Manzala) included *Ceratophyllum demersum* L., *E. crassipes*, *Echinochloa stagnina* (Retz.) P. Beauv, *Potamogeton pectinatus* L., *Phragmites australis* (Cav.) Trin. ex Steud, and *Typha domingensis* (Pers.) Poir. ex Steud. On the other hand, there were some plant species that were unique for certain lakes (Table S3). For example, *Halodule uninervis* (Forssk.) Asch, *Halophila stipulacea* (Forssk.) Asch, and *Ruppia cirrhosa* (Petagna) Grande were only observed in Bardawil (the only nondeltaic lake); *A. filiculoides* and *L. gibba* occurred only in Manzala; *Nymphaea lotus* L. and *Ludwigia stolonifera* (Guill. & Perr.) P.H. Raven only occurred in Edku; and *Atriplex portulacoides* L., *Atriplex prostrata* Boucher ex DC., and *Schoenoplectus litoralis* (Schrad.) Palla only occurred in Burullus. Both Mariut and Bardawil had no annual plant species within the recorded species, while Manzala had the highest number of perennials (13). Hydrophytes plant species (e.g., *C. demersum*, *P. pectinatus*, and *E. crassipes*) were highest in Manzala, while Bardawil had neither phanerophyte nor geophytes-helophytes (Table 1B).

Table 1. (**A**) Sørensen similarity index between Egyptian northern lakes, and (**B**) summary for the total plant species, growth habit, families, and life forms for the identified plant species in the Egyptian northern lakes.

(**A**)

	Burullus	Edku	Mariut	Manzala
Edku	0.48			
Mariut	0.70	0.57		
Manzala	0.62	0.44	0.64	
Bardawil	0.12	0.00	0.00	0.11

(**B**)

Lake	Growth habit		Life forms				Total number of families	Total number of species
	Annuals	Perennials	Phanerophytes	Chamaephytes	Geophytes-helophytes	Hydrophytes		
Burullus	1	11	1	3	5	3	8	12
Edku	1	12	0	3	5	5	10	13
Mariut	0	8	1	0	3	4	7	8
Manzala	1	13	1	2	5	6	9	14
Bardawil	0	4	0	1	0	3	4	4

Sørensen similarity indices indicated that Burullus and Mariut had the highest similarity coefficient (0.70), while Bardawil had the lowest with the rest of the lakes (Table 1A). Application of the TWINSPAN, as a classification technique, on the vegetation composition of the 29 species recorded in the five lakes resulted in three groups of lakes that were similar in their species composition at level two of classification (Figure 2A): group 1: Bardawil; group 2: Edku; and group 3: Manzala, Mariut, and Burullus. In addition, three groups of species were classified at level two (Figure 2B and Table S2). Group 1 had four species (*E. compressa*, *Halodule uninervis*, *Halophila stipulacea,* and *R. cirrhosa*—all were unique to Bardwail); group 2 had three species (*Arthrocnemum macrostachyum* (Moric.) K. Koch, *Tamarix nilotica* (Ehrenb.) Bunge, and *T. domingensis*); and group 3 had 22 species (the most common species were: *C. demersum*, *E. stagnina*, *E. crassipes*, *P. australis,* and *P. pectinatus*). These results were confirmed by application of the DCA, as an ordination technique, on the same set of data (Figure 2C,D).

