Phytoplankton response to nutrient runoff in a large lagoon system in the Gulf of California

Respuesta del fitoplancton al aporte de nutrientes en un sistema lagunar del Golfo de California

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ABSTRACT

To evaluate changes in abundance and composition of phytoplankton in the San Ignacio-Navachiste-Macapule Lagoon Complex in the Gulf of California during the wet-dry transition months, 18 sampling sites were established. Samples were analyzed for abundance, chemical water composition, temperature, and Secchi disk measurements in September, October, and November 1998. The combined effects of rainfall, municipal wastewater, and agricultural drainage yielded runoff that generate low salinity, high concentration of nutrients, low pH, and high biochemical oxygen demand conditions. Temporal and spatial patterns of phytoplankton related to these drainage waters were mapped. The highest concentrations of chlorophyll (15 mg/m^3), maximum phytoplankton abundance (3.7×10^6 cells/L), and dominance by microphytoplankton (cells $>$ 20 µm) occurred with the high runoff contribution of September. Phytoplankton concentrations (cells/L) decreased in October (1.6×10^6) and November (2.3×10^6), and the community was dominated by nannoplankton (cells $<$ 20 µm). Cluster analysis showed the influence of runoff in the distribution of species, as well as abundance of cyanobacteria (5.5×10^5 cells/L), higher in the inner lagoon in September and October. The study clearly showed a relationship between the development of phytoplankton blooms and the input of nutrients.

Key words: Wastewater, phytoplankton, Gulf of California, Navachiste, nutrients.

RESUMEN

Con el propósito de describir los cambios en abundancia y composición del fitoplancton durante la transición entre la temporada de lluvias a secas en el Sistema Costero San Ignacio-Navachiste en el Golfo de California, se establecieron 18 puntos de muestreo. En estos sitios se midieron la temperatura y profundidad de disco de Secchi y se colectaron muestras para la determinación de abundancia de fitoplancton y composición química de la columna de agua durante septiembre, octubre y noviembre de 1998. Los resultados obtenidos muestran que las aguas pluviales, municipales y agrícolas originan bajos valores de salinidad y pH, alta demanda bioquímica de oxígeno y concentraciones elevadas de nutrientes. Las distribuciones temporal y espacial se encontraron determinadas por la influencia de los aportes. Los valores máximos de clorofila (15 mg/m^3) y de abundancia fitoplanctónica (3.7×10^6 células/L), con predominio del microfitoplancton (células $>$ 20 µm), estuvieron asociados al mayor aporte de agua de los drenes durante septiembre. En octubre y noviembre las concentraciones promedio de fitoplancton fueron menores (1.6×10^6 y 2.3×10^6 células/L, respectivamente) y la comunidad estuvo dominada por el nanoplancton (células $<$ 20 µm). La influencia de los aportes de los drenes se denotó en la distribución de las especies, lo mismo que las altas abundancias de cianobacterias (5.5×10^5 células/L) en la parte más interna de la laguna durante septiembre y octubre. Los resultados del presente trabajo indican claramente la relación entre el desarrollo de la proliferación del fitoplancton y la entrada de nutrientes al sistema.

Palabras clave: Aguas residuales, fitoplancton, Golfo de California, Navachiste, nutrientes.

INTRODUCTION

Coastal ecosystems in the Gulf of California support diverse and important fisheries, and are reservoirs of great biological diversity. In northern Sinaloa, population growth and development, as well as increased use of these natural systems for recreation, has substantially increased the pressure placed upon marine resources. Discharge of untreated wastewaters generated by diverse human activities has been notably altered its health and integrity, principally along the lagoon's eastern shore (De la Lanza-Espino, 1991; Escobedo-Urías, 1997).

In the late 60s, agriculture moved into a dominant role in coastal northern Sinaloa. The coastal plain encompasses more than 200,000 hectares under cultivation that now introduces large amounts of organic material, pesticides, heavy metals, and fertilizers into the lagoon systems at drainage discharge points (Escobedo-Urías *et al.,* 1999; Ayala-Baldenegro, 2004). The municipality of Guasave discharges approximately 709,660 m^3/year of wastewater into the tripartite lagoon of San Ignacio-Navachiste-Macapule (HAMG, 1996).

Nutrient runoff into the lagoon system can stimulate episodes of rapid phytoplankton growth. Some of the episodes may benefit the lagoon as an important source of food for bottom living organisms. However, proliferation of some planktonic species represents a risk to public health because they produce toxins eaten by consumable fish and shellfish. Certainly, for public health, it is essential to develop an inventory of the species in the lagoon and their dynamics in the ecosystem.

In Sinaloa, studies of phytoplankton dynamics have focused on the coastal waters around Mazatlán, in the southern portion of the state (Caballasi-Flores, 1985; Cortés-Altamirano & Pastén-Miranda, 1982; Cortés-Altamirano & Nuñez- Pastén, 1992; Cruz & Calvario, 1994; Alonso-Rodriguez *et al.,* 2000). In the northern coastal region, the few studies available have been of a descriptive nature, providing valuable information on phytoplankton composition (Gómez-Aguirre, 1969; Licea-Durán, 1971; Meraz-Del Angel, 1997). For the tripartite lagoon system of San Ignacio-Navachiste-Macapule, the studies (Vicencio, 1979; Páez-Osuna *et al.,* 1991; Escobedo-Urías *et al.,* 1999) do not include information about phytoplankton, even though this lagoon system is the second largest in the state and one of the most productive coastal habitats in terms of fish capture.

