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Abstract: In this study, weekly distributions of inorganic nutrients and phytoplankton cell volumes were investigated in relation to the hydrology of the Dardanelles. The data were collected between March 2001 and March 2002. NO^{-}_{2}+NO^{-}_{3}, PO_4^{-3}, and SiO_4 concentrations ranged between 0.050-6.887 µM, 0.051-1.152 µM, and 0.64-10.74 µM, respectively. During the study, the highest nutrient values were measured between late fall and mid-winter. Inorganic N:P and Si:P ratios in the surface water were lower due to high PO_4^{-3} concentrations. The chlorophyll a concentrations ranged from 0.03 to 8.67 µg L^{-1}. Phytoplankton cell density and cell volume ranged from 1.54E + 05 to 6.46E + 07 cell L^{-1} (mean 7.65E + 06; SD 1.44E + 07 cell L^{-1}) and from 2.51E + 09 to 8.66E + 10 μm^{-3} L^{-1} (mean 1.98E + 10; SD 1.86E + 10 μm^{-3} L^{-1}) between less productive and high productive periods. During the study period, 8-10 species controlled the phytoplankton community structure in the coastal zone of the Dardanelles. Others did not contribute to the phytoplankton population and they only can be considered as accessory species, which do not cause significant fluctuations in the phytoplankton production. Relationships between chlorophyll a, cell density, and cell volume of phytoplankton revealed that chlorophyll a is rather controlled by the cell density than by the cell volume. Furthermore, the physicochemical variables, such as nutrients and chlorophyll a and phytoplankton cell density and cell volume, are affected by the counter flows in the Dardanelles. Phytoplankton population was more limited by nitrogen than by phosphate due to extra phosphate inputs coming from various sources, such as domestic waste waters as well as the vertical mixing between upper and lower layers.

Key words: Turkish Straits System, Dardanelles, phytoplankton, chlorophyll a, nutrients

Çanakkale Boğazı (Türk Boğazlar Sistemi) yüzey sularında fitoplankton, besin tuzları ve klorofil a da meydana gelen zamansal değişimler: Haftalık zaman aralığında bir kıyısal istasyon örneği

Özet: Bu çalışmada, Mart 2001 ve Mart 2002 döneminde Çanakkale Boğazı'nda hidrolojik yapıya bağlı olarak inorganik besin tuzlarının ve fitoplankton hücre hacimlerinin haftalık dağılımları araştırılmıştır. NO^{-}_{2}+NO^{-}_{3}, PO_4^{-3} ve SiO_4 konsantrasyonları sırasıyla 0,050-6,887 µM, 0,051-1,152 µM ve 0,64-10,74 µM arasında değişim gösterdi. Çalışma süresince, en yüksek besin tuzu değerleri geç sonbahar ve orta kış dönemi arasındaki periyotlarda ölçülmüştür. Çanakkale Boğazı yüzey sularında, NO^{-}_{2}+NO^{-}_{3} ve SiO_4 düzeyleri yüksek olduğu halde inorganik N:P ve Si:P oranları daha yüksek PO_4^{-3} konsantrasyonları nedeniyle düşüktür. Klorofil a konsantrasyonları 0,03 ile 8,67 µg L^{-1} arasında değişim göstermiştir. Düşük üretim ve yüksek üretim dönemlerinde fitoplankton ve biyo-hacim sırasıyla 1,54E + 05 ile 6,46E + 07 hücre L^{-1} (ortalama 7,65E + 06; SD 1,44E + 07 hücre L^{-1}) ve 2,51E + 09 ile 8,66E + 10 μm^{-3} L^{-1} (ortalama 1,98E + 10; SD 1,86E + 10

μm^{-3} L^{-1}) arasında değişim göstermiştir. Örnekleme süresince, 8-10 tür Çanakkale Boğazındaki kıyısal zonun fitoplankton kommunite yapısını kontrol etmektedir. Diğerleri fitoplanktona önemli katkısı olmayan yardımcı türlerdir. Klorofil a, hücre yoğunluğu ve hücre biyohacim arasındaki ilişkiler klorofil a düzeyinin hücre hacminden daha ziyade hücre sayısı tarafından kontrol edildiğini göstermiştir. Bunun yanı sıra, besin tuzları, klorofil a ve fitoplankton gibi fizikokimyasal değişkenler Çanakkale Boğazındaki çift yönlü akıntı sisteminden etkilenmektedir. Üst ve alt tabaka sularında dikey yönde oluşan karışımdan kaynaklanan yüzey sularına gelen ilave fosfatın yanında özellikle evsel, tarımsal ve endüstriyel kaynaklardan gelen çok daha yüksek fosfat nedeniyle, fitoplankton gelişimi fosfattan daha çok azot tarafından kısıtlanmaktadır.

Anahtar sözcükler: Türk Boğazlar Sistemi, Çanakkale Boğazı, fitoplankton, klorofil a, besin tuzları

Introduction

Cultural eutrophication is often described as the over-enrichment of inland waters with inorganic nutrients, especially phosphorus and nitrogen, due to anthropogenic activities (1,2). Similarly, the causes and development of the eutrophication in the eastern Mediterranean and the Black Sea region is a result of rapidly expanding population, heavy urbanization, and industrial agriculture (3,4). Although the Mediterranean waters are naturally poor in nutrients, leaching of agricultural fertilizers and the discharge of urban or industrial waste water have been causing increases in the eutrophication processes since the 1960s (4,5). In the same way, agricultural, industrial, and urban pollution has been causing localized eutrophication in the Black Sea region, especially in the northwestern part, where a number of major rivers affected by these pollutants enter the sea (6,7). This area provides a unique platform to explore the nature of eutrophication processes because, in addition to the atmospheric inputs and anthropogenic discharges, physicochemical changes encountered in the Mediterranean and the Black Sea waters are controlled by the water exchanges through the Turkish Straits System (TSS) (6-13).

TSS, including the Sea of Marmara, the Dardanelles, and the Bosporus, is a water passage between the Mediterranean and the Black Sea regions (8, 14). The Sea of Marmara is a semi-enclosed basin with an 11,500 km^2 area and 3378 km^3 total volume (8). The Dardanelles is located between the Aegean Sea and the Sea of Marmara and has a 50 m mean depth, while the Bosporus is located between the Sea of Marmara and the Black Sea and has a 35 m mean depth (8,9,15).

