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Controlling Factors of Phytoplankton Productivity in Marshes in a Hot Climate with High Seasonal Variation

Fuad Ameen [1,*], Alaa I. Albueajee [2], Fikrat M. Hassan [3], Steven L. Stephenson [4] and Ali A. Z. Douabul [5]

1 Department of Botany & Microbiology, College of Science, King Saud University, Riyadh 11451, Saudi Arabia
2 General Education Directorate of Wasit Province, Education Ministry, Wasit 52002, Iraq; alaissaalajiavi@gmail.com
3 Department of Biology, College of Science for Women, University of Baghdad, Baghdad 10070, Iraq; fikrat@csw.uobaghdad.edu.iq
4 Department of Biological Sciences, University of Arkansas, Fayetteville, AR 72701, USA; slsteph@uark.edu
5 Marine Science Center, University of Basra, Basra 61004, Iraq; ali.douabul@gmail.com
* Correspondence: fuadameen@ksu.edu.sa

Abstract: In this work the Auda marsh, which is part of a system of Iraqi marshes, was sampled to assess the seasonal dynamics and controlling factors of microalgae productivity. The marshes are situated in a hot climate with high seasonal variation near the Arabian Gulf. Physicochemical and biological measurements were taken for water in three areas. Bio-optical models were constructed to describe the primary productivity and chlorophyll-*a* concentrations in the wet and dry seasons separately and also for the entire area of the Iraqi marshes. The models, as well as almost all measurements, showed high seasonal variation. The mean water temperature was 16 °C in the wet season and 28 °C in the dry season. An almost twofold difference was measured for turbidity and the concentrations of dissolved oxygen and chlorophyll-*a* for the two seasons. Chlorophyll-*a* appeared to be a better indicator of ecosystem conditions than primary productivity or biological oxygen demand, according to the results obtained from canonical correlation analysis. Nitrogen or phosphorous did not explain primary productivity or chlorophyll-*a* to an appreciable extent. Biological variables were related most strongly to water temperature and turbidity, which were the factors most important for controlling phytoplankton productivity in the marshes.

Keywords: wetland; seasonal variation; wetland regime primary productivity; chlorophyll-*a*; microalgae; nutrients

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1. Introduction

Wetlands are facing rapid and unpredictable changes in response to global warming. The warming of the climate has been shown to change wetland ecosystems throughout the world, and it is also likely to affect the wetlands in areas where the climate is already hot and the conditions are extreme [1]. Warming affects the hydrological regime of the wetlands, which largely controls the organisms present [2]. Moreover, warming itself creates stressful conditions for these organisms, changing the functioning of the entire ecosystem [3].

Warming generally increases the primary productivity of aquatic ecosystems. Primary production is enhanced by high temperatures that indirectly weaken water current in tidal wetlands, thus increasing the concentrations of nutrients available to organisms such as phytoplankton [4–7]. However, the changes reported in phytoplankton biomass have been highly variable and even contrasting, depending on the area studied [8,9]. Therefore, local information on wetlands is needed.

The changes in a wetland ecosystem can be assessed by measuring, for instance, the concentrations of various nutrients, oxygen, turbidity, and primary production as the concentration of chlorophyll [4]. Measuring only single variables such as a particular nutrient or oxygen concentration does not provide enough data for large and spatio-temporally variable areas. A method offering the possibility of assessing environmental changes in large areas is the analysis of Landsat data [10]. This type of analysis has been shown to be useful in assessing water quality in areas with high seasonal variation [11–13].

There is an extensive tidal wetland area situated in Iraq called the Iraqi marshes or Mesopotamian marshes. The area used to be the largest wetland ecosystem in southwest Asia (20,000 km^2) [8]. Large-scale desiccation took place in the marshes in the 1990s and reflooding occurred thereafter in 2003 [9]. At present, physicochemical variables such as salinity, sulfate, and nutrient concentrations are near the pre-desiccation conditions, and the area is considered to have recovered from desiccation from a physicochemical point of view [10,13]. Ecosystem functioning, in contrast, may not be totally recovered [14,15]. The Iraqi marshes are bordered by the Arabian Gulf, which is an ocean vulnerable to global warming and dependent on freshwater transport [16]. Thus, the changes in the marshes may have wider consequences for the Arabian Gulf.