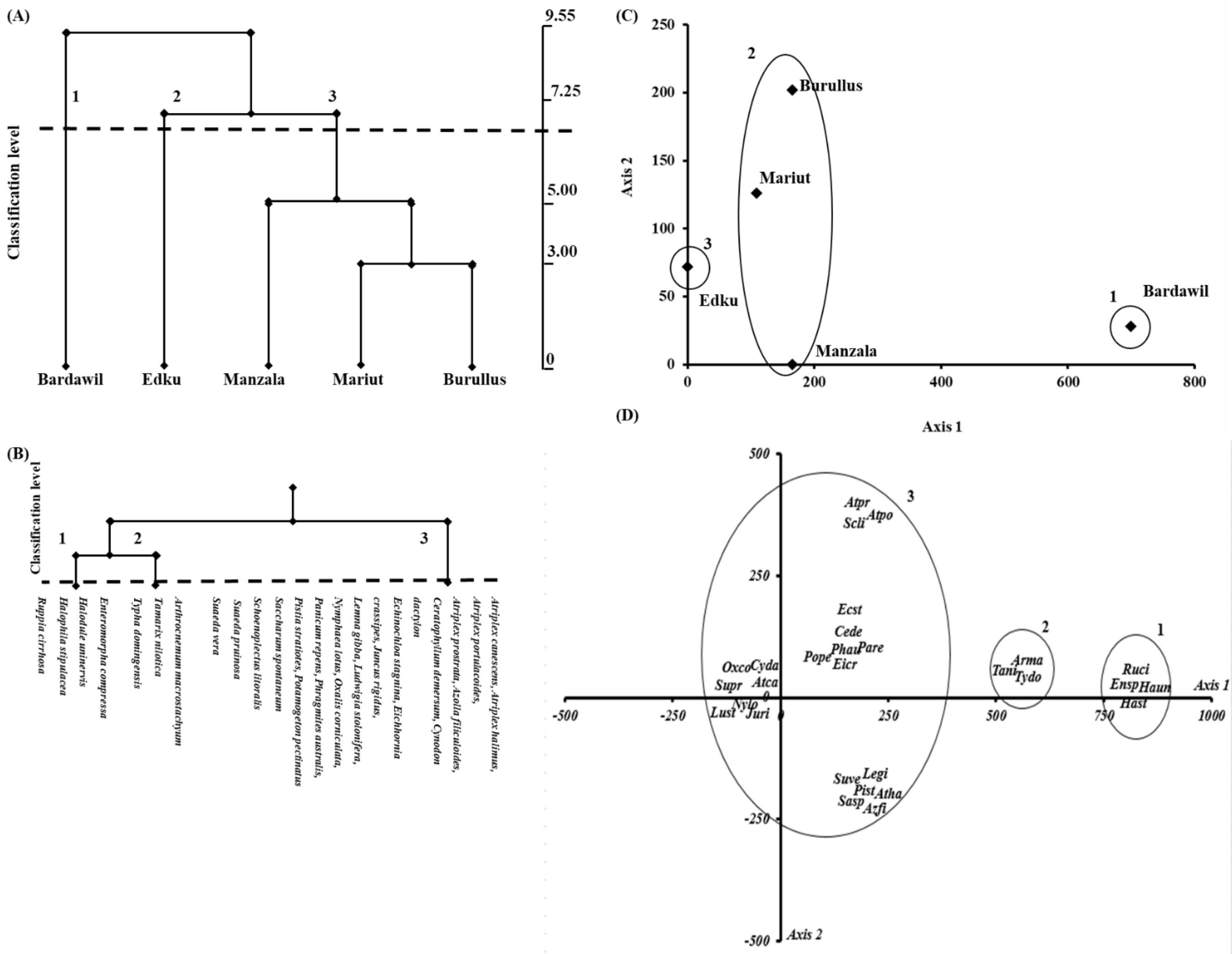

Figure 2. Classification of lakes and plant communities (**A**,**B**) after the application of the two-way species indicator analysis (TWINSPAN). Ordination results (**C**,**D**) from Detrended Correspondence Analysis technique (DCA) showing three vegetation groups for the five Egyptian northern lakes. For plant species abbreviation, see Table S2.

Application of principal component analysis (PCA) on the set of data for the five lakes indicated that the most effective variables were salinity, transparency, and water depth and temperature (Figure 3). *Halodule uninervis*, *Halophila stipulacea,* and *R. cirrhosa* were located at a high position along the gradient of salinity, while *P. australis* was located at a low position along the moisture gradient. Lake Bardawil was located at a high position along the gradient of salinity. On the other hand, Mariut was located at an intermediate position along the total dry weight gradient (Figure 3A,B).