The physicochemical dynamics in the TSS are affected by a distinctly different 2-layer flow regime. This causes seasonal and episodic inorganic nutrient and organic matter fluxes, such as phytoplankton as well as microorganisms to the adjacent seas (8,10,11,16). For instance, some of the biogenic organic matter in the Black Sea can be naturally exported to the Sea of Marmara basin and then reach the eastern Mediterranean especially north western part of the Aegean Sea via the Dardanelles (8,15,16). Additionally, as cited in many studies (8,17,18), much of the phosphorus and nitrogen in the Black Sea surface outflow is utilized by microorganisms and lost before reaching the Dardanelles. On the other hand, the salty, nutrient deficient Mediterranean waters become enriched by 5-9 folds during its passage through the Sea of Marmara before reaching the Black Sea. Due to surface counter flow and vertical mixing, almost 50% of this nutrient enriched inflow of salty water return back to the Aegean basin while the rest reaches the Black Sea (8). In addition to these flow-nutrient interactions, a baseline data set, obtained at the exits of the Bosporus and Dardanelles from 1980 through 2000, allowed us to understand the seasonal variations in the nutrient properties of the counter flows in the TSS (16). In this system, net primary production is limited by nitrogen and is highest in regions of high nutrient availability, such as the continental shelf and upwelling areas (11, 19-24).

The peaks of phytoplankton in the TSS normally are known to occur 3 times during a year. Although dinoflagellates bloom throughout the year, diatoms mainly bloom in late winter-early spring and in late July-early August and coccolithophores bloom in late spring and early summer (10,19,25,26). This is similar to the pattern observed in the Black Sea (27,28-32). However, additional summer blooms with a predominance of dinoflagellates and coccolithophores have been increasing in recent years as a result of eutrophication in the TSS (10,11,19-21,25,26,33).

In the present study, we explored weekly distributions of phytoplankton, chlorophyll a and inorganic nutrient concentrations in relation to the other environmental parameters, such as temperature, salinity, pH as well as dissolved oxygen of the Dardanelles from March 2001 through March 2002. We also tried to explain the relationship between eutrophication and phytoplankton cell densities during the year. This study can be considered unique since it contains the first short time series data about the nutrient, chlorophyll a, and phytoplankton interactions with respect to environmental parameters in weekly time intervals in a coastal station sample of the Dardanelles. Although the data set is of coastal surface waters, it will suffice to understand the short time variations and interactions in biological and physicochemical properties of 2 counter flows in the Dardanelles, because the sampling station is a mixing area.

Materials and methods

Sampling period and area

In this study, phytoplankton and chlorophyll a, nutrient and other environmental data, such as temperature and salinity (CTD probe data), were collected in the surface water of a coastal station in the Dardanelles (40°09′05″N latitude and 26°23′36″E longitude) (Figure 1). Sampling period was from March 2001 through March 2002. The surface samples were collected in weekly time intervals during the sampling period. Fifty-six surface (0.5 m) samples for nutrient, chlorophyll a and phytoplankton were collected in the sampling period.

Collection, preservation and measurement of samples

Probe (CTD data) measurements

Temperature (T), salinity (S), pH, and dissolved oxygen (DO) were measured in surface water (0.5m).

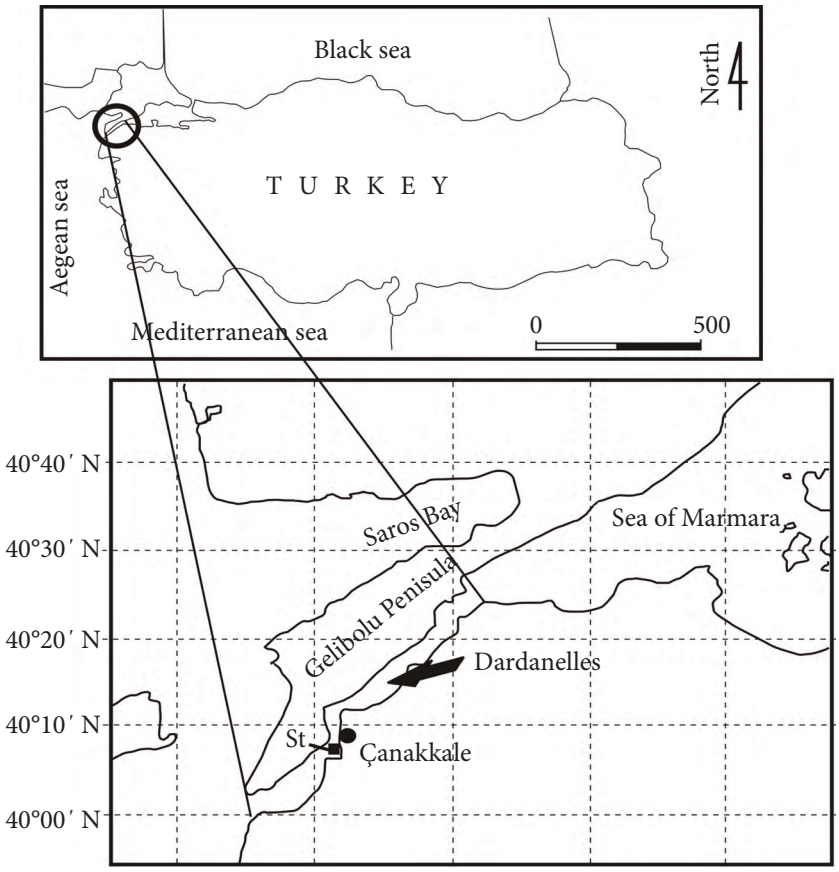

Figure 1. The Dardanelles and the location of coastal sampling station.

Water quality parameters were measured in situ using a YSI 556 Model Multiple Water Analysis Probe. Nutrient, chlorophyll-a, and phytoplankton samples were collected from the surface with a Hydro-Bios Universal Series Water Sampler (HBUSWS) (5 L).

Nutrient measurements

Nutrient samples collected from the surface with a HBUSWS were transferred to 100 mL polyethylene bottles and kept frozen until analysis. Nutrient analyses including nitrate (NO^-_3), nitrite (NO^-_2), soluble reactive phosphorus (PO^{-3}_4), and silicate (SiO_4) were conducted using a Technicon model 2-channel auto-analyzer according to Strickland & Parsons (34).

Chlorophyll a measurements

Samples for chlorophyll a determination had been collected immediately after the water samples were collected by HBUSWS. The samples were filtered through GF/F glass fiber filters. Chlorophyll a concentration was analyzed spectrophotometrically after extraction by 90% acetone (34). Filters that were used for filtration of surface water were wrapped in aluminum foil and kept frozen until analysis.