More information is needed to understand the dynamics of wetlands throughout the world [17]. Herein we focus on wetlands where the climate is highly seasonal with hot, dry summers and cool, wet winters. Iraqi marshes are situated in a hot climate where seasonal variation is high; water temperature ranges from 11.9 to 33 °C in winter and summer, respectively [18]. Our objective was to understand the seasonal variation in primary productivity and the factors that control this variation in a wetland in the system of Iraqi marshes.

2. Materials and Methods

2.1. Study Area

The Auda marsh is a body of water in southern Iraq (31°33′ N; 46°51′ E) (Figure 1). The area of the marsh is ca. 7500 ha during the wet season. The water depth ranges from 1 to 4.3 m. Auda marsh was desiccated during the 1990s and reflooded naturally after 2003 [19]. This marsh is currently dominated by emergent aquatic plants such as *Phragmites australis* (Cav.) Trin. ex Steud and *Typha domingensis* Pers. Detailed characteristics of the study sites are given in Table 1. Water samples were collected into glass bottles (three stations [S1, S2, and S3] Figure 1), 13 times monthly from January 2018 to January 2019.

Table 1. Characteristics of the three study sites in the Auda marsh.

Site	Depth	Ditching	Vegetation
S1	3.3 m	Channels 5–15 m width, represent permanent part of the marsh	Low cover
S2	2.7 m	One main channel 35 m width, moderate open area	High cover dominated by *Phragmites australis*
S3	1.5 m	Large open area	Vegetation consists of *Phragmites australis*, *Typha domingensis* and the free-floating plant *Ceratophyllum demersum*

2.2. Chemical and Biological Analyses

Water samples were collected using a horizontal Van Dorn water sampler from the midpoint of the total depth, which was measured. Samples for chemical analysis (1 L) were transferred into polyethylene containers. The samples for chlorophyll a (Chl *a*) (1 L) were filtered immediately in the field using pre-weighed Whatman GF/F (0.45 µm) filters. The filters were preserved by adding 5 mL of 1% magnesium chloride and kept cold. The species of phytoplankton were identified morphologically as described by Ameen et al. [19].

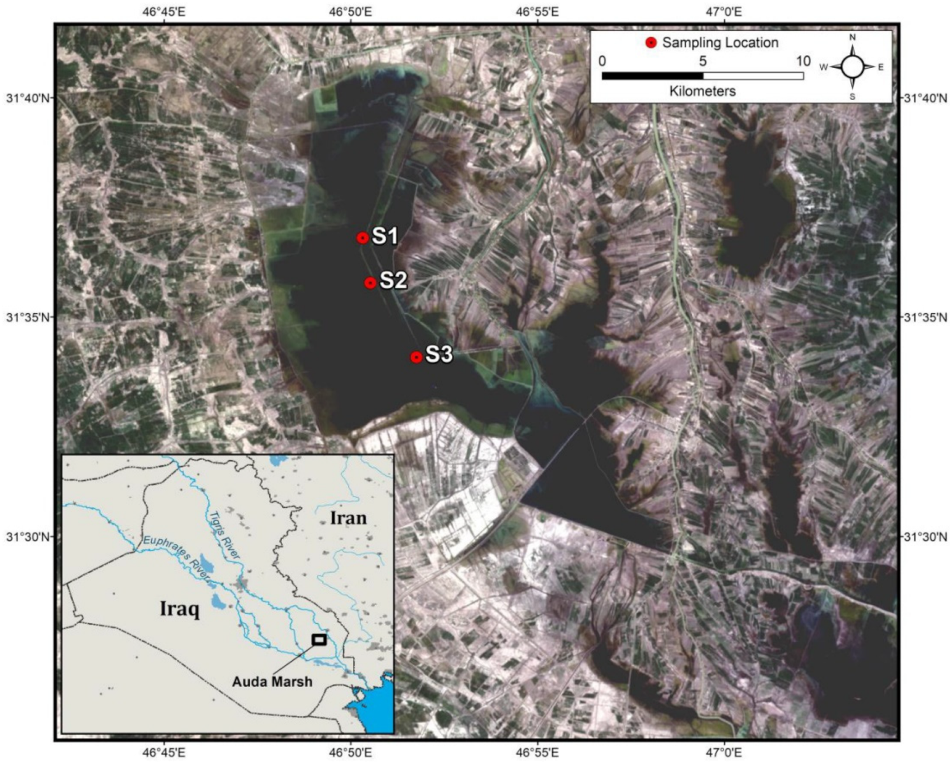


Figure 1. Map of Iraqi marshes and the satellite image of the general study area (Landsat 8) and the specific study sites (S1, S2, S3).