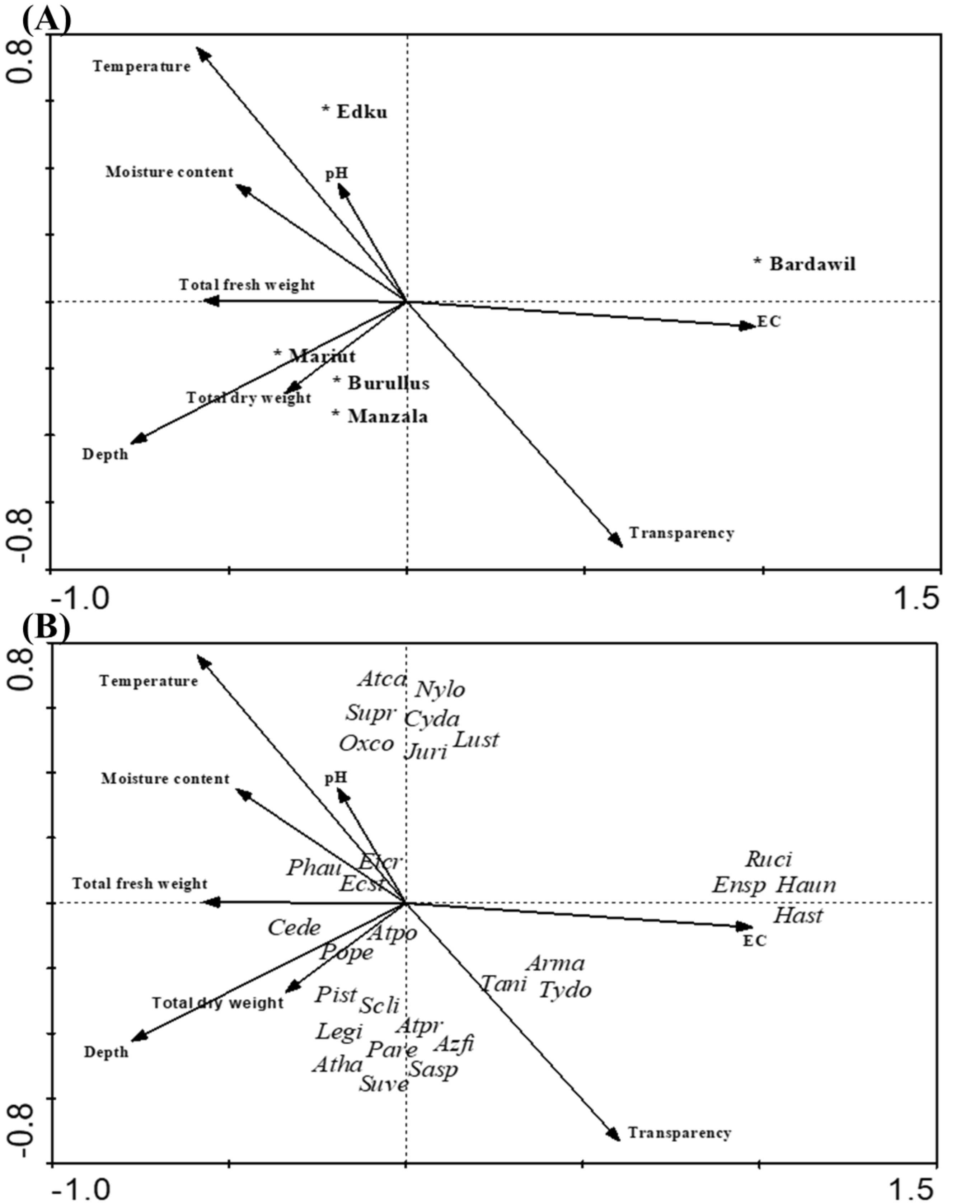

Figure 3. Principal component analyses (PCA) for: (**A**) the water variables and the Egyptian northern lakes, and (**B**) the water variables and the recorded plant species. For plant species abbreviation, see Table S2.

3.2. Aboveground Biomass

Among all lakes, *A. portulacoides* recorded at Burullus Lake had the maximum aboveground biomass (3.2 kg dry wt. m^{-2}), while both *A. filiculoides* and *L. gibba* had the lowest (0.01 kg dry wt. m^{-2}) at Manzala (Figure 4). In Edku and Mariut, *Juncus rigidus* and *T. nilotica* had the maximum aboveground biomass (1.2 and 3.0 kg m^{-2}, respectively), while *C. demersum* had the lowest (0.2 and 0.5 kg dry wt. m^{-2} at Edku and Mariut, respectively). At Bardawil, *A. macrostachyum* had the highest aboveground biomass (1.2 kg dry wt. m^{-2}), while *Halophila stipulacea* had the lowest (0.1 kg dry wt. m^{-2}).