The impact of wastewater in the coastal zone on production and biomass varies among systems (NRC, 2000). However, to understand how the anthropogenic factors interact with the natural variations of phytoplankton biomass and, in turn, be able to assess their impact on coastal systems, it is necessary to document the seasonal variability of phytoplankton and their physical-chemical environment. This study discusses the changes in abundance and composition of phytoplankton in the San Ignacio-Navachiste-Macapule lagoon complex during late summer and early autumn. The annual rainfall maximum in this region coincides with the start of the fall/winter agricultural cycle, the period of heaviest application of fertilizers and subsequently the period of highest nutrient input to the system.

METHODS

The San Ignacio-Navachiste-Macapule Lagoon Complex (25°15′–25°35′ N, 108°30′–109°03′ W) covers an area of 220 km² (HAMG, 1996; Magaña–Álvarez, 2004). The lagoon complex has three entrances: Ajoro, Vasiquilla, and Bocanita (Fig. 1). Mean depth of the three lagoons is 2.5 m, with a range from 0.5

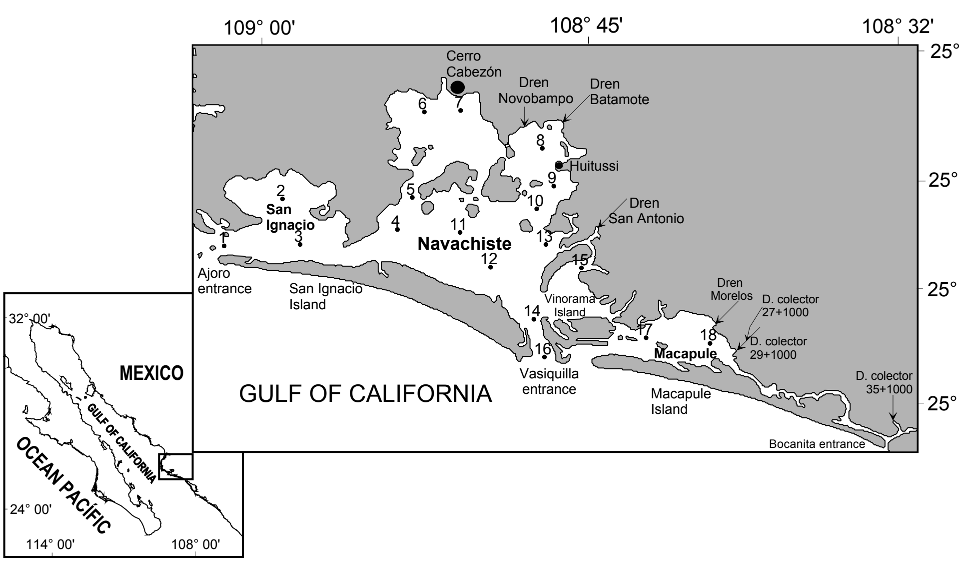

Figure 1. Localization of Navachiste-San Ignacio-Macapule lagoon complex (Gulf of California), and

Table 1. Averaged, minimum and maximum values of physico-chemical variables in the lagoon system, during September, October, and

Month		T°C	S‰	pH	DO mg/l	% SAT	BOD mg/l	NO_3 µM	NO_2 µM	NH_4 µM	PO_4 µM	TSS mg/l	SECCHI m
	Max	32.70	35.00	7.68	9.32	150	3.63	0.20	0.19	3.00	2.14	147	2.10
SEP	Min	29.00	31.00	7.10	4.32	69	0.69	0.03	0.01	0.09	0.07	75	0.30
	Ave	31.19	33.67	7.32	7.02	114	1.54	0.05	0.03	0.88	0.96	95	1.08
	Max	29.00	36.00	8.02	9.01	143	6.32	0.66	0.46	3.65	2.11	107	2.20
OCT	Min	27.00	33.00	7.51	6.52	100	1.72	0.01	0.02	0.02	0.56	49	0.70
	Ave	27.69	34.81	7.86	7.71	119	3.19	0.08	0.15	1.17	1.40	66	1.23
	Max	23.80	41.00	8.94	7.86	116	2.49	0.57	1.35	4.00	1.80	107	3.00
NOV	Min	22.50	36.00	8.56	6.52	94	0.96	0.01	0.02	0.69	0.45	59	0.50
	Ave	23.29	36.94	8.74	7.20	105	1.58	0.17	0.24	1.89	0.97	72	1.44

