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Groundwater as a possible controller of surf diatom biomass

Agua subterránea como posible controlador de la biomasa de diatomeas de la zona de rompiente de las olas

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ABSTRACT

Several South African beaches have high nutrient loads, both as point sources and as seepage from freshwater aquifers that are located just behind beach foredunes. While point sources may have nitrogen loads up to 100 times higher than that of non-polluted sea water, the seepage water appears to contribute more to the increased nutrient loading of the surf-zone. *Anaulus australis* Drebes et Schulz accumulates to high cell concentrations in several of the surf-zones of South Africa. The accumulations colour the water brown if the conditions are suitable. All sandy beaches longer than 5 km, including the highly polluted False Bay beaches, south-western coast of South Africa, were investigated in this study. Nutrient inputs and phytoplankton standing stocks were measured at each site. A correlation between several environmental variables and phytoplankton biomass showed that the higher the total inorganic nitrogen input from groundwater, the higher the biomass. Eutrophication, while not causing accumulations of *A. australis*, can be considered to change the natural dynamics of this surf diatom resulting in elevated standing biomass. At sandy beaches where human impacts are minimal, large coastal aquifers can provide nitrogen to maintain a biomass level proportional to the magnitude of the nutrient supply. While surf energy is the major driving force controlling the presence or absence of surf diatoms, nutrients may well control their standing stocks.

Key words: Aquifer, nitrate, silicon, *Anaulus australis*.

RESUMEN

Varias playas arenosas de Sudáfrica tienen altas cargas de nutrientes, ya sea a través de puntos focales de origen como por medio de filtraciones de acuíferos de agua dulce localizados inmediatamente detrás de las dunas. Mientras que los puntos focales pueden tener cargas de nitrógeno hasta 100 veces más altas que las de aguas no contaminadas, las aguas afectadas por filtraciones parecen tener una mayor contribución en las altas cargas de nutrientes de la zona de rompiente. *Anaulus australis* Drebes et Schulz produce acumulaciones de altas concentraciones en varias de las zonas de rompiente de Sudáfrica. Como efecto de las acumulaciones, y si las condiciones son apropiadas, el color del agua llega a ser café. Todas las playas arenosas con longitudes superiores a 5 km, incluyendo las altamente contaminadas de False Bay, sudoeste de Sudáfrica, se investigaron en este estudio. En cada sitio se midió cantidad de nutrientes y biomasa de fitoplancton. La correlación entre varias variables ambientales y biomasa fitoplantónica mostró que mientras más alta sea la contribución de nitrógeno inorgánico desde el agua subterránea, mayor es esa biomasa. La eutroficación, aun cuando no causa las acumulaciones de *A. australis*, puede ser considerada como un cambio de la dinámica natural de esta diatomea de la zona de rompiente de las olas lo que resulta en altas biomasas. En playas arenosas donde los impactos humanos son mínimos, acuíferos grandes pueden proveer de nitrógeno para mantener un nivel de biomasa proporcional a la magnitud de la oferta de nutrientes. Aun cuando la energía de la zona de rompiente de las olas es la fuerza mayor que controla la presencia o ausencia de diatomeas, los nutrientes pueden también controlar la biomasa de las mismas.

Palabras clave: Acuífero, nitrato, sílice, *Anaulus australis*.

INTRODUCTION

The significance of groundwater as a source of nutrients to coastal marine ecosystems was largely ignored until 1980. Following a review of the topic by Johannes (1980) the possible contribution of nutrients of terrestrial origin to nearshore waters emerged. There are many coastal ecosystems that rely on nutrients supplied by groundwater. For example, groundwater entering estuaries dilutes the salinity of the water and its lower pH influences the solubility of several elements (Vermeer 1991). The importance of

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coastal aquifers has also been highlighted in studies on marsh vegetation (Merendino et al. 1990; Teal & Valiela 1978) where up to 22% of the nitrogen requirement of coastal marshes is provided by groundwater seepage (Teal & Valiela 1978).

A recent synopsis of the importance of coastal aquifers in southern Africa (Campbell et al. 1992) showed that they played a significant role in the health and survival of coastal ecosystems in general, including surf-zones. However, initial calculations estimated that coastal aquifer seepage could only provide approximately 6% of the nitrogen requirements of the surf diatom population at the Sundays River beach (McLachlan & Illenberger 1986).