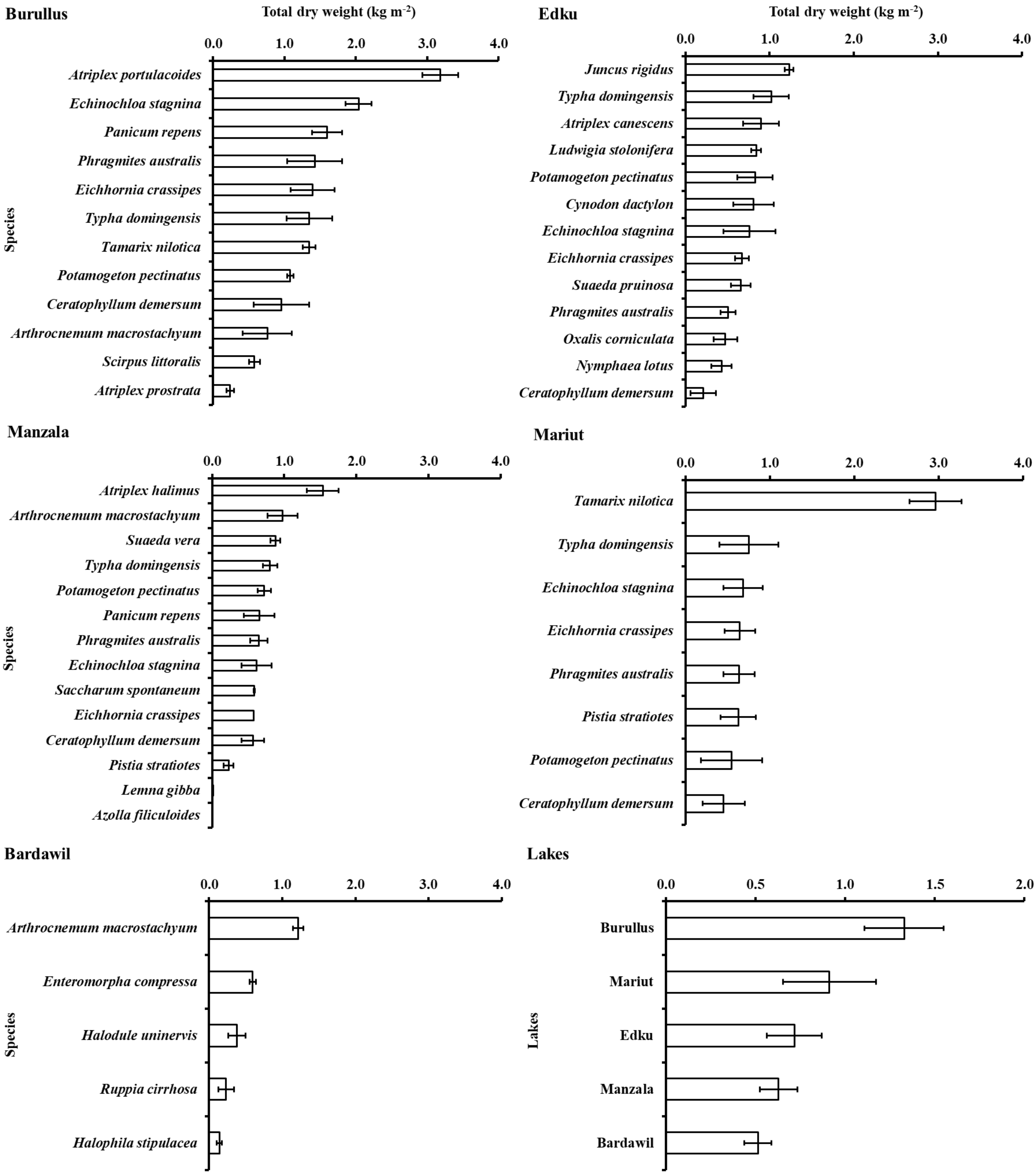

Figure 4. Aboveground biomass (kg dry weight m^{-2}) (mean ± SE) for identified plant species in the Egyptian northern lakes.

3.3. Macro and Micronutrient Analyses

3.3.1. Sediment Analyses

For sediment macronutrients, both total P and Ca content were significantly ($p < 0.05$) different between lakes, with the highest concentrations at Mariut (1.3 and 1777.1 g kg^{-1}, respectively, Table 2). Other macronutrients (K, Mg, and S) did not show differences between lakes ($p > 0.05$). On the other hand, however, all sediment micronutrients (Al, Na, Fe, and B) showed significant differences between lakes ($p < 0.05$). Bardawil Lake, for example, had the highest concentrations for both Na and B (9.6 and 0.1 g kg^{-1}, respectively). For all plots where *E. crassipes* was recorded near the southern parts of deltaic lakes (Burullus, Manzala, Edku, and Mariut), an average total sediment P content of 995.6 ± 243.29 mg kg^{-1} was determined, which could be used as a proxy of excess nutrient runoff.

Table 2. Macro and micronutrient concentrations (mean ± SE) in sediment, water, and plant materials of the Egyptian northern lakes. *p* values here represent one-way ANOVA between lakes, while means in the same row with different letters are significantly different at $p \leq 0.05$ according to Tukey's test.

