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Research Article

Characterization and comparison of microphytoplankton biomass in the lower reaches of the Biobío River and the adjacent coastal area off Central Chile during autumn-winter conditions

Bárbara Léniz[1,2], Cristian A. Vargas[1] & Ramón Ahumada[2]
[1]Laboratorio de Funcionamiento de Ecosistemas Acuáticos (LAFE), Unidad de Sistemas Acuáticos
Centro de Ciencias Ambientales EULA Chile, Universidad de Concepción, Concepción, Chile
[2]Laboratorio de Ciencias Ambientales y Oceanografía, Facultad de Ciencias
Universidad Católica de la Santísima Concepción, Concepción, Chile

ABSTRACT. The Biobío River in central Chile is the third largest watershed and second largest river in Chile in terms of discharge volume. Three sampling campaigns were made in the lower reaches of the river and the adjacent coastal ocean to evaluate the influence of the river plume on the physical/chemical conditions and the abundance/biomass of microphytoplankton during autumn-winter conditions. In addition, a preliminary quantification of riverine nutrients, dissolved silica, and phytoplankton carbon flux to the adjacent ocean was also conducted. High nitrate (NO_3^-) and silicic acid ($Si(OH)_4$) concentration (>18 and 50 µM, respectively) was observed in the lower reaches of the river during all field campaigns. $Si(OH)_4$ was even high in surface river plume waters. Hydrographic conditions indicate that river plume waters were piled coastward, and they could drove to the south at the Arauco Gulf. In all sampling, highest microphytoplankton biomass (>5000 µgC m^{-3}) was associated to the lower reaches of the river and river plume waters as they were moving southward. During autumn-winter conditions a significant flux of phytoplankton carbon and nutrients to the adjacent coastal ocean also played an important role in the high biological productivity of this coastal upwelling area. These preliminary results evidence the need to conduct large-term studies, which should consider the importance of these allochthonous carbon sources in global carbon budgets and coastal food-web models.

Keywords: phytoplankton carbon, river plume, nutrient fluxes, silicic acid, coastal food webs, Chile.

Caracterización y comparación de la biomasa microfitoplanctónica en el curso inferior del río Biobío y la zona costera adyacente frente a Chile Central durante condiciones de otoño-invierno

RESUMEN. El río Biobío, en la zona central de Chile es la tercera cuenca más grande y segundo río más grande de Chile en términos de volumen de descarga de agua dulce. Se realizaron tres campañas de muestreo en el curso inferior del río y la zona costera adyacente para evaluar la influencia de la pluma del río Biobío, en las condiciones físicas/químicas relacionadas con la abundancia/biomasa del microfitoplancton en condiciones de otoño-invierno. Además, se realizó una cuantificación preliminar de los flujos de nutrientes fluviales, sílice disuelta, y el flujo de carbono fitoplanctónico al océano adyacente. Se observó alta concentración de nitrato (NO_3^-) y ácido silícico ($Si(OH)_4$) (>18 y 50 µM, respectivamente) en el curso inferior del río en todas las campañas de terreno. La concentración de $Si(OH)_4$ fue también alta en las aguas superficiales de la pluma del río. Las condiciones hidrográficas revelaron que las aguas de la pluma del río se apilaron hacia la costa y al sur, en el golfo de Arauco. En todas las muestras, la más alta biomasa microfitoplanctónica (>5000 µgC m^{-3}) estuvo asociada a la porción baja del río y las aguas de la pluma que se estaban moviendo hacia el sur. Durante las condiciones de muestreo en otoño-invierno el significativo flujo de carbono fitoplanctónico y nutrientes hacia el océano costero adyacente, podría desempeñar un papel importante en la alta productividad biológica de esta área de surgencia costera. Estos resultados preliminares evidencian la importancia de realizar estudios de más largo plazo que consideren estas fuentes de carbono alóctono en los balances globales de carbono y modelos de tramas tróficas en el océano costero.

Palabras clave: carbono fitoplanctónico, pluma de ríos, flujo de nutrientes, ácido silícico, trama trófica costera, Chile.

Corresponding author: Cristian A. Vargas (crvargas@udec.cl)

INTRODUCTION

Rivers constitute the primary interface between terrestrial and ocean environments. Approximately 40% of the freshwater entering the ocean is transported by large rivers, discharging more than 35×10^9 ton of suspended and dissolved solids annually (Farnsworth & Milliman, 2003). In addition to human disturbances on global runoff, anthropogenic loading of nutrients in rivers has increased over the last decades (Jickells, 1998). The effect of nutrient loading is becoming increasingly widespread and severe as a consequence of the global expansion of industrialized activities (Jickells, 1998; Turner & Rabalais, 1999). For instance, it has been observed that runoff exerts a strong consistent biological influence in adjacent coastal ecosystems, stimulating phytoplankton blooms within days of fertilization and irrigation of agricultural fields throughout the watershed (Berman *et al.*, 2005). In the adjacent coastal area, it has been hypothesized that nutrient regeneration within the river plume may greatly amplify the effect of this nutrient loading from rivers (Dortch *et al.*, 1992).