Attempts to isolate the factors controlling surf diatom accumulation occurrence along the coast of southern Africa (Campbell & Bate 1990) resulted in the conclusion that the following physical features of surf zones were a prerequisite for surf diatom accumulation development: 1. A well-developed surf-zone (wide, long, with high energy); 2. Rip activity and 3. An adjacent coastal dunefield.

The mechanisms of the first two have been elaborated on by various authors (Lewin et al. 1975; Talbot et al. 1990). The association of surf diatom accumulations with an adjacent dunefield led to the reinvestigation of the possibility of groundwater nutrients contributing to diatom accumulations at sandy beaches of South Africa.

MATERIALS AND METHODS

The study area

All sandy beaches longer than 5 km (Campbell & Bate 1988b) along the southern coast of Africa were investigated (Fig. 1). Each is referred to by its decimal degree east in the figures, for example the data for Muizenberg (at 18° 34.2'E) is plotted against 18.57° E (Table 1).

Environmental variables

Wave height was estimated visually. The topography of the substrate was classified into four states. They are, in order of high to low energy: dissipative, longshore bar-trough, rhythmic bar, and reflective beach states (Wright & Short 1983). Surf-zone width was estimated visually by counting the

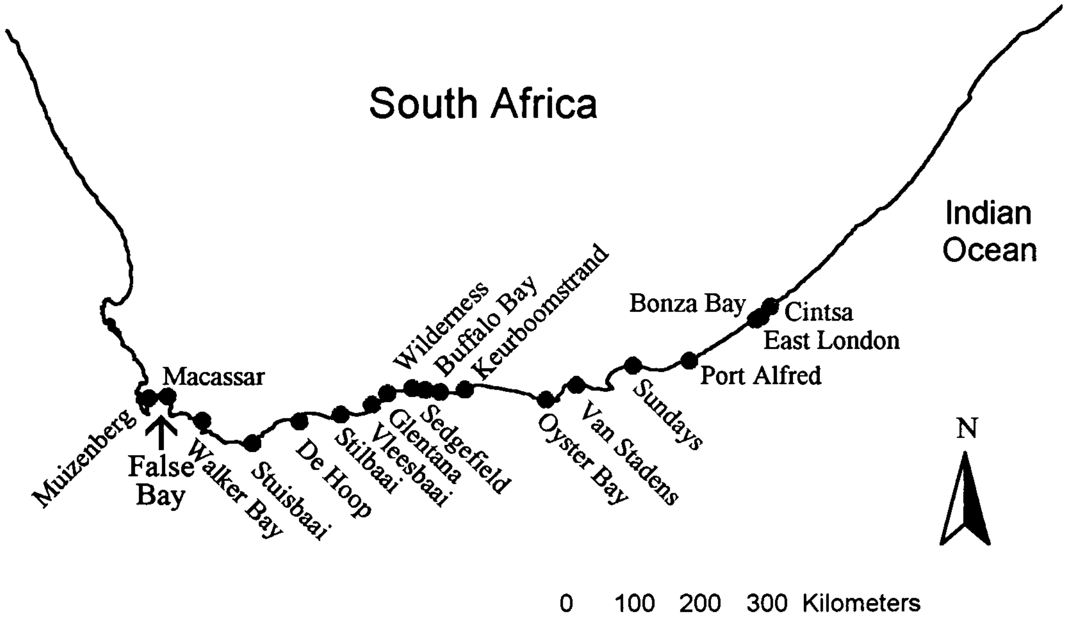

Fig. 1: A map of the south coast of South Africa showing the location of the beaches sampled.
Mapa de la costa sur de Sudáfrica mostrando la localización de las playas muestreadas.

TABLE 1

The list of beaches that were sampled in this study; co-ordinates are given as decimal degrees east

Lista de playas muestreadas en este estudio; se entregan las coordenadas en grados decimales este

Number	Beach	Co-ordinate (°E)
1	Muizenberg, False Bay	18.50
2	Macassar, False Bay	18.78
3	Walker Bay	19.30
4	Stuisbaai	20.05
5	De Hoop	20.80
6	Stilbaai	21.45
7	Vleesbaai	21.93
8	Glentana	22.17
9	Wilderness	22.57
10	Sedgefield	22.77
11	Buffalo Bay	23.00
12	Keurboomstrand	23.38
13	Oyster Bay	24.65
14	Van Stadens	25.12
15	Sundays	26.00
16	Port Alfred	26.88
17	East London	27.90
18	Bonza Bay	27.97
19	Cintsa Bay	28.12

number of wave bores. Wind velocity and direction were measured using a hand-held anemometer and a compass. These variables were used in a multiple linear regression to determine which were correlated to standing stock.