	Bardawil (n = 11)	**Manzala (n = 11)**	**Burullus (n = 12)**	**Edku (n = 10)**	**Mariut (n = 10)**	***p* Value**
Macronutrients in sediment (g kg^{-1})						
P	$0.3^{C} \pm 0.1$	$0.9^{A} \pm 0.2$	$0.9^{A} \pm 0.1$	$1.1^{A} \pm 0.1$	$1.3^{A} \pm 0.3$	0.0023
Ca	$34.4^{C} \pm 9.8$	$109.1^{B} \pm 25.7$	$94.3^{B} \pm 17.6$	$68.9^{CB} \pm 10.7$	$177.1^{A} \pm 24.7$	<0.0001
K	$2.5^{A} \pm 0.6$	$2.6^{A} \pm 0.5$	$3.3^{A} \pm 0.4$	$4.0^{A} \pm 0.4$	$3.4^{A} \pm 0.5$	0.2009
Mg	$25.4^{A} \pm 12.7$	$7.1^{A} \pm 1.0$	$9.8^{A} \pm 1.0$	$11.2^{A} \pm 0.9$	$15.6^{A} \pm 1.5$	0.2117
S	$4.9^{A} \pm 1.8$	$8.0^{A} \pm 1.4$	$8.1^{A} \pm 1.1$	$5.9^{A} \pm 0.8$	$8.2^{A} \pm 1.2$	0.2733
Micronutrients in sediment (g kg^{-1})						
Al	$9.7^{C} \pm 2.6$	$15.5^{BAC} \pm 2.9$	$18.9^{BA} \pm 2.3$	$21.0^{A} \pm 2.0$	$13.3^{BC} \pm 2.5$	0.0187
Na	$9.6^{A} \pm 2.1$	$3.0^{B} \pm 0.3$	$4.7^{B} \pm 0.6$	$3.8^{B} \pm 0.4$	$4.5^{B} \pm 0.7$	0.0004
Fe	$13.1^{B} \pm 3.9$	$23.0^{BA} \pm 4.0$	$29.8^{A} \pm 3.7$	$35.0^{A} \pm 3.2$	$24.4^{BA} \pm 7.8$	0.0262
B	$0.10^{A} \pm 0.05$	$0.02^{B} \pm 0.002$	$0.02^{B} \pm 0.002$	$0.02^{B} \pm 0.002$	$0.03^{B} \pm 0.01$	0.0261
	Bardawil (n = 25)	**Manzala (n = 39)**	**Burullus (n = 30)**	**Edku (n = 25)**	**Mariut (n = 19)**	***p* value**
Macronutrients in water (mg L^{-1})						
P	$0.03^{B} \pm 0.005$	$0.2^{B} \pm 0.04$	$0.2^{B} \pm 0.08$	$0.2^{B} \pm 0.02$	$0.7^{A} \pm 0.18$	<0.0001
N	$73.7^{A} \pm 2.3$	$80.3^{A} \pm 4.4$	$75.1^{A} \pm 3.4$	$76.5^{A} \pm 3.9$	$83.1^{A} \pm 4.2$	0.4988
Mg	$1375.9^{A} \pm 45.2$	$248.8^{B} \pm 56.4$	$303.5^{B} \pm 42.3$	$62.6^{C} \pm 5.1$	$296.7^{B} \pm 80.4$	<0.0001
K	$779.7^{A} \pm 19.9$	$96.0^{B} \pm 16.8$	$136.4^{B} \pm 13.4$	$40.8^{C} \pm 3.5$	$101.6^{B} \pm 20.9$	<0.0001
Ca	$30.5^{A} \pm 2.5$	$4.0^{C} \pm 0.5$	$3.1^{C} \pm 0.6$	$1.8^{C} \pm 0.1$	$11.4^{B} \pm 2.6$	<0.0001
Micronutrients in water (mg L^{-1})						
Na	$12{,}901.1^{A} \pm 409.9$	$1656.2^{B} \pm 377.3$	$2584.3^{B} \pm 309.0$	$351.2^{C} \pm 38.3$	$1752.6^{B} \pm 447.3$	<0.0001
	Bardawil (n = 7)	**Manzala (n = 21)**	**Burullus (n = 17)**	**Edku (n = 19)**	**Mariut (n = 15)**	***p* value**
Macronutrients in plant material						
C %	$23.5^{B} \pm 1.8$	$33.1^{A} \pm 1.0$	$35.2^{A} \pm 0.8$	$32.6^{A} \pm 1.1$	$34.0^{A} \pm 1.3$	<0.0001
N %	$1.3^{C} \pm 0.2$	$2.2^{A} \pm 0.2$	$1.7^{BC} \pm 0.1$	$2.3^{A} \pm 0.2$	$2.1^{BA} \pm 0.2$	0.0009
CN ratio	$21.8^{A} \pm 2.7$	$23.1^{A} \pm 3.1$	$23.4^{A} \pm 1.4$	$17.0^{A} \pm 1.4$	$20.3^{A} \pm 2.3$	0.2197
P (g kg^{-1})	$1.2^{B} \pm 0.3$	$3.5^{A} \pm 0.5$	$2.4\ B^{A} \pm 0.4$	$3.1^{A} \pm 0.4$	$2.9^{A} \pm 0.5$	0.0501
K (g kg^{-1})	$18.5^{A} \pm 3.9$	$21.9^{A} \pm 4.0$	$16.1^{A} \pm 1.4$	$20.1^{A} \pm 3.2$	$24.4^{A} \pm 4.7$	0.5768
Ca (g kg^{-1})	$44.3^{A} \pm 9.6$	$18.3^{A} \pm 4.5$	$26.9^{A} \pm 9.0$	$34.7^{A} \pm 13.3$	$19.8^{A} \pm 5.0$	0.4007
Mg (g kg^{-1})	$11.3^{A} \pm 1.7$	$5.5^{B} \pm 0.6$	$6.1^{B} \pm 0.7$	$6.9^{B} \pm 1.2$	$5.3^{B} \pm 0.8$	0.0057
S (g kg^{-1})	$7.4^{BA} \pm 0.6$	$6.0^{BA} \pm 0.6$	$5.3^{B} \pm 0.8$	$5.0^{B} \pm 0.3$	$8.5^{A} \pm 1.3$	0.0183
Micronutrients in plant material (g kg^{-1})						
Al	$4.7^{A} \pm 1.5$	$2.7^{B} \pm 0.6$	$1.6^{B} \pm 0.5$	$2.6^{B} \pm 0.5$	$1.0^{B} \pm 0.3$	0.0145
Na	$36.1^{A} \pm 11.1$	$21.3^{A} \pm 5.6$	$26.0^{A} \pm 7.5$	$16.4^{A} \pm 5.7$	$16.9^{A} \pm 2.2$	0.38
Fe	$7.7^{A} \pm 3.0$	$3.7^{B} \pm 0.8$	$3.4^{B} \pm 1.1$	$3.5^{B} \pm 0.8$	$1.4^{B} \pm 0.4$	0.0282
B	$0.42^{A} \pm 0.16$	$0.10^{B} \pm 0.04$	$0.11^{B} \pm 0.06$	$0.09^{B} \pm 0.04$	$0.10^{B} \pm 0.05$	0.0151