Many rivers in Chile discharge their waters to the coastal ocean. Most of them are relatively short, they arise in the Andes and flow west to the Pacific Ocean. In the northern and central regions, the rivers are fed primarily by the perpetual snow cover of the Andes Mountain. The association found by different authors (Montes & Quiñones, 1999; Quiñones & Montes, 2001) between populations of primary producers, benthic, and demersal resources and freshwater inflow from rivers in Central Chile (Itata and Biobío rivers), reinforces the hypothesis that the high biological productivity of the continental shelf off central-south Chile is the outcome of several simultaneous factors other than preformed nutrients supply only by the coastal upwelling processes (Ahumada, 1994, 2002), such as the influence of freshwater, carbon, and nutrient discharge from rivers.

The lower reaches of the Biobío River is characterized by low or no slope, a low-velocity river flow, temperate waters, which run through sandy and muddy bottoms. This makes freshwaters calm and stable, which enhance conditions for high phytoplankton biomass in this area. On the other hand, in the mouth river area, the formation of frontal zones between the surface brackish river plume and the more oceanic waters has been reported (Basualto *et al.*, 1992), suggesting that high phytoplankton abundance may occur associated to such frontal zones. In this regard, the main aim of the present study was to describe the area influenced by the Biobío River discharge, in terms of the physical/chemical conditions, as well as to describe the abundance and biomass of microphytoplankton during autumn-winter conditions. Finally, we conduct a preliminary quantification of allochthonous particulate carbon export, as biogenic carbon from freshwater phytoplankton exported from the Biobío River to the adjacent coastal area, at this time of the year.

MATERIALS AND METHODS

Study sites

Our study area is located on the continental shelf in the lower reaches of the Biobío River and the adjacent coastal ocean, off Central Chile (36ºS). The Biobío River is Chile's second-longest river (the longest being Loa River) and Biobío basin is Chile's third largest watershed, and in its lower reaches passes agricultural land, towns and cities, and industrial areas (Karrasch *et al.*, 2006). Its flow rates range between 120 and 8500 $m^3 s^{-1}$, being the most important hydrographic basin in terms of freshwater discharge. The hydrological regime is strongly influenced by a maximum flow rate peak during the rainy season in winter (June-July) and a minimum flow rate during summer (February-March), with a medium level in spring due to melting of ice (Barra *et al.*, 2001). The runoff from these rivers supply significant amounts of silicates, nitrate, and phosphate as well as trace metals to the coastal ocean (Sánchez *et al.*, 2008). The adjacent coastal area is not only influenced by a seasonally variable flow of the Biobío River, but also by intense seasonal coastal upwelling events (Sobarzo *et al.*, 2007). The freshwater discharge, associated to this river-influenced continental shelf, has large seasonal runoff variations, with monthly values from about 200 $m^3 s^{-1}$ in summer to a maximum of about 2800 $m^3 s^{-1}$ during winter (Sobarzo *et al.*, 1993). The seasonal variation of winds and runoff creates two distinct modes of water circulation in the adjacent continental shelf, a summer upwelling and a winter downwelling situation with a thick surface layer to which the maximum riverine freshwater flow is added (Sobarzo *et al.*, 1993).

Collection of samples

Samples were collected during three field campaigns on May 14-15th, June 9-10th, and August 10-11th 2009, conducted in the lower reaches of the Biobío River and the adjacent coastal area (<10 nm from the coast). Discrete seawater samples were collected from six stations located in the adjacent coastal area (Fig. 1). Mean depth at each sampling station ranged from 40 to 60 m deep. At each station, temperature and salinity profiles were recorded from near the bottom to the surface using a CTD RBR XR-620. Based on the hydrographic information the Brunt-Väisälä frequency was estimated as an index of water column stratification in the surface layer (0-5 m). River flow data was obtained from the National Water Directorate (http://www.dga.cl), and for each campaign the flow data was averaged from the daily cycle considering the last 2-days (Fig. 1).

Water samples for microplankton (2.50 L) abundance, biomass, and nutrient analyses were collected at 0, 5, 10 and 20 m depth with a Niskin bottle. Microplankton sub-samples (250 mL) were preserved in an alkaline solution of lugol 1% (Levinsen & Nielsen, 2002). Samples for nutrient analysis, including nitrate (NO_3^-), nitrite (NO_2^-), phosphate (PO_4^{-3}), and silicic acid ($Si(OH)_4$) were stored in polyethylene bottles until analyses in the laboratory (<4-5 h from collection). In addition, freshwater samples were collected in the lower reaches of the Biobío River, at 10.8 km from the river mouth (Fig. 1) during flood tide. Surface samples (10 L from the upper 1 m depth) were collected from the central channel of the river using a clean, sample-washed, plastic bucket. Considering the high-energy level of the river upstream and the reduced depth in the lower reaches (<2 m depth), we did not consider depth-integrated water samples. NO_3^- and NO_2^- concen-tration was determined spectrophotometrically follo-wing Strickland & Parsons (1968), whereas PO_4^{-3} concentration according with Murphy & Riley (1962). $Si(OH)_4$ concentration was determined following Koroleff (1972).