Groundwater discharge

According to Darcy's Law and the Ghyben-Herzberg relation (Raghunath 1982) groundwater discharge is directly proportional to the slope of the groundwater surface in an unconfined aquifer. Because porosity data was not available for most of the sites, groundwater discharge into the sea was estimated by measuring the slope of the groundwater table.

The slope of the groundwater table was determined by drilling two wells in the sand using an auger, one close to the swash line and the other behind the foredune. When water was found, the difference in height between the water table of the two wells was measured with a dumpy level. The slope was calculated as this difference in height divided by the horizontal distance between the wells. This procedure assumes a free groundwater table terminating at sea level at the time of sampling and results in an index of groundwater flow rather than an actual measurement.

Nutrients

Nitrate was determined according to Bate & Heelas (1975) by reduction to nitrite and the nitrite analysed by the method of Greiss (1879) and Ilosvay (1889). Ammonium, phosphorus and silicon were determined according to Strickland & Parsons (1972).

Diatom biomass

At each beach, water samples were taken every 1 km based on the recommendation of Campbell (1987). The chlorophyll a concentration in each sample was measured on ethanol extracts, using the spectrophotometric method recommended by Nusch (1980). The chlorophyll a concentration of some of the samples was also measured by high performance liquid chromatography (HPLC) using a 1608 Micro Pak HCH-5n reverse-phase column and isocratic elution with 70% methanol: 30% acetone. Duplicate samples showed less than 5% difference using the two methods.

Results were expressed as the amount of chlorophyll a per running metre of surf-zone. This was done because the surf-zone is a semi-closed ecosystem (McLachlan 1980) with little or no exchanges on the seaward side. Surf-zone widths vary and the standing biomass of the surf-zone was estimated for the whole volume of the surf-zone for a 1 m wide section, i.e. a running metre.

RESULTS

Environmental variables

The beaches sampled span 10° longitude (Table 1) with a sea temperature range of approximately 4° C during one sampling period (from 16.2° C to 20.5° C). Wave heights ranged from 0.5 m to 3 m with low waves associated with east-facing coastline. Surf widths, which ranged from 50 m to 500 m, were also narrower at east facing beaches.

Most of the beaches were in a longshore bar-trough state (24 out of 40 recordings) while 9 were dissipative and 5 were in a rhythmic-bar state. Two beaches had no distinctive morphology.

Groundwater discharge

The rate of groundwater discharge, estimated as the groundwater table slope is presented in Fig. 2. The slope was negative at three stations, one at Walker Bay and the other two at the eastern end of Cintsa Bay. These positions would have no net groundwater discharge. The remainder of the sites had positive slopes and so some groundwater would be discharged into their surf zones.

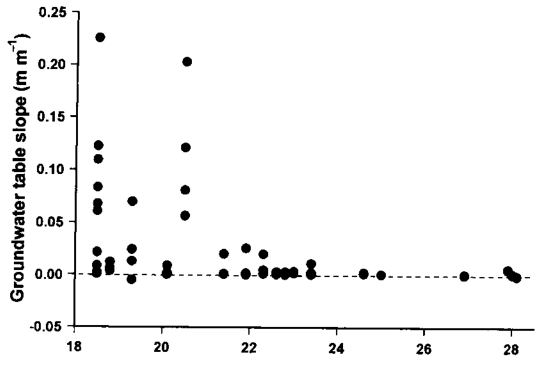

Fig. 2: The groundwater table slope measured in beach sand adjacent to the surf- zone of southern Africa.

Pendiente de la capa de agua subterránea medida en arenas adyacentes a la zona de rompiente de playas arenosas de Sudáfrica.

Nutrients

Phosphate concentrations in surf water (4.38 ± 0.13 μmol l^{-1}, Fig. 3) were similar to that of the groundwater entering the surf-zone (4.63 ± 0.10 μmol l^{-1}, Fig. 3). Groundwater was, with a few exceptions, not a source of phosphate to surf-zones.

Ammonium concentrations in surf water (23.56 ± 0.90 μmol l^{-1}, Fig. 4) were also similar to the concentrations in groundwater (24.61 ± 0.69 μmol l^{-1}, Fig. 4), with one exception at Vleesbaai. Groundwater was also not a source of ammonium to coastal waters.