3.3.2. Water Analyses

All macronutrients including (P, Mg, K, and Ca) in the lakes' water were significantly different in their concentrations between lakes except for total N, which showed no significant differences (Table 2). Mariut Lake had the highest load of total P (0.7 mg L^{-1}), while Bardawil Lake had the highest concentrations of Mg, K, and Ca (1375.9, 779.7, and 30.5 mg L^{-1} respectively, Table 2). For micronutrients, Bardawil Lake had the highest Na concentrations (12,901.1 mg L^{-1}) in their water among all lakes, while Edku Lake had the lowest (351.2 mg L^{-1}, Table 2).

3.3.3. Plant Material Analyses

For macronutrients in plant materials, both total C and N percentages were significantly ($p < 0.05$) different among the lakes, while Bardawil Lake had the lowest (23.5 and 1.3%, respectively; Table 2). Moreover, Bardawil Lake had the lowest load of total P (1.2 g kg^{-1}) in its plant materials. Both K and Ca concentrations had no significant differences among the lakes. Bardawil Lake had the highest Mg concentrations (11.3 g kg^{-1}) in the plant materials, while Mariut Lake had the highest concentrations of S (8.5 g kg^{-1}). For micronutrients in plant materials, Bardawil Lake had the highest concentrations of Al, Na, Fe, and B (4.7, 36.1, 7.7, and 0.42 g kg^{-1}, respectively).

Some plant species had higher nutrients in their plant tissues than others (Table S4). For example, in Burullus Lake, *P. australis*, an emergent grass, had the highest concentration of C (42.0%) but the lowest concentration of Na, Ca, Mg, and S (3.2, 1.2, 1.2, and 2.6 g kg^{-1}, respectively). On the other hand, however, *C. demersum*, a submerged aquatic species, had the highest concentration of Ca (98.3 g kg^{-1}) and the lowest concentration of C (26.0%) (Table S4). On the hypersaline lake, Bardawil, *Halophila stipulacea*, a seagrass species, had the highest concentration of Ca and Mg (78.3 and 17.9 g kg^{-1}, respectively) but had the lowest concentration of C (17.4%), and K and S (10.2 and 6.2 g kg^{-1}, respectively) (Table S4).

The occurrence of some nutrients in sediment, water, and plant materials was associated with the existence of some specific nutrients and not the others. For example, in sediment, the existence of total P was highly associated with the existence of Al, Fe, and K (r = 0.6 and $p \leq 0.001$, Table 3A), but not with the existence of Mg or Na (r = 0.0). The presence of Ca in the lake's water was highly associated with the existence of Mg, K, and Na (r = 0.9 and $p \leq 0.001$), but not with the presence of total P or N (Table 3B). Total P in plant materials was highly associated with the presence of total N (r = 0.8 and $p \leq 0.001$, Table 3C).

Table 3. Pearson correlation coefficient (r) for nutrients in (**A**) sediment, (**B**) water, and (**C**) plant materials for the Egyptian northern lakes. * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, and ns: not significant (e.g., $p > 0.05$).

(A) Nutrients in sediment (g kg^{-1})	**Al**	**B**	**Ca**	**Fe**	**K**	**Mg**	**Na**	**P**
B	0.1 ns							
Ca	−0.1 ns	−0.1 ns						
Fe	0.8 ***	0.0 ns	−0.1 ns					
K	0.9 ***	0.3 *	0.0 ns	0.7 ***				
Mg	0.2 ns	1.0 ***	0.0 ns	0.0 ns	0.3 *			
Na	0.2 ns	0.8 ***	−0.1 ns	0.1 ns	0.5 ***	0.8 ***		
P	0.6 ***	−0.1 ns	0.2 ns	0.6 ***	0.6 ***	0.0 ns	0.0 ns	
S	0.6 ***	0.3 *	0.3 *	0.6 ***	0.6 ***	0.4 **	0.4 **	0.5 ***
(B) Nutrients in water (mg L^{-1})	**P**	**N**	**Mg**	**K**	**Na**			
N	0.1 ns							
Mg	−0.3 **	0.0 ns						
K	−0.2 **	−0.1 ns	1.0 ***					
Na	−0.3 **	0.0 ns	1.0 ***	1.0 ***				
Ca	−0.2 *	−0.1 ns	0.9 ***	0.9 ***	0.9 ***			
(C) Nutrients in plant tissues (g kg^{-1})	**C**	**N**	**P**	**K**	**Ca**	**Mg**	**S**	
N	0.1 ns							
P	−0.2 *	0.8 ***						
K	−0.2 *	0.5 ***	0.7 ***					
Ca	−0.7 ***	−0.2 ns	0.0 ns	−0.1 ns				
Mg	−0.8 ***	−0.2 ns	0.0 ns	0.0 ns	0.6 ***			
S	−0.2 *	0.2 *	0.1 ns	0.0 ns	0.2 ns	0.3 **		
Na	−0.2 *	−0.3 **	−0.3 **	−0.1 ns	−0.1 ns	0.4* **	0.1 ns	