Phytoplankton cell density and bio-volume measurements

Phytoplankton samples were preserved with acidic Lugol 2%-4% v/v and kept at 2-4 °C pending microscopic analysis. For phytoplankton census, Uterhmöhl Sedimentation Chambers, Neubauer and Sedgwick-Rafter counting slides were used in combination according to the dimensions of the organisms (35-37). Phase-contrast microscopy was used for the taxonomic description of phytoplankton species (38,39). Depending on the density, sample volumes of 2-8 mL were used. At least 20 random fields of view were counted at 1000×, 400×, and 200× magnifications for different cell-size classes of phytoplankton. This resulted in at least 400 individuals counted of each dominant phytoplankton species, and a ±10% counting precision within 95% confidence limit (40). Phytoplankton cell volume and phytoplankton species diversity index values were calculated using geometric models improved by Sun & Liu (41) and Biodiversity Pro/BD2.bdp designed and developed by McAleece et al. (42), respectively. Papers used for phytoplankton species identification were Tregouboff and Rose (43), Cupp (44), Sournia (45), Ricard (46), Delgado and Fortuna (47).

Evaluation of statistical analysis

Bray-Curtis cluster analysis, Simpson's diversity index, descriptive statistics, and Pearson correlations were conducted using Biodiversity Professional Version 2 for Windows (48). Pearson correlations are significant (P) at 0.05 and 0.01 levels (2-tailed).

Results

CTD data

Temporal variations of some physicochemical variables, such as temperature, salinity, pH as well as dissolved oxygen in the surface water of the coastal area in the Dardanelles, were obtained at weekly intervals (Figure 2). Simple descriptive statistical results and correlation relationships between bio-physicochemical data groups are displayed in Tables 1 and 2, respectively.

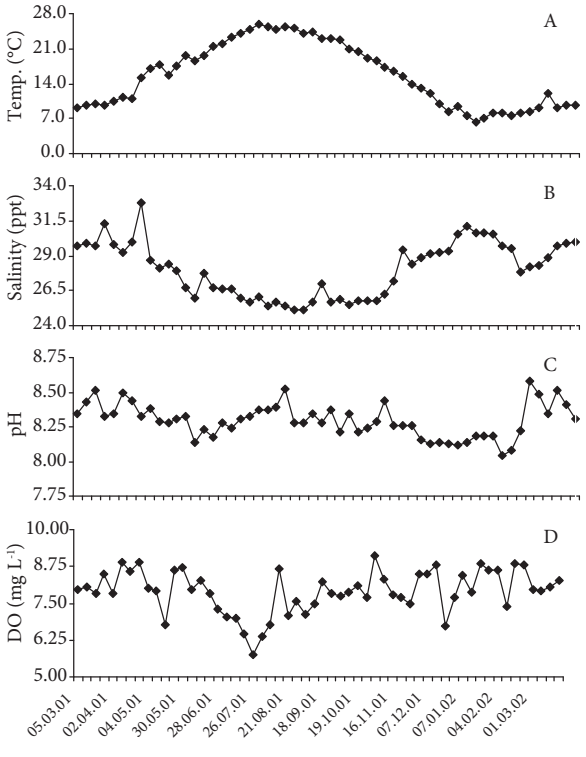

Figure 2. Temporal variations of temperature (A), salinity (B), pH (C) and dissolved oxygen (DO) (D) in the coastal surface water of the Dardanelles in the period of March 2001 and March 2002.

Table 1. Descriptive statistics of biological and physicochemical parameters in coastal surface waters of the Dardanelles in the period of March 2001 and March 2002.

	N	Minimum	Maximum	Mean	Std. Dev.
Temperature (°C)	55	6.35	26.0	15.7	6.40
Salinity (ppt)	55	25.1	32.8	28.0	1.98
PH	55	8.04	8.58	8.29	0.12
DO (mg L^{-1})	55	6.75	10.1	8.93	0.75
NO^-_2+NO^-_3 (µM)	55	0.05	6.89	0.75	1.43
PO^{-3}_4 (µM)	55	0.06	1.15	0.34	0.27
SiO_4 (µM)	55	0.64	10.7	3.02	1.63
N:P	55	0.25	41.7	2.19	5.50
Si:P	55	2.59	57.3		
Chlorophyll a (µg L^{-1})	55	0.03	8.67	1.11	1.33
Dinoflagellates (Cell L^{-1})	55	2.20E+04	2.79E+06	4.06E+05	5.35E+05
Diatoms (Cell L^{-1})	55	6.60E+04	6.45E+07	6.77E+06	1.35E+07
Other Taxonomic Groups (Cell L^{-1})	55	0.00E+00	1.54E+07	4.78E+05	2.17E+06
Total Phytoplankton (Cell L^{-1})	55	1.54E+05	6.46E+07	7.65E+06	1.44E+07
Dinoflagellates (µm^3 L^{-1})	55	1.5E+08	3.79E+10	7.22E+09	8.09E+09
Diatoms (µm^3 L^{-1})	55	4.79E+08	8.57E+10	1.25E+10	1.65E+10
Other Taxonomic Groups (µm^3 L^{-1})	55	0.00E+00	4.94E+08	4.96E+07	1.12E+08
Total Phytoplankton (µm^3 L^{-1})	55	2.51E+09	8.66E+10	1.98E+10	1.86E+10
Simpson's Diversity	55	0.09	1.00	0.35	0.24

Temperature and salinity

Temperature and salinity varied in the system within a range from 6.35 to 26.0 °C (mean 15.7±6.40 °C) and from 25.1 to 32.8 ppt (mean 28.0 ± 1.98 ppt), respectively. Although the cause of the annual temperature variation in the surface water was due to atmospheric changes rather than changes between surface and deep waters due to vertical mixing, the cause of annual surface salinity variations and of some large deviations during study period was vertical mixing between 2 layers with different temperature and salinity values (Figure 2). Furthermore, due to the effect of salty Mediterranean deep waters in the lower layer on the brackish Black Sea surface waters in the upper layer of the Dardanelles, especially in periods of strong wind from the southwest (southwester), salinity values of spring, autumn, and winter were generally higher (30.0-32.0 ppt) than the summer salinity values (24.0-26.0 ppt) in the Dardanelles (Table 1 and Figure 2). This is supported by negative correlation (r = -0.858) between temperature and salinity data groups measured during the study period (Table 2).

pH

Although the temporal cycle of pH (min-max: 8.04-8.58; mean: 8.29 ± 0.12) showed fluctuations throughout the year (Table 1 and Figure 1), winter and summer values were lower (<8.25) than the spring and fall values (>8.25) (Figure 2).