Phytoplankton abundance and biomass

Subsamples of 50 mL were allowed to settle for 24 h in Uthermöhl sedimentation chambers before diatoms and dinoflagellates were identified, counted and measured using phase contrast inverted microscope (Olympus IX-51) at 200× magnifications. Diatoms and dinoflagellates were measured and identified down to genus level when possible based on cell size and shape, and body contour. Some individuals were identified to the species level. Plasma volumes were calculated (Edler, 1979) and averaged from a minimum of 50 ind/species. Carbon to plasma volume ratios of 0.11 pgC µm^{-3} for diatoms (Edler, 1979), 0.3 and 0.19 pgC µm^{-3} for heavily thecate and athecate dinoflagellates forms respectively (Gifford & Caron, 2000) were applied.

An analysis of similarities (ANOSIM) based upon Bray-Curtis distances between river and coastal phytoplankton assemblages was conducted for each sampling campaign considering the mean surface biomass for river and coastal stations, respectively, by using the software Statistica. A Spearman correlation analysis was conducted to explore the connection between the abundance and biomass of microphytoplankton and both physical and chemical variables measured during each field campaign.

A gross estimation of biogenic carbon and riverine nutrient fluxes to the adjacent coastal ocean was assessed by using information of microphytoplankton carbon (mgC m^{-3}) and nutrient concentration, and mean river flow data (m^3 s^{-1}) averaged for the last three days of each field campaign, and expressed as ton d^{-1}.

RESULTS

An analysis of the hydrographic conditions during May and August in a north-south transect, as represented in the Fig. 1, showed that temperature values ranged from 11.6 to 12.2°C and exhibited weak horizontal and vertical gradients along the transect (Figs. 2a, 2b). A thermal inversion associated to the river mouth was clearly observed during May (Fig. 2a). However, lower temperatures were also observed in surface waters associated to this area and southward (Stn 1) in August (Fig. 2b). Haline stratification in the adjacent coastal area was clearly modulated by the freshwater discharge of the Biobío River. Freshwater effects were most pronounced in the first 5 m of the surface layer and during the field campaign in May (Fig. 2c). Salinity distribution also revealed that surface waters were piled coastward, and they drove to the south at the Arauco Gulf (Figs. 2c-2d).

During the field campaign in May, only NO_3^- data was available, mostly due to analytical problems with PO_4^{-3} and $Si(OH)_4^{-2}$ analyses. High NO_3^- concen-tration was observed in the lower reaches of the Biobío River (Stn 7 and 8, 14 to 23 µM), which suggest a high degree of human intervention in this river section. In our study, the highest NO_3^- concentration in the river was observed during the

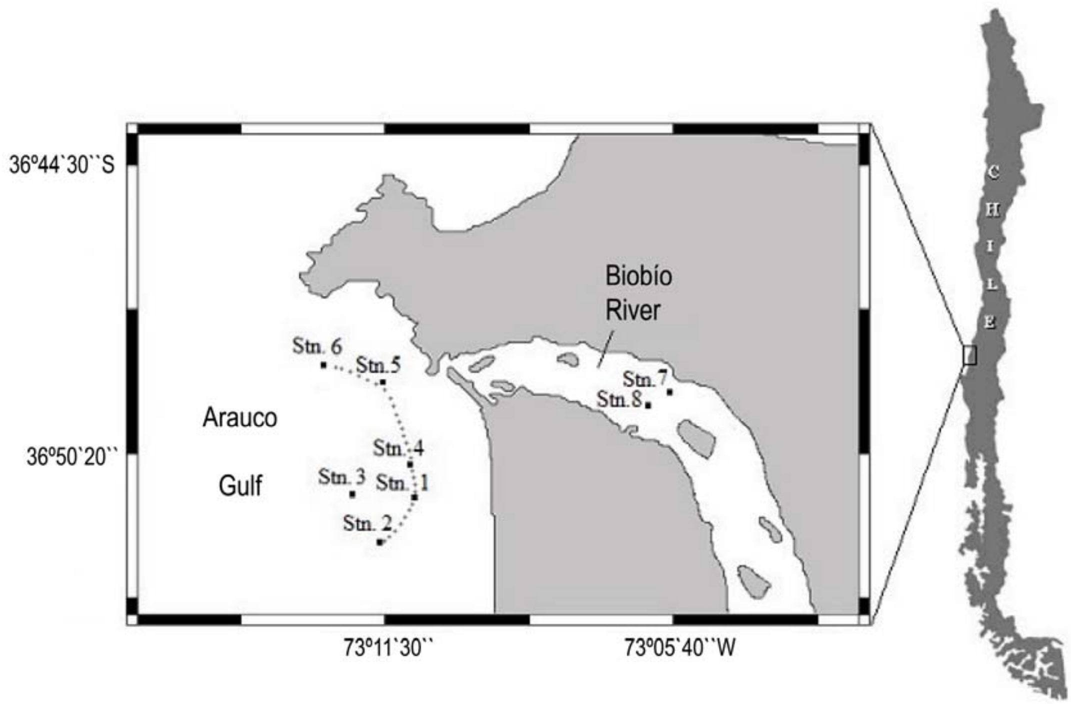

Figure 1. Study area including the location of sampling stations.