4. Discussion

The Egyptian flora includes 2121 native and naturalized species [36,49]. The Egyptian northern lakes represent a small area (2269 km^2) relative to Egypt's area [27]. However, they conserve 19% of the total flora of Egypt [29]. These northern coastal lakes play vital roles for fish production and migratory birds [2,3] in addition to being considered as hot spots for the conservation of Egyptian flora [50,51]. In the current study, 28 aquatic vascular species were recorded within the water bodies for the Egyptian northern lakes in addition to one macro-algal species (*E. compressa*). The species richness in our study is lower than those in other studies conducted at the Egyptian northern lakes [27,52] as we were interested only in the plant species within the aquatic bodies of these lakes. Lake Manzala had the highest number of species (14 species), followed by Edku (13 species), Burullus (12 species), Mariut (8 species), and Bardawil (4 species plus *E. compressa*). The salinity gradient within the lakes might play a role in plant species distribution, where fresh-brackish plant species (e.g., *C. demersum*, *E. stagnina*, and *E. crassipes*) occur near the southern parts of the lakes where the main source of freshwater reaches the lakes through the agricultural canals/streams. On the other hand, and at the northern parts of the lakes where the sea water enters the lakes through Boughaz inlets, halophytic plant species becomes more dominant (e.g., *A. macrostachyum*). Moreover, each lake had its own unique species. For example, *Halodule uninervis*, *Halophila stipulacea*, and *R. cirrhosa* were unique in their presence at Bardawil Lake (a hypersaline lake), while *A. filiculoides* and *L. gibba* were unique in their presence at Manzala Lake (a brackish lake). Similar research studies concluded that salinity impacts plant species distribution among the Egyptian northern lakes [27,52].

Application of the TWINSPAN on the floristic composition of the 29 species recorded in the five lakes resulted in the appearance of three groups of lakes (as had been reported by similar research studies [27]: 1 (Lake Bardawil), 2 (Lake Edku), and 3 (Lake Manzala, Mariut, and Burullus) and three groups of species. Group 1 had four species (*E. compressa*, *Halodule uninervis*, *Halophila stipulacea,* and *R. cirrhosa*), group 2 had three species (*A. macrostachyum*, *T. nilotica* and *T. domingensis*), and group 3 had 22 species (the most common were: *C. demersum*, *E. stagnina*, *E. crassipes*, *P. australis*, and *P. pectinatus*). Clustering of the plant species into three groups can be interpreted from a water characteristics perspective. Bardawil Lake is considered as a hyper saline Lake (EC 48.1 mS cm^{-1}, [9]), which leads to the separation of their species into a separate group from the rest of the other lakes (Mariut, Edku, Burullus, and Manzala), which are considered brackish lakes, as had been reported by many research studies [35,53–55]. This species and lake separation was further confirmed after applying the DCA and having the same results.

In the current study, we reported at least six plant species (*C. demersum*, *E. crassipes*, *E. stagnina*, *P. australis*, *P. pectinatus*, and *T. domingensis*) that were common among four lakes (Mariut, Edku, Burullus, and Manzala). *P. australis*, the common reed, is a widely distributed wetland grass that exists in all northern lakes except Bardawil Lake, as reported by many studies including the present study [27,29,36,49]. In the brackish lakes, for example, Burullus Lake, the common reed is an important reed bed, especially for wintering and migrating birds for foraging, refuge, and breeding. Plant materials for the common reed in Burullus Lake had the highest C content (42%), which is a major macronutrient for growth. Accordingly, local communities and government policy makers should manage the growth of the common reed in the Egyptian lakes instead of the idea of complete eradication.