Table 2. Pearson correlations between biological and physicochemical data groups in coastal surface waters of the Dardanelles in the period of March 2001 and March 2002 (N: 55; P value significant 2-tailed; (**): Correlation is significant at the 0.01 level; (*): Correlation is significant at the 0.05 level).

	Temp.	Salin.	pH	DO	NO^-_2+ NO^-_3	PO^{-3}_4	SiO_4	Chl-a	Phyto-Den.	Phyto-Vol.
Temp.	1									
p	.									
Salin.	-0.858(**)	1								
p	0.000	.								
pH	0.139	-0.127	1							
	0.313	0.354	.							
DO	-0.504(**)	0.415(**)	0.083	1						
p	0.000	0.002	0.545	.						
NO^-_2+ NO^-_3	-0.277(*)	0.283(*)	-0.333(*)	-0.007	1					
p	0.040	0.036	0.013	0.958	.					
PO^{-3}_4	-0.303(*)	0.233	-0.238	-0.024	0.382(**)	1				
p	0.024	0.087	0.080	0.862	0.004	.				
SiO_4	0.051	-0.010	-0.118	-0.338(*)	0.276(*)	0.535(**)	1			
p	0.714	0.944	0.391	0.011	0.041	0.000	.			
Chl-a	0.169	-0.155	-0.116	-0.317(*)	0.103	0.067	0.005	1		
p	0.216	0.258	0.399	0.019	0.454	0.627	0.972	.		
Phyto-Den.	0.184	-0.099	-0.007	-0.325(*)	-0.069	0.063	0.113	0.709(**)	1	
p	0.179	0.471	0.961	0.015	0.618	0.647	0.411	0.000	.	
Phyto-Vol.	0.123	0.068	0.152	-0.002	-0.115	-0.040	-0.015	0.398(**)	0.599(**)	1
p	0.370	0.621	0.269	0.990	0.405	0.772	0.912	0.003	0.000	.

Dissolved oxygen (DO)

Dissolved oxygen (DO) concentrations in the coastal station of the Dardanelles varied from 6.75 to 10.1 mg L^{-1} (mean 8.93 ± 0.75 mg L^{-1}) during the study period, being higher in spring and winter compared to summer (Table1 and Figure 2). Oxygen enters the water by the transfer of oxygen across the air-water interface as well as photosynthesis of aquatic biota, such as phytoplankton and benthic algae. However, the levels of DO in the aquatic systems also depend on the water temperature and salinity. While DO concentration levels are correlated with temperature as negative (r = -0.504), they are correlated with salinity as positive (r = 0.415). Furthermore, correlations between DO with chlorophyll a (r = -0.317) and phytoplankton (r = -0.325) were significant at the 0.05 level (Table 2).

Nutrient data

Temporal profiles of inorganic NO^-_2+NO^-_3, PO^{-3}_4, SiO_4, and ratios of N:P and Si:P in the coastal surface water of the Dardanelles were obtained at weekly intervals (Figure 3). Simple descriptive statistical results and correlation relationships between bio-physicochemical data groups are displayed in Tables 1 and 2, respectively.

Nitrite+nitrate (NO^-_2+NO^-_3)

NO^-_2+NO^-_3 concentrations were higher (min-max: 0.05-6.89 μM, mean: 0.75 ± 1.43 μM) (Table 1) than previously recorded values (mean: 0.50 μM) (8). As

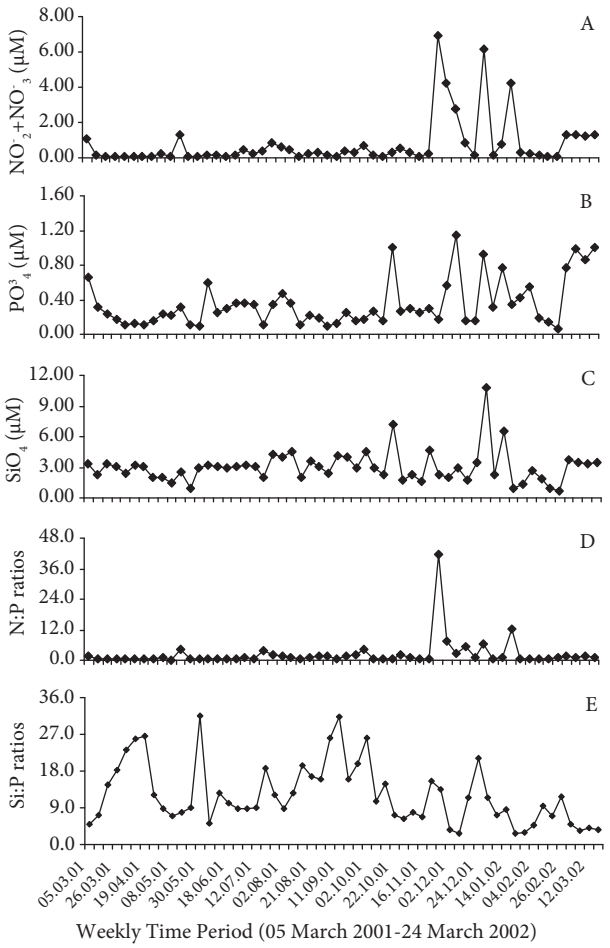

Figure 3. Temporal variations of $NO^-_2+NO^-_3$ (A), PO^{-3}_4 (B), SiO_4 (C), N:P (D) and Si:P (E) ratios in the coastal surface water of the Dardanelles in the period of March 2001 and March 2002.

displayed in Figure 3, $NO^-_2+NO^-_3$ concentration had 3 peaks in late November (6.89 µM), early (6.17 µM) and late January (4.25 µM). If these peak values in $NO^-_2+NO^-_3$ concentrations in the period of late November to late January are ignored, $NO^-_2+NO^-_3$ values varied between 0.05 and 1.34 µM. In addition to the peak values in late November and late January, some periods, such as 05 March 2001, 16 May 2001 and full period of March 2002 contain high $NO^-_2+NO^-_3$ values (1.04-1.34 µM) (Figure 3).