Nitrate concentrations of surf water averaged 16.55 ± 0.45 μmol l^{-1} (Fig. 5) including False Bay beaches and 6.31 ± 0.28 μmol l^{-1} excluding False Bay beaches. Groundwater contained substantially more nitrate with an average of 52.66 ± 0.91 μmol l^{-1} (Fig. 5) for all samples taken and 65.07 ± 2.07 μmol l^{-1} for beaches excluding False Bay.

Silicon is required for diatom frustule development. Soluble reactive silicon concentrations in surf water was low (13.74 + 0.7 μmol l^{-1}; Fig. 6) when compared to that of the groundwater (63.81 + 1.78 μmol l^{-1}; Fig. 6) and so groundwater was a source of silicon to surf diatom populations.

Nutrient index

Nutrient loading indices were calculated to rank the beaches based on the input of nutrients from terrestrial sources. The following equation was used:

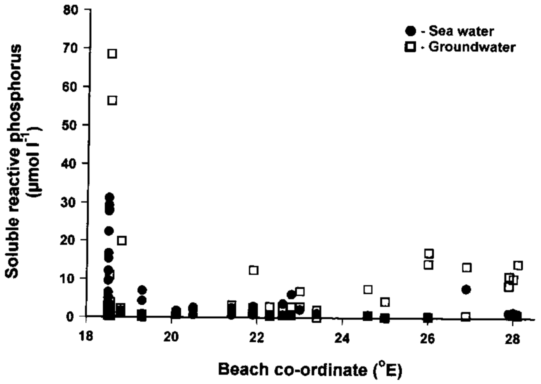

Fig. 3: The soluble reactive phosphorus concentration in surf water and groundwater measured at the longer beaches of southern Africa.

Concentración de fósforo soluble reactivo en el agua de la zona de rompiente de las olas y en las aguas subterráneas a lo largo de las playas de Sudáfrica.

Index_N = nutrients . 35 - salinity/35 .100 .slope (equation 1)

Where Index_N = a unitless ranking parameter of nutrient input to beaches from groundwater; nutrients = the mean inorganic nutrient concentration in the groundwater; salinity = the mean salinity of the groundwater in parts per thousand (to correct for the amount of sea water in the samples that would dilute the nutrients in the groundwater); 100slope = the groundwater table slope multiplied by 100 to increase the number to an integer.

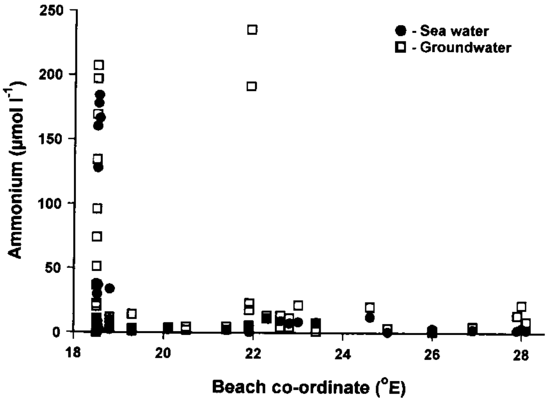

Fig. 4: The ammonium concentration in surf water and groundwater measured at the longer beaches of southern Africa.

Concentración de amonio en el agua de la zona de rompiente de las olas y en las aguas subterráneas a lo largo de las playas de Sudáfrica.

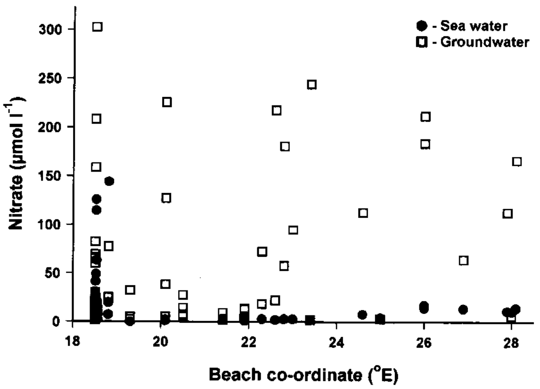

Fig. 5: The nitrate concentration in surf water and groundwater measured at the longer beaches of southern Africa.

Concentración de amonio en el agua de la zona de rompiente de las olas y en las aguas subterráneas a lo largo de las playas de Sudáfrica.