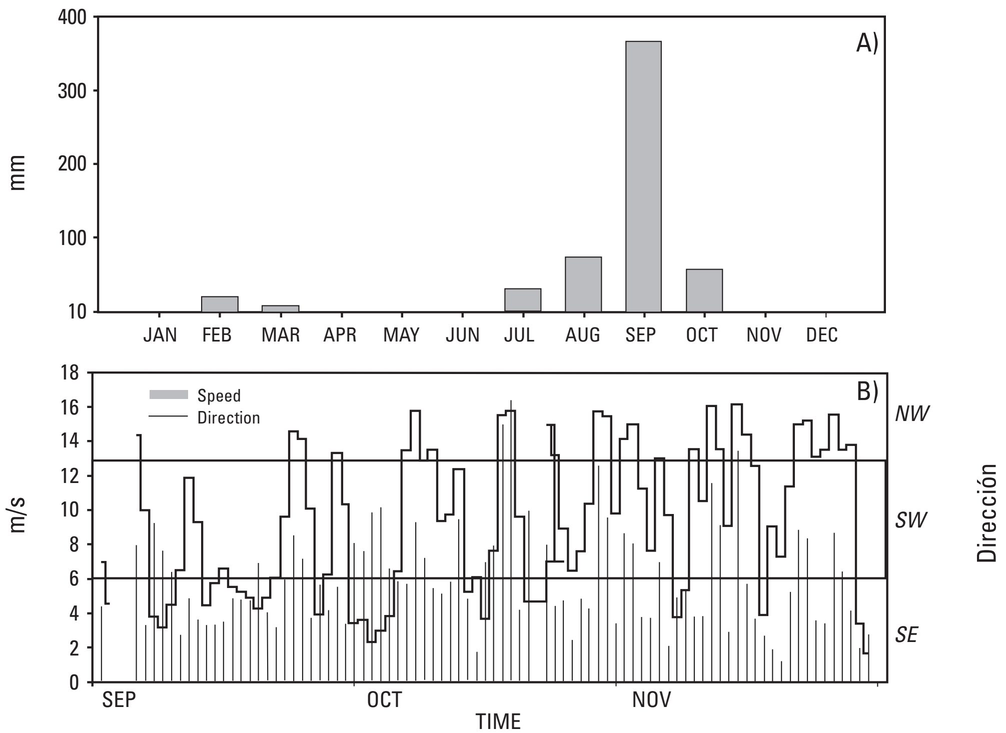

Figure 2. (A) Monthly rainfall at Guasave meteorological station during 1998. (B) Daily speed and wind direction during September, October,

m to 5 m and the greatest depth at the Vasiquilla entrance (11 m). Annual precipitation averages about 300 mm, with the rainy season occurring in late summer and early fall (Vicencio, 1979; Escobedo-Urías *et al.,* 1999). The tides in this lagoon complex have a strong semi-diurnal component with two unequal flood and ebb cycles every 24.84 hours. Tidal amplitude is about 1.08 m, and maximum current speed during ebb tide is approximately 2.1 m/s at the Vasiquilla entrance (Escobedo–Urías *et al.,* 2001). Circulation patterns indicate a major influence of continental shelf waters at the northern entrance (Ajoro) (Escobedo-Urías *et al.,* 2001; Ulloa–Pérez, 2005). Seasonal condition defines two periods, one cold season (December to March) and a warm season (May to September) (Magaña–Álvarez, 2004; De Silva–Dávila *et al.*, 2006). The system is anti-estuarine (annual mean = 36 psu) with higher average salinity during the wet season and lower average salinity during the dry season (30–45 psu) (Escobedo-Urías *et al.*, 2001). Agricultural and municipal wastewater drains are the main source of freshwater, in

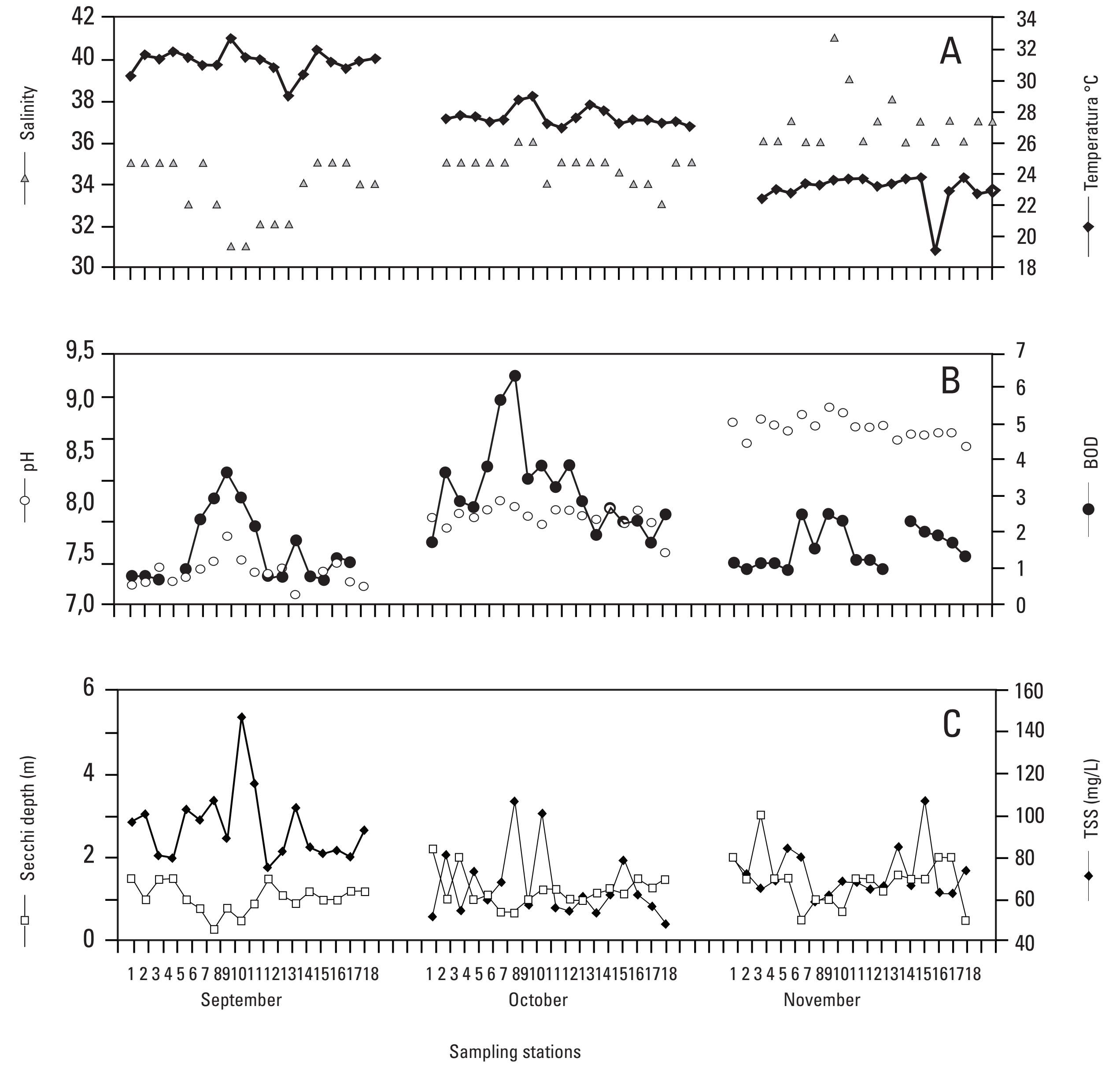

Figure 3. (A) Temperature and salinity, (B) pH and biochemical oxygen demand, (C) Total suspended solids (TSS) and Secchi disc depth in San Ignacio-Navachiste-Macapule during September, October, and November 1998.

addition to runoff during the wet season (De Silva-Dávila *et al.,* 2006).