Phosphate (PO^{-3}_4)

Similar to $NO^-_2+NO^-_3$ concentrations, PO^{-3}_4 concentrations (min-max: 0.06-1.15 µM, mean: 0.34±0.27 µM) (Table 1 and Figure 3) were higher than previously measured values (0.02-0.5 µM) (8,9). Although phosphate showed more irregular fluctuation in relation with $NO^-_2+NO^-_3$, temporal profile of the PO^{-3}_4 was roughly similar to $NO^-_2+NO^-_3$ profile (Figure 3). It is supported by the correlation, which is significant at the 0.01 level, between PO^{-3}_4 and $NO^-_2+NO^-_3$ (r = 0.386).

That the positive relationship of PO^{-3}_4 with silicate (r = 0.535) is more important than its relationship with $NO^-_2+NO^-_3$ (r = 0.382) showed that phosphate and silicate were more affected by domestic and terrestrial sources than by lower layer waters in the coastal waters of the Dardanelles. However, the negative relationship of $NO^-_2+NO^-_3$ (r = -0.277) and PO^{-3}_4 (r = -0.303) with temperature revealed that they were higher in winter than summer. It was supported by nutrient values in the system during the study period.

Silicate (SiO_4)

Similar to $NO^-_2+NO^-_3$ concentrations, SiO_4 concentrations (Figure 3) were also higher than previously measured values (8,9). Like other nutrients, SiO_4 concentrations showed high variations and ranged between 0.64 and 10.7 µM (mean: 3.02 ± 1.63 µM) during the sampling period (Table 1). Similar to $NO^-_2+NO^-_3$ concentration, SiO_4 had 3 peaks throughout the year (Figure 3). Temporal profile of the SiO_4 was more similar to PO^{-3}_4 profile than $NO^-_2+NO^-_3$ profile (Figure 3). This was supported by the correlation, which is significant at the 0.01 level, between SiO_4 and PO^{-3}_4 (r = 0.535).

N:P and Si:P ratios

N:P (min-max: 0.25-41.7, mean: 2.19 ± 5.50) and Si:P ratios (min-max: 2.59-57.3, mean: 13.0 ± 9.29) without ammonia added as a nitrogen source in the coastal surface water of the Dardanelles were significantly lower than the assimilatory optimal of the Redfield ratios (Table 1 and Fig. 3).

Phytoplankton data

Temporal profiles of phytoplankton chlorophyll a, phytoplankton cell density, phytoplankton cell volume, and Simpson's diversity index in the coastal surface water of the Dardanelles were obtained at weekly time intervals (Figure 4). Simple descriptive statistical results, correlation relationships between

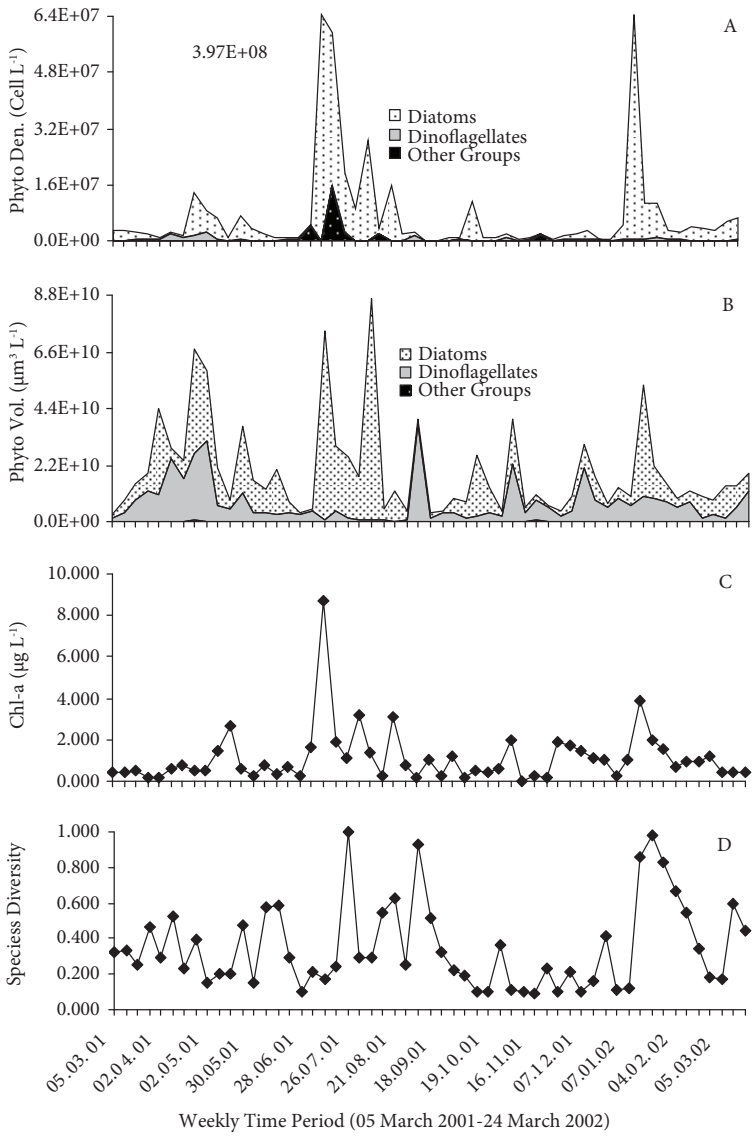

Figure 4. Temporal variations of phytoplankton cell density (A) and cell volume (B), chlorophyll-a (C) and Simpson diversity index (D) in the coastal surface water of the Dardanelles in the period of March 2001 and March 2002.

biological data groups are displayed in Tables 1 and 2, respectively. Furthermore, contributions of different taxonomic groups to the total phytoplankton population and contributions of different species to related taxonomic groups are displayed in Table 3.

Phytoplankton chlorophyll a

The spatial distribution of phytoplankton chlorophyll a in the surface waters of the Dardanelles is shown in Figure 3. The chlorophyll a concentrations ranged from 0.056 to 2.670 µg L^{-1} in spring, from 0.29 to 8.67 µg L^{-1} in summer, from 0.03 to 1.98 µg L^{-1} in autumn, and from 0.290 to 3.883 µg L^{-1} in winter. Results indicated that the relationship between chlorophyll a and cell density (r = 0.709) was more important than the relationship between chlorophyll a and bio-volume (r = 0.398). This relationship revealed that chlorophyll a is rather controlled by phytoplankton cell density than by phytoplankton bio-volume.

Table 3. Contributions of different taxonomic groups to total phytoplankton cell volume and of different species to related taxonomic groups in coastal surface waters of the Dardanelles in the period of March 2001 and March 2002.