Figura 1. Área de estudio incluyendo la ubicación de estaciones de muestreo.

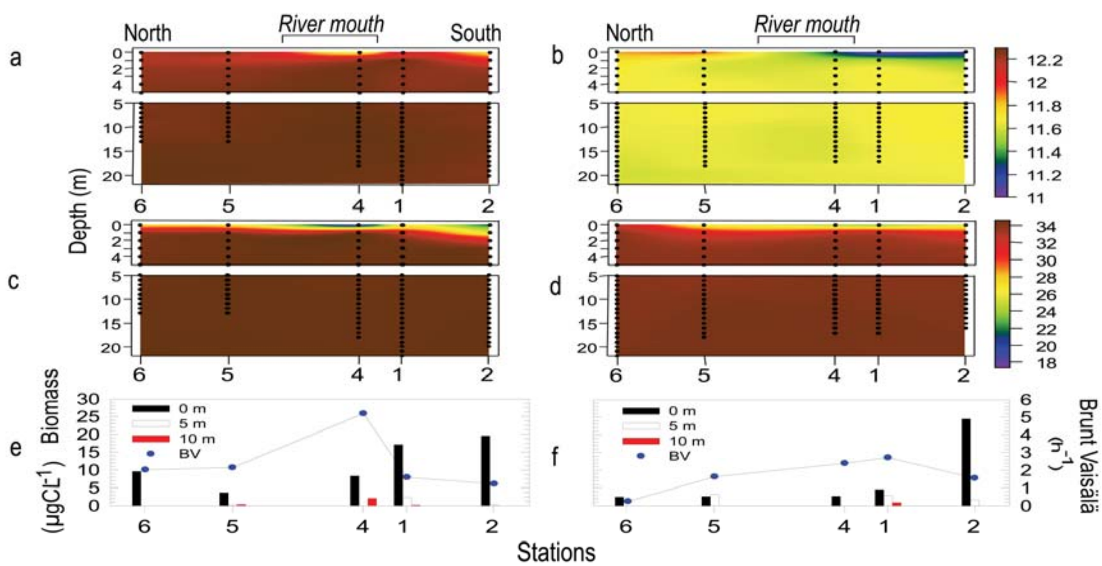

Figure 2. Vertical distribution of (a, b) temperature and (c, d) salinity in the upper 20 m depth water column in (a, c) May and (b, d) August. Microphytoplankton biomass at three depth levels and Brunt-Väisälä frequency in the surface layer is included for both e) May and f) August field campaigns. Note that there is a distortion in the transect shape and its graphical representation.

Figura 2. Distribución vertical de (a, b) temperatura y (c, d) salinidad en los primeros 20 m de columna de agua en (a, c) mayo y (b, d) agosto. Biomasa microfitoplanctónica en tres profundidades y la frecuencia de Brunt-Väisälä en la capa superficial se incluye para e) mayo y f) agosto. Notar que existe una distorsión entre la forma del transecto y su representación gráfica.

May and August campaigns (23.5 and 18 µM, respectively). No clear seasonal pattern in $Si(OH)_4$ concentrations in the river was observed, but its concentration was significantly higher than in the adjacent coastal sea (54 to 193 µM, Fig. 3). Differences in $Si(OH)_4$ concentration between Stn 7 and 8 were probably associated to the geomorphologic heterogeneity and water flow between northern and southern portion in this river section. The influence of freshwater run-off was also visible in low PO_4^{-3} and high $Si(OH)_4$ concentrations in the less saline waters of the upper 5 m, specially in the area associated to the river mouth and southward (Stns 5, 4, and 1) (Fig. 3). In fact, a Spearman Rank correlation analysis evidenced a negative correlation between salinity an $Si(OH)_4$, N:P and Si:N ratios, which in turns evidence the influence of less saline waters determining high concentration of $Si(OH)_4$ and NO_3^- (Table 2).

Between 60 and 99% of the total microphytoplankton abundance was concentrated in the surface layer (0-5 m depth, Figs. 2d and 2f). During our study, centric diatoms were the main contributors to the biomass in the surface layer (53 to 77%), whereas armored and naked dinoflagellates did a minor contribution (<2%) (Table 1). Both, in the river mouth and adjacent ocean, the freshwater and marine genera *Guinardia* spp., *Melosira* spp., *Navicula* spp., *Cymbella* spp., *Fragilaria*, spp., and the freshwater species *Asterionella formosa* Hassal, 1850 contributed mostly to the microplankton abundance in surface waters (>3000 cels L^{-1}, Table 1). Freshwater dinoflagellates from the genus *Ceratium* (i.e. probably *Ceratium hirundinella* (O.F. Müller) Dujardin 1841) were abundant in the river mouth in May, whereas, small marine *Prorocentrum* species were abundant in June and August. *Kryptoperidinium* sp. occurred in the brackish river plume during May and August campaigns. The silicoflagellate *Dictyocha* sp. was abundant in river plume in June. The ANOSIM showed differences in the microphytoplankton assemblages between the river mouth and adjacent ocean environments during May and August, but non-significant differences between both communities were observed during June (Table 1). In August, some diatoms species were only observed in the oceanic station, including freshwater species (Table 1).