The concentrations of total nitrogen (TN) and total phosphorous (TP) were measured according to Stainton et al. [20]. Turbidity was measured spectrophotometrically at 750 nm. Silicate, biological oxygen demand (BOD_5), and dissolved oxygen (DO) concentrations were measured using standard methods for water analyses according to the American Public Health Association [21].

For the extraction of Chl-*a*, the filter was placed into a test tube with 10 mL of 90% ice-cold acetone. The tube was kept at 4 °C for 24 h, allowed to warm to room temperature, and then centrifuged for 10 min at 5000 rpm. The colorless biomass was discarded. The pigment was analyzed by comparing the sample against a blank (acetone) with 100% transmission. The concentration of chlorophyll-*a* in the supernatant was measured spectrophotometrically at the wavelengths of 750 and 665 nm. Samples were then acidified with HCl (1 M) and measured at the same wavelengths. The chlorophyll content was calculated as described in the literature [21].

Primary productivity was determined using the light and dark bottles method according to the literature [21]. The water samples were collected into Winkler bottles (300 mL) from a depth of 20–30 cm. Two bottles for initial (Li), light (L1 and L2), and dark (D) were incubated at the depth of 20–30 cm for four hours. The oxygen concentration was measured using the Azide method, and primary productivity (PP) was calculated as described by [22] (using the bottles).

2.3. Modeling Primary Production

Three time periods (wet, intermediate, and dry seasons) were used to assess changes in primary productivity and the chlorophyll-*a* metric. Dates for analysis were decided based on field sampling dates and available cloud-free satellite imagery. The wet season analysis was performed on Landsat 8 satellite imagery sourced on 6 January 2018, and the dry season analysis was based on data for 17 July 2018 data. The algorithm supplied by Brivio et al. [23] was used to analyze Landsat 8 satellite data was used.

2.4. Statistical Analysis

Descriptive statistics along with the Pearson correlation were calculated and canonical correspondence analysis (CCA) was performed on the entire dataset (n = 39).

3. Results and Discussion

In total, 7 different phyla and 93 genera of phytoplankton were identified. Members of Bacillariophyta were found most frequently (56 strains) followed by the Euglenozoa (15 strains), Cyanobacteria (10 strains), and Chlorophyta (8 strains). The respective percentages were 62%, 16%, 11%, and 9% (Figure 2). Charophyta and Mioza were uncommon (1.08%). The community structure resembles that of the Iraqi Mesopotamian marshes, where more than half of the species of phytoplankton belonged to Bacillariophyceae and Chlorophyceae [19].