Date M/Y	**Dinoflag. (%)**	**Important dinoflagellate species and their contribution to dinoflagellates**	**Diatoms (%)**	**Important diatom species and their contribution to diatoms**	**Other taxon. groups (%)**	**Important species of other taxonomic groups and their contribution to the other taxonomic groups**
Mar. 2001	55.62	*P.micans* (30.3%), *D.rudgei* (18.7%)	42.94	*Licmophora* spp. (20.4%), P.calcar-avis (%13.5)	1.44	*Octactis octonoria* (1.44%)
April 2001	23.5-71.1	*P.micans* (18.1-44.5%), *D.lenticula* (0-11.9%)	28.9-76.5	*Leptocylindrus* spp. (3.38-57.6%), *Licmophora* spp. (0.63-33.8%), *P.calcar-avis* (0-18.9%), *P.alata* (0-15.6%)	0 – 0	
May 2001	96.7-97.9	*N.scintillans* (93.3-97.1%) *P.micans* (0.25-0.60%)	2.10-2.40	*Leptocylindrus* spp. (0-1.21%), *R.setigera* (0-1.16%), *P.alata* (0.15-0.67%)	0 - 0	
June 2001	26.0-47.7	*Ceratium* spp. (4.91-13.5 %), *P.micans* (11.5-36.5%)	52.7-74.4	*R.setigera* (0-45.7%), *Thalassiosira* spp. (0-11.7%), *Licmophora* (0-16.8%), *Coscinodiscus* (0-26.9%)	0 – 0	
July 2001	14.4-89.2	*Gonyaulax* spp. (1.68-12.7%), *P.micans* (4.60-60.7%), *P.minimum* (3.18-10.8%), *Ceratium* spp. (0-4.50%)	9.59-84.9	*P.pungens* (0-33.4%), *P.calcar-avis* (0-11.8%), *Licmophora* spp. (2.08-11.0%), *Chaetoceros* spp. (2.92-10.6%), *R.alata* (0-4.21%)	0.74-1.18	Coccoid cyanobacteria (0.74-1.18%)
Aug. 2001	3.31-13.5	*Ceratium* spp. (8.59-8.66%), *G.marina* (0-8.59%), *Prorocentrum* spp. (0-2.58%), *S.trochoidea* (0-4.81%)	85.9-96.7	*Climacosphenia* spp. (0-19.0%), *Leptocylindrus* spp. (3.94-18.4%), *Licmophora* spp. (10.6-35.2%), *P.calcar-avis* (0-42.9%), *S.delicatula* (0-19.0%), *Thalassiosira* spp. (2.07-33.9%)	0-0.59	Coccoid cyanobacteria (0-0.59%)
Sept. 2001	34.1-44.0	*Ceratium* spp. (4.13-44.0%), *P.lima* (0-10.5%), *P.divergens* (0-19.4%)	56.0-65.9	*H.hauckii* (0-9.91%), *S.unipunctata* (0-12.6%), *Thalassiosira* spp. (31.3-55.3%)	0 – 0	
Oct. 2001	7.87-54.0	*P.lima* (0-6.40%), *Ceratium* spp. (1.47-540%)	41.6-92.1	*H.hauckii* (0-11.2%), *Pleurosigma* spp. (0-6.75%), *D.fragilissimus* (0-8.10%), *Thalassiosira* spp. (0-81.5%)	0-4.34	*D.fibula var.messanensis* (0-4.34%)
Nov. 2001	52.3-83.9	*P.micans* (0-3.41%), *Ceratium* spp. (8.32-67.0%), *D.rotundata* (0-21.8%), *P.divergens* (0-35.7%)	15.7-44.4	*R.delicatula* (0-7.33%), *D.fragilissimus* (0-17.1%), *Thalassiosira* spp. (7.49-23.2%)	0.33-3.30	*D.fibula var. messanensis* (0-3.30%), *Coccoid cyanobacteria* (0-0.33%)
Dec. 2001	86.4-96.3	*Prorocentrum* spp. (0-22.3%), *Ceratium* spp. (2.39-64.8%), *Dinophysis* spp. (0-25.7%), *N.scintillans* (0-88.4%)	3.68-13.6	*Licmophora* spp. (0-1.59%), *P.pungens* (0-0.86%), *Rhizosolenia* spp. (0-2.76%), *S.unipunctata* (0-0.78%), *Thalassiosira* spp. (1.64-7.38%)	0 – 0	
Jan. 2002	63.8-97.5	*P.micans* (1.05-27.2%), *P.horologium* (0-19.4%), *Ceratium* spp. (0-8.73%), *N.scintillans* (0-95.8%)	2.52-36.2	*P.pungens* (1.00-35.6%)	0 – 0	
Feb. 2002	62.3-90.1	*N.scintillans* (0-88.1%), *P.micans* (0.54-62.3%)	9.92-37.7	*Chaetoceros* spp. (1.88-3.52%), *Coscinodiscus* spp. (0-16.3%), *P.pungens* (0.59-13.9%), D.*fragilissimus* (0-4.69%)	0 – 0	
Mar. 2002	8.40	*P.micans* (2.08%), *P.scutellum* (6.32%)91.6		*Licmophora* spp. (72.4), *Thalassiosira* spp. (13.8%)	0 – 0	

Phytoplankton cell density

Phytoplankton cell density ranged from 1.54E + 05 to 6.46E + 07 (Mean: 7.65E + 06 cell L^{-1}; SD: 1.44E + 07 cell L^{-1}) cell L^{-1} during the study period. Weekly temporal profiles of phytoplankton cell density in the coastal surface water of the Dardanelles showed that there were 3 important phytoplankton production periods in terms of cell numbers. Of these periods, the most important one is the period of early July to late August. Of the extensive phytoplankton blooms in this period, *Pseudo-nitzschia pungens* (Grunow ex P.T. Cleve) Hasle, 1993, *Pseudo-nitzschia delicatissima* (P.T. Cleve) Heiden in Heiden & Kolbe, 1928, *Climacosphenia* spp., *Chaetoceros* spp. Ehrenberg, 1844, *Cylindrotheca closterium* (Ehrenberg) Reiman and Lewin, 1964, *Licmophora abbreviata* C.A. Agardh, 1831, *Dactyliosolen fragilissimus* (Bergon) G. R. Hasle, 1991, *Skeletonema costatum* (Greville) P.T. Cleve, 1878 were responsible for extensive diatom blooms. It is known that this period is especially a high Bacillariophyceae (diatom) production period in the Dardanelles (10,11,20,22-24). Second important period for phytoplankton cell density has become mid-winter period (January). *P. pungens* was the responsible species for this winter peak. Third important period was spring, especially April and May period. Diatoms *Thalassionema frauenfeldii* (Grunow) Hallegraeff, 1986, *P. pungens*, *Proboscia alata* (Brightwell) Sundström, 1986, *Rhizosolenia setigera* Brightwell, 1858, *Leptocylindrus danicus* P.T. Cleve, 1889, *L. abbreviata* were the responsible species for this period. Moreover, there is another important production period in October because of the diatom *Thalassiosira* spp. P.T. Cleve, 1873 emend. Hasle, 1973. In addition to high diatom production in terms of cell numbers during the study period, the period of July and August is also an important production period for coccoid forms of blue green algae.