The Index$_N$ for each beach, using inorganic nitrogen, silicon and all nutrients is presented in Table 2.

Biomass

Biomass measured as chlorophyll a concentration of surf water is presented in Fig. 6. These values could be correlated to the nutrient indices calculated above. Diatom biomass was significantly correlated (Table 2) to inorganic nitrogen ($r = 0.817$, $n = 19$, $p > 0.05$) and soluble reactive silicon ($r = 815$, $n = 19$, $p > 0.05$). When correlating biomass with all the inorganic nutrients, the correlation coefficient did not increase much ($r = 0.820$, $n = 19$, $p > 0.05$) over the coefficient of nitrogen or silicon alone. The correlation coefficients for the individual nutrients and environmental variables are given in Table 3. All groundwater nutrients are significantly correlated to phytoplankton standing stock, while only sea water ammonium is significantly correlated.

DISCUSSION

Because soluble reactive phosphorus and ammonium concentrations in groundwater were similar to that of the sea water, the groundwater flowing into the sea was no source of these nutrients to surf diatoms. At most beaches with surf diatom accumulations, the nitrate concentrations of groundwater was much higher than that of the sea; on average 10 times higher. Groundwater discharge was also a source of silicon required by diatoms. D R du Preez (personal communication, August 1989) has shown that it is impossible to culture cells of the diatom *Anaulus australis* Drebes et Schulz without elevated levels of silicon, while other diatoms obtain sufficient silicon simply by culturing them in a glass vessel. Surf diatoms appear to require higher concentrations of silicon than most other species.

The rate at which the aquifer water seeps into the Sundays River surf-zone has been estimated at 1 m^3 m^{-1} d^{-1} (McLachlan &

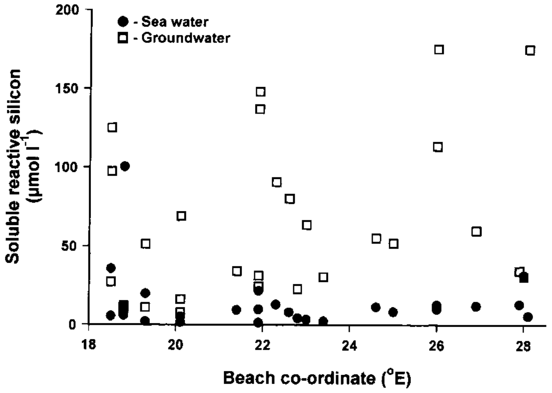

Fig. 6: The soluble reactive silicon concentration in surf water and groundwater measured at the longer beaches of southern Africa.

Concentración de sílice soluble reactivo en el agua de la zona de rompiente de las olas y en las aguas subterráneas a lo largo de las playas de Sudáfrica.

TABLE 2

The mean biomass, expressed as mg chlorophyll a per running metre of beach irrespective of the surf-zone width, and nutrient loading indices calculated using equation 1, of the longer beaches of southern Africa

Biomasa promedio, expresada como mg clorofila a por metro lineal de playa independiente del ancho de la zona de rompiente e índices de cargas de nutrientes calculados según la ecuación 1, en las playas más largas de Sudáfrica

Beach	Biomass (mg chl *a* m^{-1})	Nitrogen index	Silicon index	All nutrient index
Muizenberg	141.1	121.0	141.4	262.4
Vleesbaai	64.4	8.8	7.3	16.1
De Hoop	47.9	0.2	0.1	0.3
Walker Bay	35.0	5.7	11.3	17.0
Sundays	25.0	1.3	0.9	2.2
Macassar	23.9	0.6	0.1	0.7
Oyster Bay	22.5	20.9	8.7	29.6
Wilderness	21.2	10.5	6.6	17.1
Port Alfred	14.8	9.7	8.6	18.3
Buffalo Bay	12.0	22.6	12.4	35.0
Sedgefield	10.3	8.0	1.4	9.4
Stuisbaai	10.2	8.9	2.7	11.6
Keurboomstrand	9.8	1.4	0.3	1.8
Cintsa	8.9	11.6	11.6	23.2
Van Stadens	8.3	0.3	2.5	2.8
Glentana	5.2	26.9	42.4	69.3
Stilbaai	4.7	0.1	0.1	0.2
East London	3.9	1.0	0.3	1.3
Bonza Bay	3.6	0.1	0.2	0.3
Correlation coefficient (r) with biomass		0.817	0.815	0.820