Surface distribution of microphytoplankton biomass showed highest biomass associated to the lower reaches of the river and southward in the river plume, mostly associated to less saline waters during both May and August (Figs. 4a and 4c). This pattern was also evident when we observe a north-south alongshore transect (Figs. 2e-2f), where maximum biomass was always associated southward to the river mouth (Stns 1 and 2), coinciding with the southward extension of surface brackish waters of the river plume (Figs. 2c-2d). In fact, a Spearman Rank correlation analyses (Table 2) showed that the abundance of microphytoplankton was negatively correlated with salinity and PO_4^{-3} concentration, which indeed suggest an association with river plume waters characterized by low salinity and PO_4^{-3}.

A preliminary estimation of the potential microphytoplankton carbon flux from the Biobío River to the adjacent coastal ocean showed that between 0.8 to 5.3 ton C d^{-1} of biogenic carbon might be exported to the continental shelf (Table 3). Similarly, between 68 to 243 ton N d^{-1} and from ~7 to 12 ton P d^{-1} are also exported from the river to the adjacent ocean. Here, we only consider the export of inorganic P and N (NO_2^- and NO_3^-), since organic N and P resulting from human activities in a heavily intervened-basin could be even more important in the total nutrient flux to the adjacent ocean. Typically, river discharges export significant amount of SiO_2 as evidenced in our preliminary estimations of ~914 to 1567 ton Si d^{-1} flowing to the adjacent coastal ocean. Highest phytoplankton carbon, silicic acid and nutrient fluxes occurred during the field campaigns with highest river flow (May and August) (Table 3).

DISCUSSION

Along the coast of central Chile, a highly productive upwelling system interacts with a range of mesoscale features, including topographic eddies, canyons, estuaries, and multiple strong freshwater inputs, such as those from Itata and Biobío rivers (Sobarzo *et al.*, 2001, 2007). Our field campaigns were conducted during relatively similar river flow conditions, which ranged from ~500 to 700 m^3 s^{-1} for all sampling periods (Fig. 1). Although restricted in the spatial and temporal scale, the field sampling in the river plume area provided a basic description about the influence of the river discharge over the adjacent continental shelf. The hydrographic conditions during our sampling days evidenced that surface waters were piled coastward, and they might drove to the Arauco Gulf. This southward geostrophic flow has been clearly showed by Sobarzo *et al.* (2007) during winter conditions, when river discharges are relatively high, and northerly winds dominated the meteorological system.

It is well known that anthropogenic activities in the Biobío River basin has resulted in an increase of nitrogen (N) and phosphorus (P) delivery to the coast (Karrasch *et al.*, 2006). Increasing N and P concentration may influence Si:N and Si:P ratios, thus

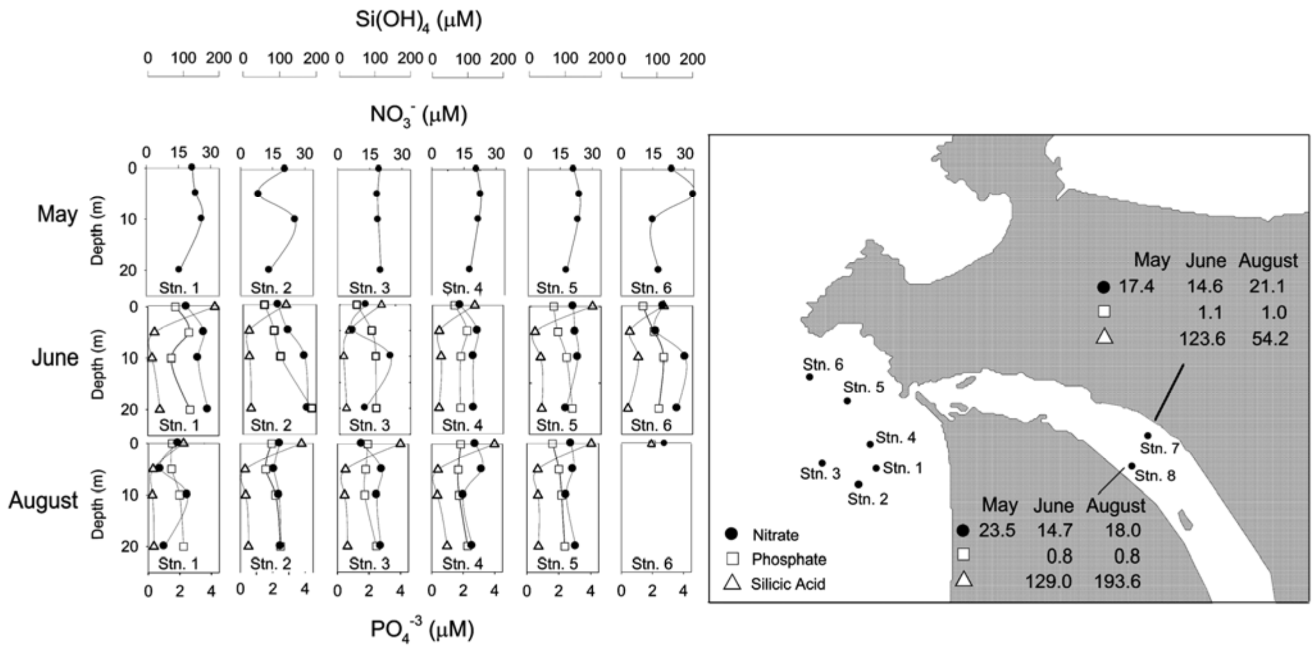

Figure 3. Vertical profiles of nutrients (NO_3^- and PO_4^{-3}) and silicic acid ($Si(OH)_4$) for all stations and sampling periods in the adjacent coastal ocean. Values are also included for measurements conducted in two stations of the lower reaches of Biobío River.