Bray-Curtis cluster analysis results of different taxonomic groups of phytoplankton showed that diatom density was more similar (93.9) to the total phytoplankton density in the coastal surface water of the Dardanelles in study period (Figure 5). However, similarity between diatom and total phytoplankton cell volume was lower (77.5) than this similarity. Moreover, although similarity between dinoflagellates and total phytoplankton cell volume was higher (53.4) than the similarity between their cell densities (10.1). On the other hand, similarities of other taxonomic groups to the total phytoplankton in terms of their cell densities (11.8) and cell volumes (0.5) were lower than those of major taxonomic groups, such as diatoms and dinoflagellates (Figure 5).

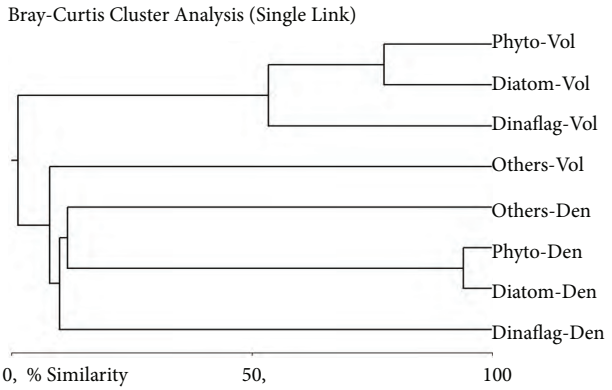

Fig. 5. Bray-Curtis cluster analysis results of different taxonomic groups of phytoplankton in the coastal surface water of the Dardanelles in the period of March 2001 and March 2002.

Phytoplankton cell volume

Although there were dramatic changes due to various algal blooms during the study period, phytoplankton cell volumes showed that the biomass was higher in spring, late summer-early fall and winter periods than any other period. Phytoplankton cell volume ranged from 2.51E + 09 in early March to 8.66E + 10 μm^{-3} L^{-1} in early August (mean: 1.98E + 10 μm^{-3} L^{-1}, SD: 1.86E + 10 μm^{-3} L^{-1}) during the study period. The phytoplankton cell volume peaks in early July and early August were due to *Pseudo-nitzchia* spp., *Climacosphenia* spp., and *D. fragilissimus* blooms (Figure 4). In these periods, the contributions of these species to the total cell volume were about 90%. The results showed that the contribution of diatoms was higher than that of Dinophyceae (dinoflagellates) species and the other groups in late summer-early fall and winter. On the other hand, the contribution of the dinoflagellates to the total cell volume was higher than that of the diatoms in April (Figure 4). In contrast to April, the contribution of diatoms was higher than dinoflagellates in May (Fig. 4). Additionally, algal

successions revealed that the major contributing species to the total cell volume were *Prorocentrum* spp., such as *Prorocentrum micans* Ehrenberg, 1834 and *Prorocentrum compressum* (Bailey, 1850) Abé ex Dodge, 1975, and *Ceratium* spp., such as *Ceratium furca* (Ehrenberg, 1834) Claparède et Lachmann, 1859 and *Ceratium fusus* (Ehrenberg, 1834) Dujardin, 1841 among dinoflagellates, *P. alata*, *Pseudonitzschia* spp., *Pseudosolenia calcar-avis* (Schultze) Sundström, 1986, *Rhizosolenia* spp., and *Climacosphenia* spp., *Leptocylindrus* spp. among the diatoms.

Species stated above were also responsible for algal blooms in different times during the sampling period. In terms of both cell density and bio-volume, although diatoms showed some algal blooms in some periods, such as in spring, summer and winter, dinoflagellates showed more regular and stabile fluctuations in the sampling period especially in bio-volume profile (Figure 4). Phytoplankton community structure was observed to be controlled by these species in the Dardanelles, as was revealed in the Black Sea ecosystem (28,30-32). Other species can be considered as accessory species that do not cause significant fluctuations in the phytoplankton density and bio-volume.

The weekly changes in the diversity indices are shown in Figure 4. The Simpson's diversity index varied from 0.091 to 0.997 (Figure 4). These indices were lower in early November and mid-January when compared to other periods. The indices below 0.200 bits indicated that there were excessive algal blooms of a few species in some periods (Figure 4).

Discussion

This short time series data may allow us to understand the effects of short time variations in the biological and physicochemical conditions on the eutrophication in the coastal waters of the Dardanelles.

Due to large salinity differences between the Aegean and the Black Sea, it is likely to observe intense vertical mixing of the counter-flows in the strait, especially near southern exits, which include the coastal study area (12,13). This way, before reaching the Aegean basin, the salinity of the Dardanelles surface flow increases by at least 4-8 ppt. The Dardanelles surface water was more saline in spring and winter compared to the other seasons.

During the study period, winter and summer pH values were lower (<8.25) than the spring and fall values (>8.25) (Figure 2). It is known that hydrogen atoms are consumed more in high phytoplankton production periods in spring and autumn compared to the low phytoplankton production period in winter and summer. Moreover, the freshwater influx causes higher productivity levels, which yields the formation of more basic or not acidic waters in that area. Besides, respiration and the breakdown of organic matter cause lower pH values in low production period in the system (11-13,22-24). Formation of the positive and negative correlations between DO and other bio-physicochemical parameters, such as salinity, chlorophyll a, and phytoplankton is due to the vertical mixing between lower and upper layer waters in the Dardanelles. It is supported by high surface salinity values in the coastal study area of the Dardanelles (Figure 2). It is known that while upper layer waters have low salinity values (24.0-25.0 ppt), lower layer waters have high salinity values (38.0-39.0 ppt) due to 2 different flow systems (8, 10-13,16).