Data of pluvial precipitation, wind direction and speed were recorded every 15 minutes in the municipality of Guasave, about 20 km from the lagoon complex (Meteorological Station of the Comision Nacional del Agua; CNA). During September, October, and November 1998, field measurements at 18 sampling stations (Fig. 1) were taken over 5–6 h of survey during flood tides, with the exception of November, when sampling was performed under ebb tidal condition. Surface temperature and salinity was obtained (Beckman salinometer) and pH measured (Corning potentiometer model 3D). Transparency of the water was estimated with the Secchi disk. Simultaneously, water samples were taken with a van Dorn bottle, filtered and frozen to determine dissolved inorganic nitrogen and phosphorus (NO_3^-+N, NO_2^-+N, NH_4^-+N and PO_4^{-3}+P) according to Strickland and Parsons (1972). Dissolved oxygen (DO), biochemical oxygen demand (BOD5), and total suspended solids (TSS) were measured according to Eaton *et al.* (1995). The effect of salinity and temperature on dissolved oxygen was normalized by estimating the percentage of saturation, according to Riley &

Chester (1971). N:P ratios were calculated from $NO_2^- + NO_3^- + NH_4^-$ nitrogen and PO_4^{3-}phosphorus. Water samples for measuring chlorophyll were filtered through GF/F glass fiber filters (0.7 µm nominal pore size). These filters were frozen at -70°C and later analyzed spectrophotometrically after extraction in 90% acetone (Venrick & Hayward, 1984). Active chlorophyll *a* was calculated according to equations in Jeffrey & Humphrey (1975). Additionally, water samples were collected to determine abundance and composition of phytoplankton. The enumeration of nannoplankton (2–20 µm) and microphytoplankton (>20 µm) was made using 1% Lugol's solution fixed samples with the standard technique of Utermöhl (Hasle, 1978) under an inverted microscope (Olympus). Identification of microphytoplankton was performed at 400× by using several standard identification references (Tomas, 1997; Hustedt, 1959; Hustedt, 1961-66), between others.

To obtain information on the degree of variability of the system using the phytoplankton assemblages, the species diversity index of Shannon-Wiener was calculated (Pielou, 1966). A multivariate analysis was used to examine relationships in the microphytoplankton data set. Cyanobacteria (individuals are < 20 µm) were included in this category because they are organized in filaments. To reduce the number of variables included in the analysis, a selection of the most frequently observed species (occurring in at least 10% of the samples) was made. The matrices of sampling stations and species categories were used for a Q-mode cluster analysis after a log (x+1) transformation.

RESULTS

Monthly precipitation in the wet season of 1998, which occurs between June and October ranged from 360 mm in September and declined to 54 mm in October (Fig. 2A). During this season, wind oscillates between its winter and summer/fall patterns. Southwest winds (average speed 6.1 m/s) prevail during September and oscillated during October and November between this direction and northwest (Figure 2B).

Physicochemical Variables. The physicochemical variables showed distinct differences among the sampled months. Temperature declined, but salinity increased. Minimum salinity occurred at stations 8-9 and the maximum was localized in the innermost part of the lagoon, farthest from the coast (station 6)