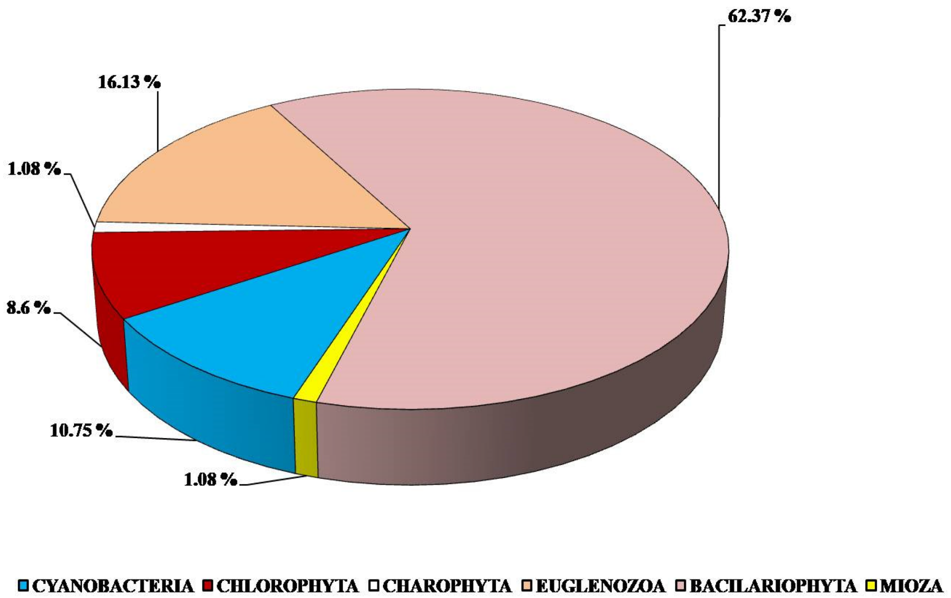


Figure 2. Distribution of the different phyla of microalgae and diatoms.

The air temperature in the three sites in the Aura marsh ranged between a minimum of 9.8 °C and a maximum of 46 °C. The water temperature ranged between 12 °C and 32 °C. In general, high temporal variation in the general study area was observed in almost all of the variables measured. Turbidity, TP, PP, and Chl-*a* were higher during the dry season, whereas DO, BOD_5, Si, and, TN were higher during the wet season (Table 2). Turbidity varied between 26 NTU in the wet season and 48 NTU in the dry season. As expected, it seemed to be most closely related to phytoplankton biomass, which varied between 125 and 176 mg C m^{-3} h^{-1}, respectively. However, the correlation was weak. It is well known that turbidity is positively related to the density of macrophytes and phytoplankton [20]. Phytoplankton biomass is described by Chl-*a* correlated strongly with turbidity (r = 0.7) (Table 3). The highest turbidity observations were recorded for the S3 site (max 130). This is probably related to low water flow, human activities, and agriculture, all of which likely increased suspended particular matter. Chl-*a* varied from 4.7 µg L^{-1} in the wet season to 9.8 µg L^{-1} in the dry season. Chl-*a* concentration did not exceed 10 µg L^{-1}, which means the Auda marsh has a mesotrophic status [21].

Table 2. Physico-chemical and biological variables in the Auda marsh (mean of the three sites S1, S2 and S3 ± SD) during the wet (January) and dry (July) seasons. The season with the higher value is indicated in bold. PP = primary productivity.

	Wet	**Dry**
Temperature (°C)	15.9 ± 0.5	**28.1** ± 0.6
Turbidity (NTU)	26.0 ± 5.1	**48.4** ± 15.3
DO (mg L^{-1})	**7.6** ± 0.3	4.5 ± 0.5
BOD_5 (mg L^{-1})	**2.1** ± 0.1	1.8 ± 0.2
Si (μg L^{-1})	**26.8** ± 3.1	19.3 ± 3.5
TP (μg L^{-1})	0.10 ± 0.01	**0.17** ± 0.01
TN (μg L^{-1})	**1.5** ± 1.5	1.0 ± 0.5
PP (mg C m^{-3} h^{-1})	125 ± 15	**176** ± 13
Chl-*a* (μg L^{-1})	4.7 ± 1.9	**9.8** ± 1.5

Table 3. Pearson's correlation coefficients ($r > 0.5$; $p < 0.05$; $n = 39$) between the physico-chemical and biological variables recorded in the Auda marsh. The highest correlation coefficient for each variable is in bold. PP = primary productivity.

	Temperature	**Turbidity**	**DO**	**BOD_5**	**SiO_3^{-2}**	**TP**	**TN**	**PP**
Temperature	1							
Turbidity	**0.84**	1						
DO	**−0.82**	−0.71	1					
BOD_5				1				
SiO_3^{-2}	−0.68	**−0.71**	0.65		1			
TP	0.55	**0.63**	−0.62			1		
TN							1	
PP								1
Chl-*a*	0.64	0.71	**−0.80**	−0.23	−0.52	0.51		0.68

DO concentration at the three sites varied between the lowest value of 0.8 mg L^{-1} in the dry season to the highest value of 9 mg L^{-1} during the wet season. The minimum concentration recommended in the literature [22] is 5.5 mg L^{-1}, which in general was not fulfilled in the Auda marsh during the dry season. Previously, in other Iraqi marshes, some areas suffered from low oxygen, with concentrations as low as 2.5 mg L^{-1} (mean through an entire year) being observed [14]. In most areas, however, the DO concentration exceeded the minimum value [14]. In the Auda marsh, the situation seemed to be worse than for Iraqi marshes in general, because the mean of all DO concentration measurements during the year was 5.6 mg L^{-1}.