Figura 3. Perfiles verticales de los nutrientes (NO_3^- y PO_4^{-3}) y ácido silícico ($Si(OH)_4$) para todas las estaciones y períodos de muestreo en el océano costero adyacente. También se incluyen los valores de las mediciones realizadas en dos estaciones de la porción baja del río Biobío.

modifying the silicon biogeochemical cycle of the receiving water bodies, leading to severe ecosystem changes, including those on microphytoplankton communities, mainly diatoms (*e.g.* Humborg *et al.*, 1997; Ittekkot *et al.*, 2000). Our values of NO_3^- concentration in the lower reaches of the Biobío River (14 to 23 µM) are significantly higher than those reported in other studies. For instance, Della-Croce & Valdovinos (1994) reported concentration from ~2 to 4 µM in the same area during August 1991, and Karrasch *et al.* (2006) between 1.7 to 5.7 µM in March 2001. However, as part of a long-term monitoring program, Parra *et al.* (2009) have reported NO_3^- concentrations in the lower reaches of the Biobío River in a range from 2.6 to 26.5 µM during the year 2004, which suggest that nutrient concentration might indeed show a high temporal variability throughout the year. Concentration of $Si(OH)_4$ was high both in the river and the adjacent coastal sea. At this respect, high concentrations of $Si(OH)_4$ have been also shown by Della-Croce & Valdovinos (1994) for the same study area. These authors even showed that river:ocean ratio for NO_3 and $Si(OH)_4$ concentration during August averaged 4:5 and 13:1, respectively. Furthermore, Karrasch *et al.* (2006) even reported higher concentration (397 ± 7 µM) of dissolved silica (SiO_2) associated to the lower reaches of the Biobío River. In our study, highest PO_4^{-3} concentration (>2 µM) was always associated to the subsurface marine layer, below the brackish river plume waters, which suggest a major contribution of sub-surface ocean waters.

The autumn-winter microphytoplankton community appears to be dominated by centric and pennate diatoms; some of them were chain-forming diatoms. Non-significant differences were found between phytoplankton communities of river lower reaches and the adjacent coastal area during June, which indeed may suggest the strong influence of freshwater phytoplankton in the oceanic environment at that time. The intrusion of marine phytoplankton species in the Biobío river should be relatively small, considering that the intrusion of seawater into the river reaches approximately 2 km (Bertrán *et al.*, 2001), a situation very different from what happens in other rivers in Chile (*e.g.* River Valdivia) (Vargas *et al.*, 2003). Despite, we were not able to identify all the microphytoplankton species, in order to estimate the total contribution of freshwater vs. marine species, Basualto *et al.* (1992) have estimated that during a low river flow period (March), around 25% of the total biomass in the River Biobío plume corresponds to the riverine contribution of freshwater species. The presence of a spatial distribution, where the largest

Table 1. Mean surface abundance of dominant genera and/or species (>30 cells L^{-1}), *P* values of the Analysis of Similarities (ANOSIM) on Bray-Curtis distances between river (n = 2) and coastal ocean phytoplankton assemblages (n = 6), and relative contribution of taxonomic groups to the total surface biomass.

Tabla 1. Abundancia promedio superficial de los géneros y/o especies dominantes (>30 cel. L^{-1}), valores de *P* de los análisis de similitud (ANOSIM) de distancias de Bray-Curtis entre las comunidades fitoplanctónicas del río (n = 2) y del océano costero (n = 6), y la contribución relativa de los grupos taxonómicos a la biomasa total superficial.