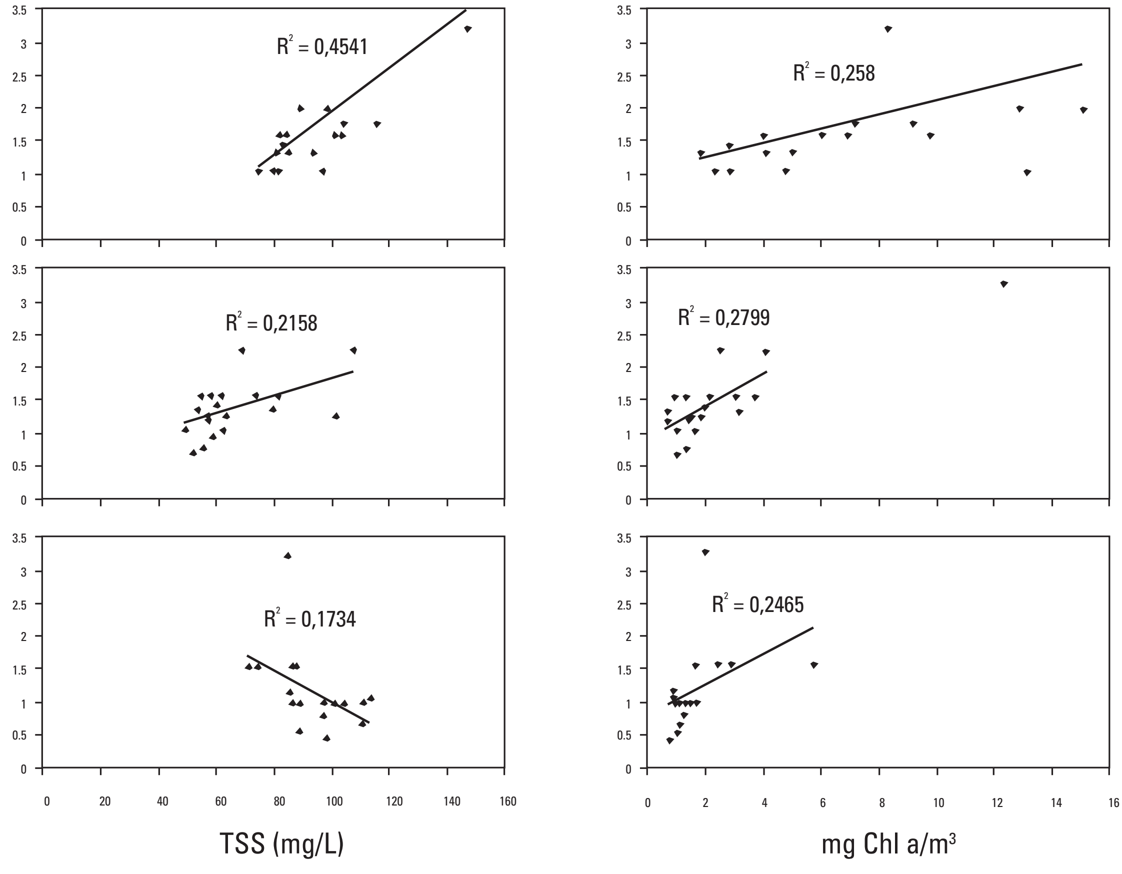

Figure 4. Regression analysis of Kd vs total suspended solids (TSS) and chlorophyll *a* (Chl*a*) concentration during September, October, and November 1998.

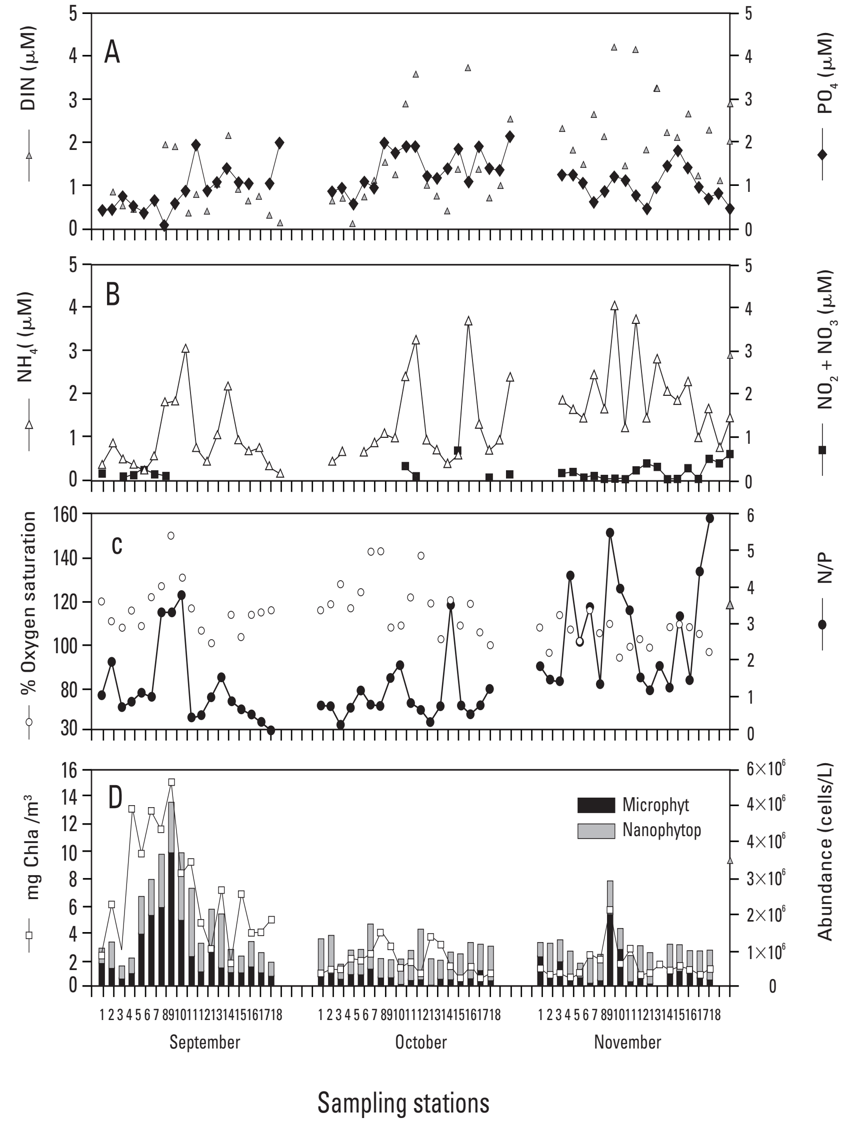

Figure 5. Occurrence of: (A) dissolved inorganic nitrogen and phosphates; (B) ammonium-N and nitrate plus nitrite; (C) oxygen saturation and N/P ratio; (D) chlorophyll *a* concentration and nannophytoplankton and microphytoplankton abundance in the San Ignacio-Navachiste-Macapule lagoon complex in September, October, and November 1998.

(Fig. 3A, Table 1). The pH increased from September to November, and BOD_5 values showed similar in September, and November, but were higher (6.32) in October, with maximum values in the innermost part of the lagoon (Fig. 3B, Table 1). Transparency was inversely related to the concentration of total suspended solids, with higher suspended solids and lower transparency at sampling sites close to drains (Fig. 3C, Table 1). A regression analysis of Kd (1.6/Secchi disc depth) vs TSS and chlorophyll *a* concentration showed strong effects of solids suspended on water transparency, resulting in 45.4% (P + 0.05) of the variance attributable to this parameter occurring in September, and declining in October and November (Fig. 4). During the study period, approximately 25% (P + 0.05) of the variance is attributable to chlorophyll *a* (Fig. 4).