In addition to the temporal variations in the nutrient concentrations, especially the southern part of the Dardanelles receives notable nutrient inputs due to domestic wastes from the city of Çanakkale (11,22-24,49). Therefore, in some periods of this study, extra accumulation of inorganic nutrients, especially phosphate was highly pronounced. Additionally, the observed maximum values in different periods were principally due to entrainment of the inorganic nutrient-enriched salty Mediterranean waters from the lower layer by intense vertical mixing with the western basin surface layer. In fact, it has been shown that nutrient concentrations encountered in the Mediterranean waters are controlled by the exchanges at the straits, the atmospheric inputs, and land based discharges (14). For example, in contrast to nitrogen, the phosphate present in some coastal waters of the Mediterranean are primarily discharged from land based sources (50,51). On the other hand, during its passage through the Dardanelles, the Black Sea surface outflow loses much of its phosphorus and nitrogen via utilization and vertical loss (8). Additionally, the salty Mediterranean inflow to the Marmara deep basin via

the Dardanelles contains low nutrient concentrations (8). However, the salty deep-waters, before reaching the Black Sea via the Bosporus, are highly enriched with inorganic nutrients in the Marmara basin by the input of external and internal sources (8,15,16). According to the estimations proposed by Polat & Tugrul (8), every year the salty Mediterranean inflow introduces about 0.19×10^4 t of phosphate, 0.31×10^4 t of nitrogen, and 0.41×10^6 t of organic carbon to the Marmara Sea via the Dardanelles. Although nearly 50% of the nutrient-enriched inflow of salty water is returned back to the Aegean basin by the surface counter flow as a result of vertical mixing, the remaining flow reaches the Black Sea with an increased nutrient load – annually 0.90×10^4 t of organic carbon and 0.51×10^4 t of nitrogen.

Relationships of NO^-_2+NO^-_3 with PO^{-3}_4 (r = 0.382) and salinity (r = 0.283) are more important than relationship with SiO_4 (r = 0.276). This correlation revealed that silicate will be affected by lower layer waters less than any other source. It is supported by a more insignificant correlation between SiO_4 and salinity (r = -0.010). Furthermore, negative relationship of NO^-_2+NO^-_3 with pH (r = -0,333) showed that NO^-_2+NO^-_3 is consumed by phytoplankton. Relationship between phytoplankton bio-volume and pH (r = 0.352) has supported this statement. It is known that pH values in aquatic systems are higher in high phytoplankton production periods than in low phytoplankton production periods (11,12,25,26).

Low N:P and Si:P ratios showed that phytoplankton is more limited by nitrogen than phosphate and silicate due to extra phosphate inputs coming from various sources, such as domestic waste waters as well as vertical mixing between upper and lower layer (8,10,11,16,19,22-24). However, N:P ratios in this study for the coastal system of the Dardanelles has substantially remained lower than the ratios reported previously for open waters of the Sea of Marmara (8,16). Moreover, the correlations between NO^-_2 +NO^-_3 and chlorophyll a (r = 0.103) were higher than the correlations between PO^{-3}_4 and chlorophyll a (r = 0.067) in the system. These correlations indicate that phytoplankton was more limited by nitrogen than by phosphate at that time. Some authors believe that the western basin of the Mediterranean is either phosphate-limited (52), or slightly nitrogen-limited in some unusual locations, such as coastal areas (53-55).

The chlorophyll a concentrations ranged from 0.03 to 8.67 μg L^{-1} during low and high productive periods, respectively. The observed mid-July maxima in 2001 was principally due to an algal bloom in the study area. Despite this high value of 8.67 μg L^{-1} in July, chlorophyll a concentration was under the 3.883 μg L^{-1} throughout the year. The mean value of chlorophyll a in the coastal surface water of the Dardanelles was lower than values in the surface waters of the Sea of Marmara (9,56) and the Black Sea (57). However, the mean value was higher than those in the northern Aegean Sea (11,58,59) and the other parts of the Mediterranean Sea (60,61). Similar to the variations in the physicochemical conditions and the nutrients, chlorophyll a concentration was also affected by the counter flows in the Dardanelles.

Bray-Curtis cluster analysis revealed that similarity or contribution of diatoms was higher than that of other taxonomic groups to the total phytoplankton population during the sampling year. On the other hand, succession of diatoms was more dominant than successions of other taxonomic groups except for some peak periods of dinoflagellates during the sampling year (Figure 5). Besides, phytoplankton cell volume, cell density, and nutrient concentrations showed that although the study area is a coastal system, this part of the Dardanelles is not a more eutrophicated area than any other coastal area, comparable to the levels found in the Black Sea (28,30-32) and the Sea of Marmara (8,15). Although diatoms and dinoflagellates were abundant in species, the variation in phytoplankton diversity was generally controlled by 8-10 species in the Dardanelles, as was shown in some eutrophicated ecosystems, such as the Sinop bay in the Black Sea (8,15,32) and İskenderun bay in the eastern Mediterranean (62). Other species can be considered as accessory species that do not cause significant fluctuations in the phytoplankton cell volume, as was shown by many researchers (28,63,64). This study showed that both phytoplankton cell volume and cell density in the coastal area of the Dardanelles is inversely proportional to diversity as shown in other similar studies (28,29-32,65). This study also revealed that the relationship between chlorophyll a and cell volume (r

= 0.399) was less important than the relationship between chlorophyll a and cell density (r = 0.709).

This study showed that the process of eutrophication is accompanied by a shift in the existing cell volume and cell density relations between major taxa due to high nutrient concentrations. Ratios have indicated a relative decrease in the cell volume of diatoms and a relative increase in the cell volume of dinoflagellates, which have a mixotrophic character in more eutrophicated areas of coastal marine ecosystems. Excessive phytoplankton densities in the Dardanelles are generally controlled by smaller forms in size and having generally a short life cycle, such as coccolithophorid *Emiliania huxleyi* (Lohmann) Hay & Mohler, 1967, dinoflagellate *Prorocentrum* spp., and diatoms *D.fragilissimus* and *Leptocylindrus* spp. Due to excessive population densities of these species and moving by surface flow, not only the Dardanelles, but also the north part of the Aegean Sea can potentially be affected by some ecosystem phenomena, such as red-tide and grazing in the Dardanelles. Therefore, both this system and neighboring systems, especially the north part of the Aegean Sea must regularly be monitored in terms of biological and physicochemical processes.

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