Only slight spatial and temporal variations of BOD_5 were observed. BOD_5 varied between 1.8 mg/L in the dry season and 2.1 mg L^{-1} in the wet season for the three sampling sites. Relatively low BOD_5 values may be due to the absence of industrial activities and low human pollution because of the few villages surrounding the Auda marsh [24]. Moreover, Al-Mosewi [25] suggested that the spread of plants and low water velocity may have contributed to the decrease in the concentration of BOD_5. The BOD_5 results indicate that the Auda marsh is a relatively clean to moderately polluted marsh [26].

Nutrient concentrations varied remarkably, both temporally and spatially. The reactive silica concentration was 19.3 μg L^{-1} in the dry season whereas the highest value of the three sampling sites (41.2 μg L^{-1}) was observed in the wet season. Iraqi soil is generally rich in silica and it is not a limiting factor for the growth of algae [15]. SiO_3^{-2} concentration showed high temporal and spatial variation. The lowest values during the dry season may be linked to the uptake by diatoms that consume an extensive amount of reactive silicate in building their cell walls [27].

TP for the three sites ranged from 0.10 μg/L in the wet season to 0.17 in the dry season. TN was lowest (1.02 μg/L) in the dry season and highest (3.80 μg/L) in the wet season. Molar N:P ratios varied between the wet and dry seasons. This was because of the higher TP concentration during the dry than the wet season and, in contrast, the higher TN during the wet as opposed to the dry season. In similar marshes, both TP and TN concentrations increase in the dry summer season [26]. In the Auda marsh, the molar N:P ratio was 2.7 in the dry season. In the wet season, the ratio was 7, both values being lower than the Redfield N:P ratio [28] found for marine phytoplankton. Previously, the N:P ratio was 16.7 for a never-dried natural area of marsh in other Iraqi marshes [19]. In dried Iraqi marshes, the ratio seems to be mostly lower than the Redfield ratio [18,29,30]. This and previous results show highly variable N and P concentrations, and their ratio in Iraqi marshes indicating a remarkable release of nutrients to marshes.

CCA analysis indicated that primary productivity was related to BOD_5, turbidity, temperature, and Chl-*a* positively and to TN, silicate, and DO negatively (Figure 3). It seems that temperature was the most important physicochemical factor explaining primary productivity. Temperature is an essential factor that affects most biological activities such as metabolic activity, feeding, breeding, and respiration [31]. The appropriate temperature for phytoplankton growth is between 10 °C and 35 °C [32], meaning that temperature was not limiting productivity in general. Another variable describing phytoplankton biomass, Chl-*a* [33,34], seemed to be a good indicator. The loading of Chl-*a* in CCA (loading on the x-axis was 0.76) was high, in the same direction as temperature and the opposite direction to DO (Figure 3). DO is conversely related to temperature as shown by the CCA ordination and with a strong negative correlation (r = −0.82) (Table 3). CCA indicates that the nutrients TN, TP, or silica seemed not to explain primary productivity or Chl-*a* to a large extent. Primary productivity was weakly correlated to both TP and TN, as indicated by CCA ($r < 0.5$). This coincides with published data [35] from southern Iraqi marshes. In other Iraqi marshes, the relation of TP and Chl-*a* has been reported to be stronger than that for TN and Chl-*a* [36]. This also was the case for our results; Chl-*a* correlated with TP moderately well ($r = 0.5$), whereas the correlation with TN was weak ($r < 0.5$) (Table 3). As such, our interpretation is that temperature represents the most important controlling factor of phytoplankton in the Auda marsh. In contrast, nutrients were not limiting factors and thus of lower importance in explaining phytoplankton productivity. This is a remarkable observation from a climate change point of view.