Species	Algal group	May		June		August	
		River	Coast	River	Coast	River	Coast
Corethron criophilum	Centric diatoms	0.0	0.0	0.0	206.1	0.0	0.0
Leptocylindrus sp.	Centric diatoms	0.0	0.0	1851.9	0.0	7555.6	700.8
Aulacoseira granulata	Centric diatoms	5639.7	765.5	0.0	391.0	0.0	0.0
Melosira sp. 1	Centric diatoms	9343.5	1037.1	1388.9	1142.8	2222.2	424.7
Melosira sp. 2	Centric diatoms	7112.8	1127.0	3703.7	1735.6	3111.1	98.9
Melosira sp. 3	Centric diatoms	0.0	0.0	463.0	77.2	0.0	0.0
Guinardia spp.	Centric diatoms	14099.4	17449.7	14351.9	15707.7	0.0	1574.8
Skeletonema costatum	Centric diatoms	0.0	0.0	0.0	3858.0	0.0	0.0
Unidentified centric diatom	Centric diatoms	0.0	0.0	0.0	6006.8	0.0	850.0
Asterionella formosa	Pennates diatoms	3745.8	1091.0	15509.3	5459.2	435.8	0.0
Cocconeis spp.	Pennates diatoms	0.0	1017.8	0.0	125.5	0.0	91.1
Cymbella spp.	Pennates diatoms	3282.8	394.8	925.9	268.8	0.0	137.9
Fragilaria sp.	Pennates diatoms	3745.8	154.3	694.4	265.5	0.0	201.4
Grammatophora sp. 1	Pennates diatoms	1473.1	291.1	0.0	128.9	0.0	0.0
Grammatophora sp. 2	Pennates diatoms	463.0	308.6	463.0	0.0	0.0	0.0
Licmophora sp.	Pennates diatoms	799.7	587.7	694.4	540.1	1333.3	46.9
Navicula sp. 1	Pennates diatoms	6060.6	2196.0	6944.5	1785.4	1777.8	875.4
Navicula sp. 2	Pennates diatoms	9764.3	3950.2	4398.2	2027.9	1333.3	394.0
Nitzchia sp.	Pennates diatoms	0.0	59.7	0.0	119.5	444.4	1569.6
Synedra sp. 1	Pennates diatoms	1599.3	652.7	231.5	371.4	444.4	0.0
Unidentified pennate	Pennates diatoms	2988.2	0.0	231.5	59.7	0.0	0.0
Freshwater *Ceratium* sp. (<200 µm)	Dinoflagellates	925.9	0.0	231.5	0.0	0.0	0.0
Freshwater *Ceratium* sp. (>200 µm)	Dinoflagellates	1262.6	0.0	0.0	0.0	0.0	0.0
Prorocentrum sp. <20 µm	Dinoflagellates	0.0	0.0	231.5	0.0	888.9	216.4
Prorocentrum sp. >20 µm	Dinoflagellates	673.4	0.0	694.4	62.8	444.4	1037.0
Kryptoperidinium spp.	Dinoflagellates	0.0	65.0	0.0	0.0	0.0	121.4
Dictyocha sp.	Silicoflagellates	0.0	0.0	0.0	485.9	0.0	31.7
ANOSIM on Bray-Curtis distances, *P* values			0.035		0.323		0.034
Contribution to total surface biomass (%)							
Large flagellates		0.0	1.9	0.0	1.2	2.1	0.0
Pennates diatoms		23.2	45.3	22.7	28.7	19.1	43.9
Centric diatoms		76.2	52.7	76.1	69.3	77.3	50.7
Dinoflagellates		0.6	0.1	1.2	0.1	1.5	5.2
Silicoflagellates		0.0	0.0	0.0	0.6	0.0	0.2

Table 2. Spearman Rank correlation analyses between abundance, microphytoplankton biomass and environmental variables. Numbers in bold indicate highly significant correlation ($P < 0.01$). n = 41. Data was log (x+1) transformed.

Tabla 2. Análisis de Correlación de Spearman entre la abundancia y biomasa del microfitoplancton y las variables ambientales. Los números en negrita indican una correlación altamente significativa ($P < 0,01$). n = 41. Los datos fueron transformados por log (x +1).

Variables	Salinity	Abundance	Biomass
Temperature	**0.93**	-0.25	-0.15
Salinity	--	**-0.41**	-0.27
NO_2^-	**0.50**	**-0.31**	-0.24
NO_3^-	-0.04	-0.23	-0.24
PO_4^{-2}	-0.29	**-0.38**	**-0.41**
$Si(OH)_4^{-2}$	**-0.57**	0.25	0.20
N:P	**-0.58**	0.14	0.05
Si:N	**-0.54**	0.26	0.20

biomass of microphytoplankton was associated with the river-influenced area, seems to be associated with the formation of frontal zones between the surface river plume and oceanic waters (Acuña & Sobarzo, 1993). Nevertheless, it has been also observed for similar river plume systems that nutrient enrichment of the surface river plume waters may result in high primary productivity at the plume boundaries and beyond, as a result of the entrainment as the freshwater moves over the seawater (Harrison *et al.*, 1991; Yin *et al.*, 2000). Entrainment between the river-discharged freshwater and the oceanic waters bellow is a common vertical mixing process that brings phytoplankton upwards into the riverine plume (Yin *et al.*, 1995). For the Biobío River plume, the entrained phytoplankton might serve as seed populations downstream and algal growth could increase when dilution rates are reduced and conditions of light penetration and salinity are improved. Finally, we have also taken into account that the present study did not consider the contribution of small cyanobacteria and nanoflagellates to the total phytoplankton biomass, in both the river and the adjacent coastal ocean. Consequently, our results represent only a fraction of the total phytoplankton biomass and the freshwater phytoplankton carbon flow to the Arauco Gulf.