A marked influence of the input of residual wastewaters, such that the maximum values of all nutrients, occurred near the agricultural and municipal outlets in the three months (Fig. 5A). The lagoon complex was nutrient rich but the ratio of dissolved inorganic N to inorganic P was far below the Redfield ratio stechiometry of 16:1 (by atoms), with average values of 2.61, 0.99, and 2.77 for September, October, and November, respectively. This indicates N limitation condition for phytoplankton growth due to the fluctuations between N and P concentrations. The concentrations of all types

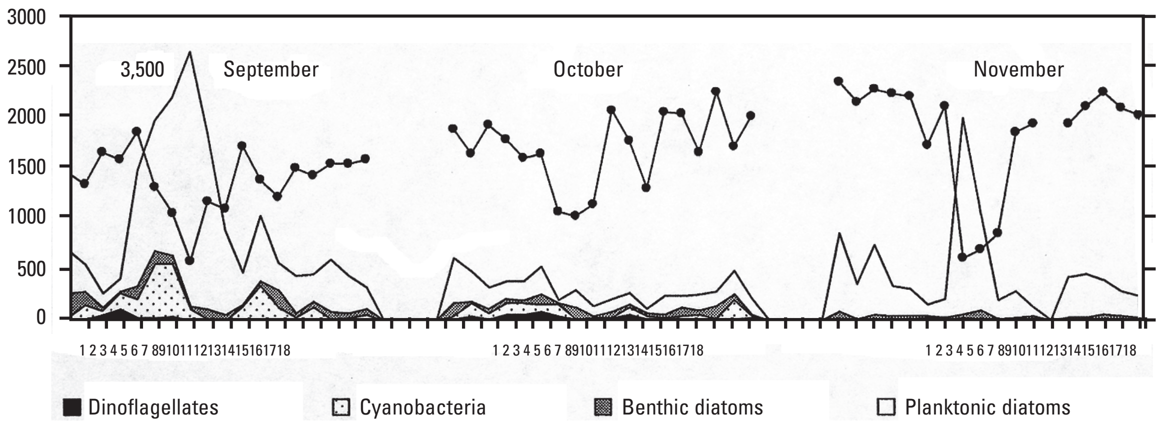

Figure 6. Abundance of microphytoplankton groups and diversity index (H×) (•–•) in the San Ignacio-Navachiste-Macapule lagoon complex during September, October, and November 1998.

of nitrogen were lowest in September and highest in November, while the average maximum concentration of orthophosphates occurred in October and was the case along the lagoon complex (Table 1, Fig. 5A). The major component of dissolved inorganic nitrogen was ammonium (average $>$ 78%), but nitrate and nitrite concentrations increased in November (Fig. 5B).

During the highest precipitation in September, there was a higher positive correlation between oxygen saturation with the abundance of phytoplankton, resulting in 44.3% ($P < 0.05$) of the variance attributable to phytoplankton.

Spatial-temporal distribution of phytoplankton. Phytoplankton abundance was highest in September, with a maximum concentration (6×10^6 cells/L) in front of the wastewater and agricultural discharge drains at Novobampo, and Batamote. The lowest phytoplankton concentrations in September (6×10^5 cells/L) occurred near the Ajoro entrance of Laguna San Ignacio. The mayor contributors to the maximum concentrations of chlorophyll *a* (15 mg Chl *a*/m^3) (Fig. 5D) were nannophytoplankton, diatoms, and cyanobacteria (Fig. 6). In October, phytoplankton declined (1.7×10^6 cells/L), but there were larger numbers of nannophytoplankton. November showed similar abundances as September, maximum of 3×10^6 cells/L and 5.73 mg Chl *a*/m^3), but microphytoplankton was dominant.

A total of 376 species belonging to the microphytoplankton size were identified. The most common and abundant groups were diatoms, dinoflagellates, silicoflagellates, and cyanobacteria, in that order, with diatoms clearly more dominant than all other groups combined. The Shannon-Wiener Diversity Index increased slightly from September to November except at stations located near the wastewater discharge (stations 7-9) (Fig. 6).

Cluster analysis. During September (S) and October (O), a similar phytoplankton assemblage was observed close to the drain outlets (clusters S1, S2, O1, and O2) (Figs. 7 and 8). In these areas, small cells, such as *Nitzschia longissima* (Brébisson) Ralfs, 1861, Cyanobacteria sp 1, *Cylindrotheca closterium* (Ehrenberg) Reimer and Lewin 1964, and *Skeletonema costatum* (Greville) Cleve 1873, were dominant. In October, cluster group O3 was distinguished by the dominant species of *Chaetoceros lasciniosus* Schütt 1895, *S. costatum,* and *Campylosira cymbelliformis* (A. Schmidt) Grunow ex Van Heurck 1885 (Fig. 8). Cyanobacteria reached their highest concentrations (5×10^5 filaments/L) in September, declining to one-fifth in October, when their distribution was more homogeneous in the lagoon complex. In November (N), there were three clusters (N1, N2, and N3) (Fig. 9). The separation of clusters N1 and N2 is based on the dominance of the diatom *Rhizosolenia setigera* Brightwell 1858. Noteworthy is that their density was one order of magnitude higher in N1 than in N2. A lesser component of these two clusters was *N. longissima* and *S. costatum*. Cluster N3 was dominated by *S. costatum* with lesser density of *R. setigera*. No cyanobacteria were present in this month.