The bio-optical modeling showed that primary productivity was higher in the dry season than the wet season, and highest (dark green areas) in the intermediate season (Figure 4). Flooded areas do not show productivity on the map because the NIR are absorbed by the deeper waters and they appear as white. A high level of surface productivity was observed, mainly in agricultural areas. The high level for the metric within this area is 0.457 at this date and it appears within the remaining shallow wetter areas of the marshland west of the S3 sampling location.

Similar to primary productivity, Chl-*a* showed higher values in the dry season than in the wet season (Figure 5). Chl-*a* metric (KIVU metric) shows the 6 January 2018 KIVA Chl-*a* metric (Figure 5A). Higher levels of Chl-*a* are found around wet or inundated areas as well as on productive agricultural lands. The Chl-*a* metric data for 17 July 2018 show higher levels in the S3 sampling site (Figure 5B). The bio-optical modeling figures altogether indicate that the Auda marsh was more productive during the dry season compared to the wet season, which supports field observations and other reports [37–39].

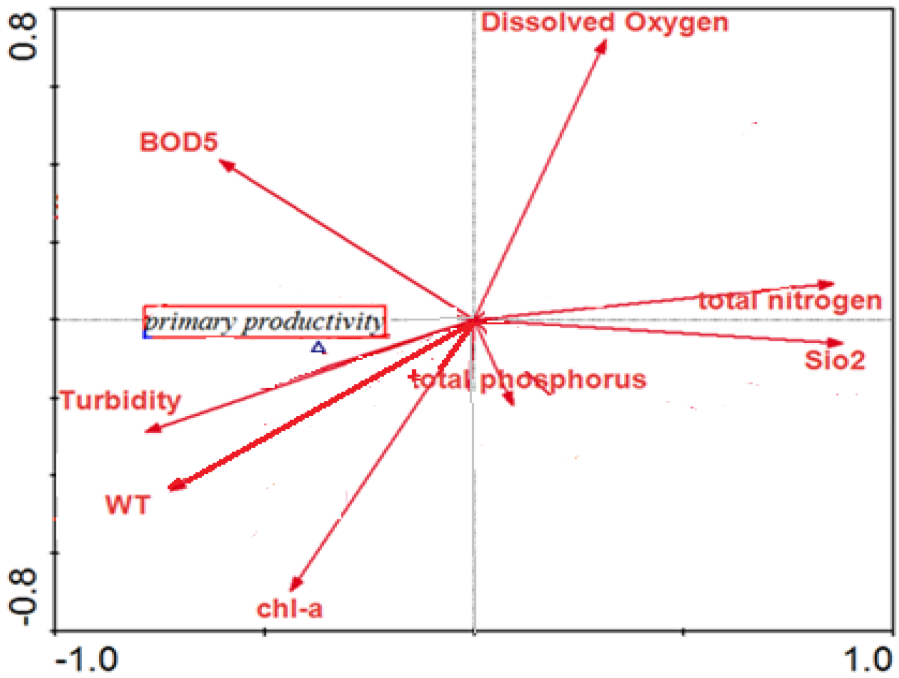
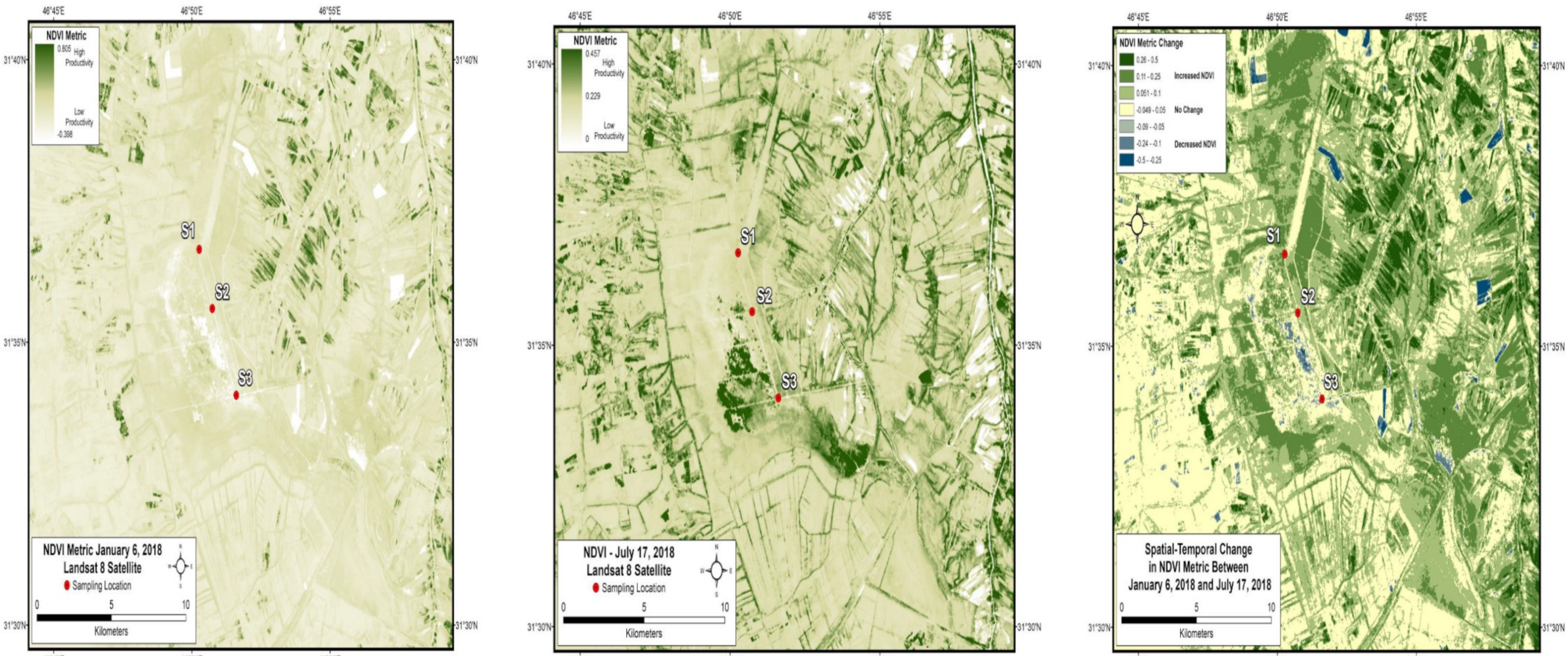