Another widely distributed and nonnative invasive species to Africa [56] is *E. crassipes* (water hyacinth), a free-floating aquatic plant, which is also present among all the brackish lakes (Mariut, Edku, Burullus, and Manzala). Due to the rapid growth of the water hyacinth and dense mat formation, it has the ability to outcompete native aquatic species, reducing oxygen levels for fish, and creating habitats for disease-carrying mosquitoes [57]. It was noticed in our study that those plots (where *E. crassipes* was recorded at the southern sections of the deltaic lakes) had an average total P content in sediment of 995.6 ± 243.29 mg kg^{-1}, which could be used as a proxy of excess nutrient runoff. Many research studies reported that the existence of the water hyacinth is associated with higher nutrient levels, especially continuous inputs for agricultural and industrial runoff [58]. Wilson et al. [59] reported an increase in the water hyacinth growth rate from 0.1 to 10 kg m^{-2} under nutrient-rich or eutrophic conditions, which resulted in biodiversity reduction in the invaded area [57,58]. In addition, the results of Eid and Shaltout 2017 [60] indicated that water hyacinth responded to an increase in nutrients with greater growth where individual biomass, leaf area, number of total leaves, and stolons and petioles proportions of water hyacinth were positively correlated with some water properties (N, P, Mg, and K). In Burullus Lake, for example, water hyacinth had a 1.4 kg dry weight m^{-2} and was dominant at the southern parts of the lakes where the main nutrient runoff reaches the lakes through the main agricultural canals and streams. Moreover, water hyacinth cannot tolerate higher salinity at the northern part of the lakes. Nutrient analyses indicated that the deltaic lakes (Mariut, Edku, Burullus, and Manzala) that are receiving agricultural and industrial runoff had higher nutrient loads where water hyacinth occur, and that played a role in less plant species diversity, especially at the southern parts of the lakes—in support of our first hypothesis. Mariut Lake, for example, had the highest content of total P in the sediment and water, which is an indication of higher nutrient load from the agricultural runoff that the lake receives—supporting our second hypothesis.

Many plant species at the Egyptian northern lakes offer several goods to local communities (e.g., medicinal plants, fodder for livestock, and thatching), in addition to the valuable ecosystem services that coastal wetlands usually offer, including, but not limited to, provisioning, regulating, cultural, and supporting services [61,62]. Although both Bardawil and Burullus lakes have been recognized as important wetland regions by the RAMSAR convention [10,50,51] and have received the Egyptian government attention, Mariut and Edku lakes require an immediate and sustainable development plan to reduce the pollution levels and maximize their ecosystem services. Conservation of the Egyptian coastal wetlands [63], similar to other coastal wetlands, is very important not only for their ecological importance, but also for the ecosystem services they provide. Accordingly, the plant species diversity at the northern coastal wetlands should receive sustainable management to reduce the severe human impacts including land reclamation, habitat fragmentation, excessive nutrient runoff, and fish farm industry.

5. Conclusions

The present study concluded that the water bodies of the Egyptian northern lakes had a total of twenty-eight aquatic vascular species in addition to one macro-algal species (*E. compressa* that was unique to Bardawil Lake). Lake Manzala had the highest plant species (14 species), while Bardawil had the lowest (4 species plus *E. compressa*). Vegetation composition analyses revealed that Burullus and Mariut were very similar (Sørensen index of 0.7) in their vegetation composition, while Bardawil Lake showed the lowest similarity when comparing it to deltaic lakes (Burullus, Edku, Maruit, and Manzala). Mariut Lake had the highest total P concentration in the sediment (1.3 g kg^{-1}) and water (0.7 mg L^{-1}). Moreover, a total P sediment content of 995.6 ± 243.29 mg kg^{-1} could be used as a proxy of excess nutrient runoff reaching the deltaic lakes at the southern parts via the agricultural canals. Salinity had a major role in plant species distribution, where plant species such as *Halodule uninervis*, *Halophila stipulacea*, and *R. cirrhosa* were unique in their presence at Bardawil Lake (a hypersaline lake), while *A. filiculoides* and *L. gibba* were unique in their presence at Manzala Lake (a brackish lake). Mariut Lake is severely polluted due to an excessive load of agricultural and industrial runoff, and the lake is no longer connected to the Mediterranean Sea—the main source of sea water. Moreover, Mariut Lake water bodies had the lowest plant species recorded among the deltaic lakes, which might be a result of higher run off with excessive nutrients and, hence, limiting plant species diversity. As these lakes are extremely valuable due to their natural resources and related economic importance, it is vital to integrate the current findings along with existing knowledge to help reduce the eutrophication levels that those lakes experience.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14106180/s1. Photo S1. Field photos showing the floating quadrat used in aboveground biomass sampling. A: *Ceratophyllum demersum* L. in lake Burullus, B: *Nymphaea lotus* L. in Lake Edku. Photos taken by A.E. Keshta. Table S1. Identified plant species in the Egyptian northern lakes along with their pertained families, life forms, and floristic categories. The life forms are: PH: phanerophytes, CH: chamaephytes, GH: geophytes-helophytes, and HH: hydrophytes. The floristic regions are: COSM: cosmopolitan, ES: Euro-Sibarian, IT: Irano-Turanian, ME: Mediterranean, SA: Saharo-Arabian, SU: Sudanian, TR: Tropical, IR—TR: Irano–Turanian, ER–SR: Euro–Siberian, NEO: Neotropical, PAL: Palaeotropical, and PAN: Pantropical. Table S2. Plant species groups identified in the Egyptian northern lakes after the application of the two-way species indicator analysis (TWINSPAN). G/P: number of species in each group in relation to the total number of species. Table S3. Absolute (AP) and relative presence (RP %) for plant species distributed in the five Egyptian northern lakes. RP: total number of lakes that have a species in relation to the total number of lakes. Table S4. Nutrients in plant tissues (mean ± SE) for identified plant species for the Egyptian northern lakes. Highest and lowest mean values are bolded and underlined.

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