DISCUSSION

Our observations of the lagoon complex of San Ignacio-Navachiste-Macapule provided ample evidence of anthropogenic effects on phytoplankton. Nitrite and ammonium were high in comparison with other impacted lagoons in the region (Paredes & López, 1988; DGO, 1990; Castro–Longoria & Grijalva–Chon, 1991; Escobedo–Urías, 1997; Escobedo–Urías *et al.,* 1999). This condition, as well as the high biological oxygen demand (2-6.32 mg/L) located near the outlet drains indicate the role of domestic and agricultural wastes (De la Lanza–Espino, 1984, 1994; Contreras–Espinosa, 1993) passing into the lagoons, mainly in Navachiste Bay. Other indicators of anthropogenic influence include high levels of organic material and heavy metals with the highest concentrations near the drain outlets (Ayala–Baldenegro, 2004).

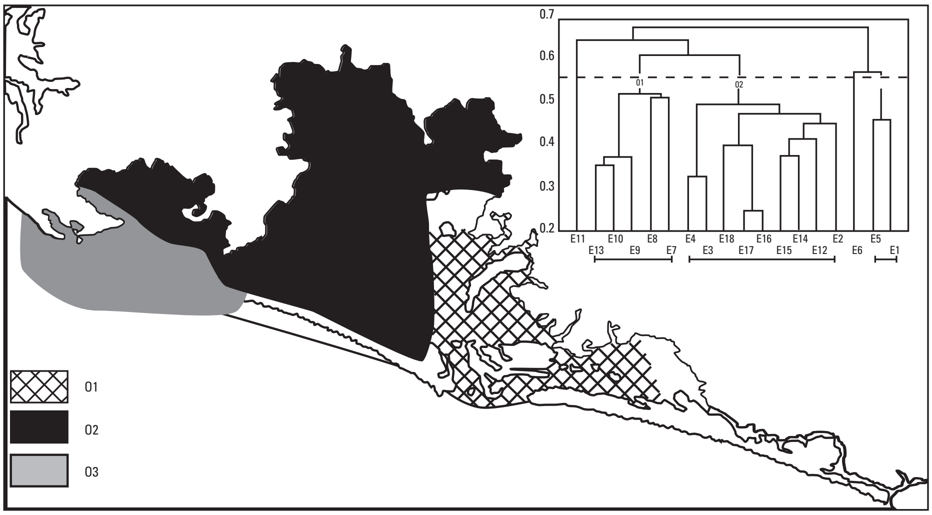

Figure 8. Dissimilarity dendrogram, based on Pearson correlation coefficients and average linkage, and the localization of clusters of sampling stations in the lagoon complex of San Ignacio-Navachiste-Macapule during October 1998.

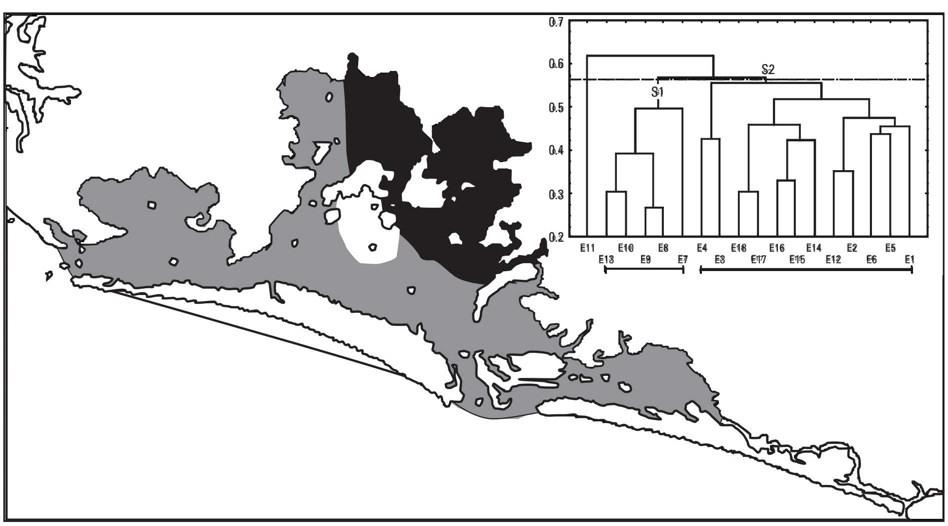

Figure 7. Dissimilarity dendrogram, based on Pearson correlation coefficients and average linkage, and the localization of clusters of sampling stations in the lagoon complex of San Ignacio-Navachiste-Macapule during September 1998.

Abundance of phytoplankton was in the range of previous studies in impacted southern lagoons in the state (Gilmartin & Revelante, 1978; Alonso–Rodriguez *et al.,* 2000), and for the Guaymas area (Gilbert & Allen, 1943). However, are higher than had been reported for the nearby area of Bahía Topolobampo and the central region of the Gulf of California (Gilbert & Allen, 1943; Álvarez-Borrego & Lara-Lara, 1991). The dominance of nannoflagellates (2-20 μm) and small microphytoplankton (diatoms and cyanobacteria) is a major feature found in this lagoon complex. This is contrary to the situation found in Mazatlan Bay, Sinaloa during the 80s (Caballasi-Flores, 1985) and for other nitrogenenriched coastal systems, such as the Bay of Brest (Del Amo *et al.,* 1997), where phytoplankton is dominated by microphytoplankton. The dominance of small-sized phytoplankton does not seem to represent a response of the community structure to the nutrient loads of freshwater runoff because the phytoplankton are better adapted to low nutrient conditions (Riegman *et al.,* 1993). Nutrients often have major regulatory effects on phytoplankton abundance and composition; however, proportions of elements are particularly important. With the high precipitation (360 mm) in September, nutrient concentrations were lower than what is usually expected at the discharge sites, probably from phytoplankton growth (the highest concentration found, 6×10^6 cells/L, and oxygen saturation).