Figure 3. Canonical Corresponding Analysis (CCA) of the physico-chemical and biological variables measured or determined at the sampling sites in the Auda marsh (n = 39).

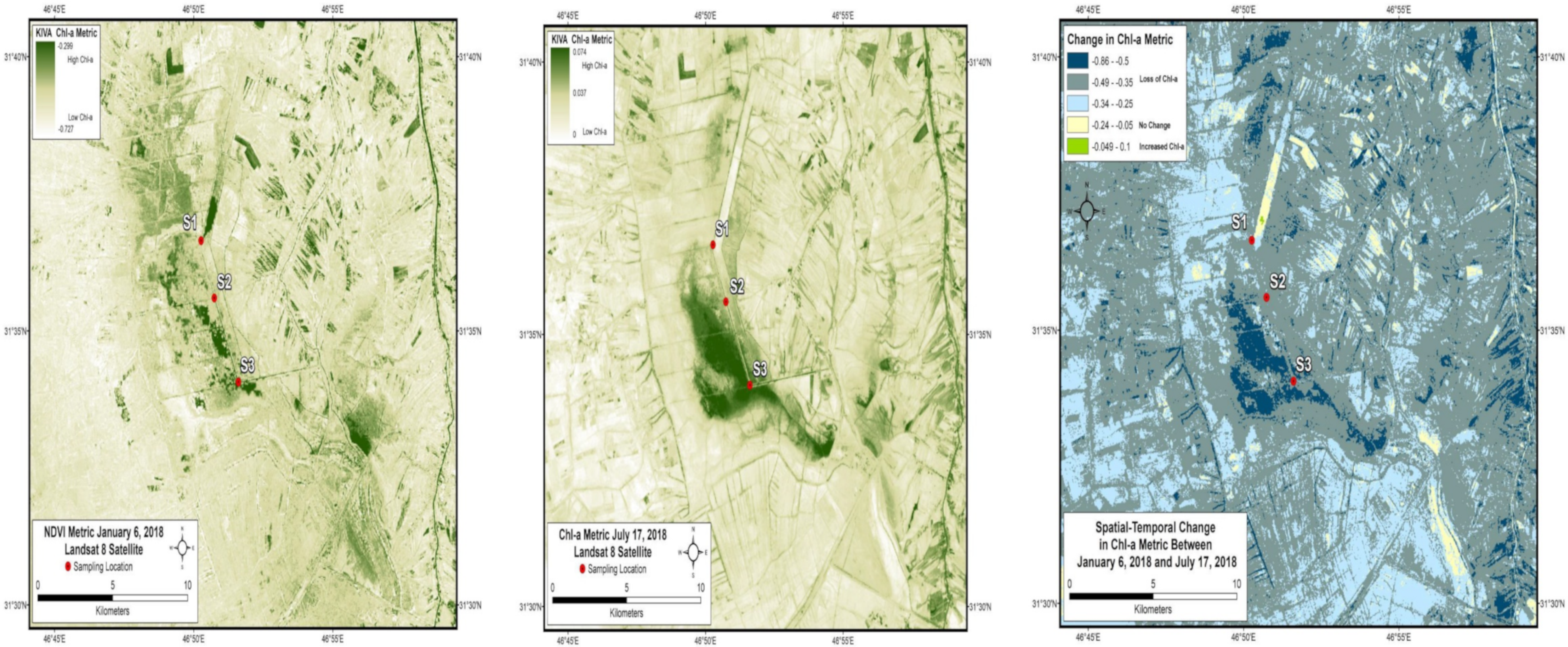
The seasonal variation of all variables except BOD_5 was high (Table 2, Figures 4 and 5) indicating that the season regulated the physicochemical and biological properties in the marshes. High phytoplankton biomass and productivity during the dry season can be explained by the low water table level and high residence time of water because the organisms making up the phytoplankton spend less time in the photic zone [40]. Other important factors influencing primary production are light and pH. In addition, biotic factors such as competition affect the competition dynamics of the phytoplankton community [41]. The high population density of organisms results in self-shading that declines photosynthesis capacity per unit population [42].

Raising temperature has been predicted to change the community composition and biomass of phytoplankton in different areas around the world. Changes in phytoplankton communities have been observed in different climates from cold to tropical [43–45]. The most important controlling factors are temperature and nutrients, as well as their complex interactions with other environmental variables such as increasing salinity and rising temperature [46]. In our study area in the Auda marsh, in a hot climate, temperature was the most important controlling factor of the phytoplankton community. However, the main driving factor may be the change in water regime due to temperature, as observed in a lake in China [47]. Water residence time was reported as the most important controlling factor of phytoplankton biomass in a California estuary and the Gulf of Mexico [13,40]. The effect of desiccation was observed previously in Iraqi marshes [19]. High temperature has been reported not only to change the community structure, but also to increase the biomass of phytoplankton in different ecosystems [48] and can be expected to also increase in the Auda marsh in the case of rising temperature.



(**A**) (**B**) (**C**)

Figure 4. Image of surface productivity metric (NDVI metric) for wet (**A**), dry (**B**), and intermediate (**C**) seasons.



(A) (B) (C)

Figure 5. Image of chlorophyll-a metric (KIVU metric) for wet (**A**), dry (**B**) and intermediate (**C**) seasons.

4. Conclusions

The phytoplankton community in the Auda marsh, which was classified as mesotrophic, was found to be greatly influenced by water temperature. Winter and summer, i.e., the wet and dry seasons, differed remarkably, and the temperature appeared to be the most important regulating factor of Chl-*a* concentration. Nutrients, in contrast, seemed not to be limiting factors and thus of lower importance in explaining phytoplankton productivity in the Auda marsh. Temperature regulates the hydrological regime, which has several consequences to the marsh ecosystem and its receiving water body, the Arabian Gulf. Therefore, considering the effects of global warming on marshes is a crucial issue.

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