Although this is a preliminary estimation of the potential contribution of riverine nutrients (68 to 243 ton N d^{-1}, ~7 to 12 ton P d^{-1}, and ~914 to 1567 ton Si d^{-1}) to the coastal ocean, this important riverine carbon, dissolved silica, and nutrient contribution, together with the influence of the coastal upwelling events, would support the great biological productivity reported in several studies for the Arauco Gulf. The influence of riverine $Si(OH)_4$ on diatom production might also have important implications for annual

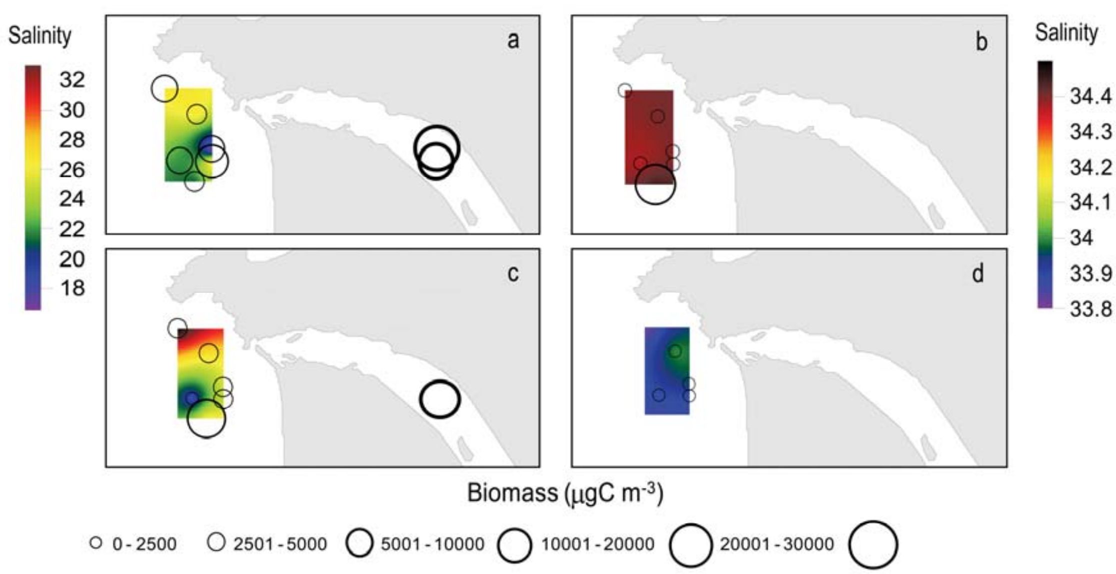

Figure 4. Spatial distribution of salinity and biomass (μgC m^{-3}) in the study area during (a, c) May and (b, d) August sampling periods, and both for the (a, c) surface and (b, d) 10 m depth layer.

Figura 4. Distribución espacial de la salinidad y la biomasa (μgC m^{-3}) en el área de estudio durante (a, c) mayo y (b, d) agosto, y para la (a, c) capa superficial y (b, d) de 10 m de profundidad.

Table 3. Mean river flow ($m^3 s^{-1}$) and phytoplankton carbon, nutrients, and silicic acid fluxes (ton d^{-1}) exported from the Biobío River to the adjacent coastal ocean.

Tabla 3. Caudal promedio del río ($m^3 s^{-1}$) y flujos de carbono, nutrientes y ácido silícico (ton d^{-1}) exportados desde el Río Biobío a la zona costera adyacente.

Month	Mean flow ($m^3 s^{-1}$)	River phytoplankton biomass (μgC L^{-1})	Phytoplankton carbon flux (ton C d^{-1})	N flux (ton d^{-1})	P flux (ton d^{-1})	Si flux (ton d^{-1})
May	2216.2 ± 796.0	28.67 ± 19.28	3.0	243.2 ± 87.4		
June	872.3 ± 38.1	11.85 ± 0.97	0.8	68.4 ± 3.0	6.7 ± 0.3	914.5 ± 39.9
August	1523.8 ± 89.9	20.74	5.3	160.1 ± 9.4	11.6 ± 0.7	1567.0 ± 92.5

variations in the accumulation of biomass in the adjacent sea as reported in other areas worldwide (Conley & Malone, 1992; Turner *et al.*, 1998). During periods of high river flow and, therefore, high loading of new Si, more Si would be available for diatom production, particularly during non-upwelling conditions. In this respect, it would be important to evaluate the contribution of $Si(OH)_4$ (upwelling *vs* river discharge) to the annual primary production observed in this highly productive coastal region. In terms of biogenic carbon, this preliminary estimation of mixohaline and freshwater phytoplankton carbon biomass, that is being exported to the adjacent coastal ocean (0.8-5.3 ton C d^{-1}), is a potential source of organic matter and carbon available to higher trophic levels (*e.g.* zooplankton and planktivorous fishes). We assume that the mean river flows used in our estimations are representative of an autumn-winter condition, which has significant limitations, considering the typically occurrence of extreme events, with high river flows during periods of high precipitation that could determine carbon and nutrient flows in excess more than those presented in this study. It is therefore highly significant that more detailed and long-term studies about riverine contribution to the coastal ocean can be conducted, as well as carbon flux models in river-influenced coastal upwelling ecosystems; consider these riverine carbon sources in global carbon budgets and coastal food-web models.

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