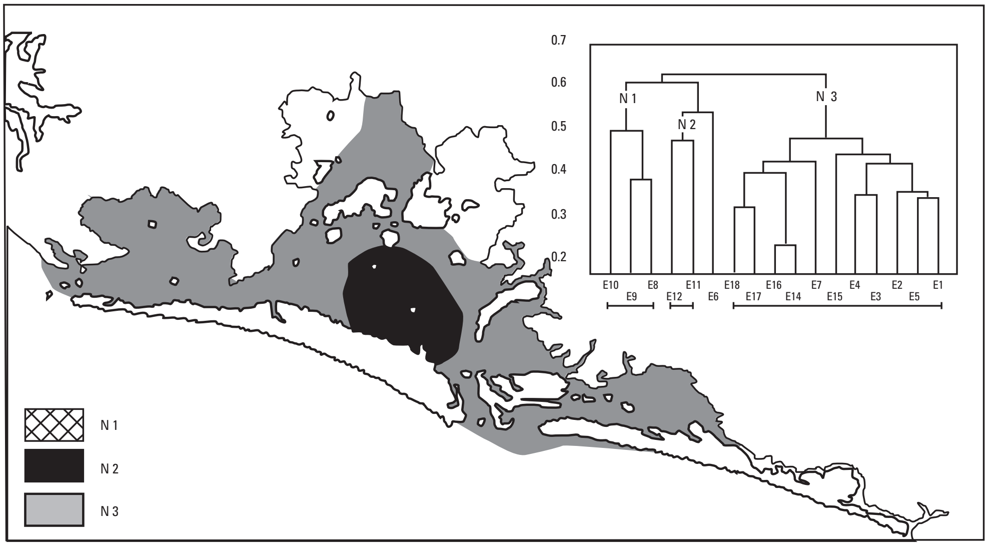

Figure 9. Dissimilarity dendrogram, based on Pearson correlation coefficients and average linkage, and the localization of clusters of sampling stations in the lagoon complex of San Ignacio-Navachiste-Macapule during November 1998.

These concentrations were six times higher than near the Ajoro entrance where water exchange with the gulf is most intense. In October, with only 54 mm of rainfall, runoff greatly declined and the concentration of phytoplankton, particularly diatoms, diminished approximately by 50%.

The ratio of dissolved inorganic nitrogen to phosphorus in surface water was lower than 16:1, indicating a nitrogen limitation on microphytoplankton growth, particularly in September and October, except in the areas close to the drain outlets, where the ratio fluctuated between 2 and 6 to1. Phosphorus as a limiting factor for growth was not observed. Phosphate concentrations were slightly higher in October, compared to the previous and following months. Higher values of DBO_5 indicated that high remineralization was occurring in this month. This condition as well a lower phytoplankton growth could explain phosphate concentrations, circumstance reported in other studies (Mee, 1977; Liss, 1976; Valiela, 1995; Magaña−Álvarez, 2004).

Under nitrogen-limiting conditions, nannophytoplankton and the diatoms *N. longissima, Cylindrotheca closterium,* and *S. costatum,* can grow rapidly (Furnas, 1990). These species are apparently able to respond rapidly to reduction of limiting nutrient conditions (Harrison *et al.,* 1977). *S. costatum* in particular, has a preference for high ammonium and phosphorus environments (Sakshaug & Andersen, 1986) with lower nitrogen to phosphorus ratios (Moisander *et al.,* 2003), as were the prevailing conditions in this lagoon complex.

In November, an increase of ammonium occurred, but the lack of significant correlation between phytoplankton density and oxygen saturation, as well as an increase in nitrate concentration, indicates high oxygen demand in the remineralization process. This process, in addition to the runoff of fertilizers at the beginning of the fall/winter agriculture cycle (Escobedo-Urías, 1997; Escobedo−Urías *et al.,* 1999; Magaña−Álvarez, 2004), promoted an increase in the dissolved inorganic nitrogen to phosphorus ratio, which occurred at the time of a bloom of larger-sized diatoms dominated by *R. setigera.* The diatom bloom was most abundant where agricultural wastewater discharged into the lagoons and the nitrogen to phosphorus ratio was close to 6 to 1, indicating a minor nitrogen limitation.

Other elements besides N and P can have a major influence on the structure of the phytoplankton community and can affect the nature of their response to nutrient inputs. The availability of silica has little or no influence on the overall rate of algal growth in an aquatic system, but when silica is abundant, diatoms are one of the major components of the phytoplankton. Although silica analysis was not performed, concentrations of this nutrient in another study of Laguna de Macapule showed abundant silica, ranging from 24.4 to 37.4 μM (Magaña-Álvarez, 2004). The relative availability of nitrogen and silica may influence the abundance of diatom species (Gilpin *et al.,* 2004), explaining why there was a diatom bloom in November.

Other indicators of wastewater influence were a low diversity index and a great concentration of cyanobacteria mainly during the rainy season (September/October). Particularly, cyanobacteria have been associated with these conditions at other sites around the world (Jones, 2000), as well as lagoons and estuaries along the eastern coast of the Gulf of California (Gómez−Aguirre, 1969; Santoyo, 1972; Gómez−Aguirre *et al.,* 1974).

For many years, there has been speculation that discharges from agricultural areas can stimulate the development of phytoplankton blooms from the considerable quantities of fertilizers used in agriculture in the state of Sinaloa (= 14 tons nitrogen/month and 3 tons phosphorus/month incorporated into coastal lagoons, Calvario-Martínez *et al.,* 2006). This study clearly shows a relationship between phytoplankton bloom development and the input of nutrients. However, comprehension of the dynamics will require long-term time-series biological and physical chemical studies, as well as physiological bioassays.

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