TABLE 3

The correlation coefficients of biomass, expressed as mg chlorophyll a per running metre of beach irrespective of the surf-zone width, and various environmental variables of the longer beaches of southern Africa

Coeficientes de correlación de biomasa, expresada como mg clorofila a por metro lineal de playa independiente del ancho de la zona de rompiente, y variables ambientales en las playas más largas de Sudáfrica

Variable	Correlation coefficient of biomass (mg m^{-1}) with variable (*=significant, n = 20)
Beach length	0.003
Wave height	0.041
Surf-zone topography	0.031
Surf-zone width	0.097
Sea water nitrate	0.025
Sea water ammonium	0.566*
Sea water phosphate	0.267*
Sea water silicate	0.022
Sea water total inorganic N	0.235
Groundwater nitrate (adjusted as Eq. 1)	0.467*
Groundwater ammonium (adjusted as Eq. 1)	0.854*
Groundwater phosphate (adjusted as Eq. 1)	0.808*
Groundwater silicate (adjusted as Eq. 1)	0.815*
Groundwater total inorganic N (adjusted as Eq. 1)	0.817*

Illenberger 1986). At this rate of flow the nitrogen supply would be just over 1 kg N m^{-1} y^{-1} into this system. The primary production at the same locality has been estimated at 120 kg C per running meter of beach per year (Campbell & Bate 1988a). The nitrogen requirements of surf phytoplankton are estimated to be 10 kg N m^{-1} y^{-1} (Campbell 1987). Because the surf-zone ecosystem is a closed system on the seaward side (Talbot & Bate 1987) and an estimated 11% of the primary producers are lost from the end of the ecosystem (Campbell & Bate 1988b), the nitrogen leaving the surf-zone would be 1.1 kg N m^{-1} y^{-1}. This means that the nitrogen entering the ecosystem from groundwater (1 kg N m^{-1} y^{-1}) would supplement most, if not all, of the nitrogen requirements of surf diatoms.

The origin of the nutrient in the groundwater could either be due to natural processes (Raghunath 1982) or due to anthropogenic influence, such as septic tank seepage (Campbell et al. 1992) or direct pollution from storm water runoff and sewage processing (Englebrecht & Tredoux 1989). Studies are underway to determine what the sources of these nutrients are at beaches along the south coast of South Africa.

A. australis cells divide once a day (Talbot & Bate 1986), irrespective of the nutrient availability (D R du Preez personal communication, August 1989). With the division rate constant, increased nutrient can only result in increased biomass or loss of nutrient to the nearshore. Observation of point source plumes show that often these pass through the surf-zone into the nearshore. It is possible that most of the nutrients from point sources ultimately end up behind the breaker line. However, groundwater and nutrients seeping into the surf-zone through the sand will have to be flushed from the system by wave action if not taken up by the surf diatom population. The residence time of these nutrients will be much higher than with a point-source.

False Bay beaches (Muizenberg & Macassar, Fig. 1) adjoin a large aquifer that is heavily polluted, both from septic tanks and storm water runoff (Englebrecht & Tredoux 1989). It is at these beaches that the water becomes so discoloured by diatom accumulations that there has been a public outcry (Bate et al. 1991). Muizenberg beach has a higher nutrient inflow than any other along the South Africa coast (Table 2). This high nutrient concentration possibly results in the sustained high biomass observed.

Eutrophication, while not causing accumulations of *A. australis*, can be considered to change the natural dynamics of this diatom resulting in elevated standing biomass. *A. australis* takes up terrestrial effluent nutrient and, as it is a nutritious organism that feeds a magnitude of surf fauna, it most likely protects adjacent waters from less desirable phytoplankton blooms.

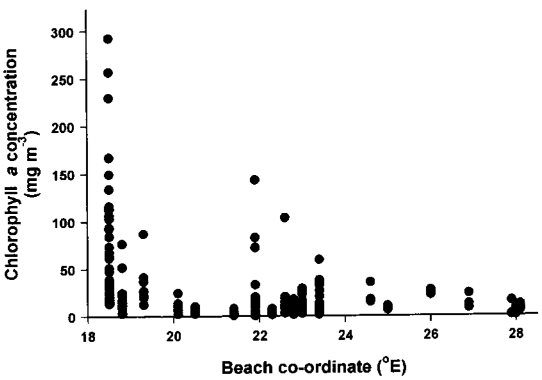

Fig. 7: The phytoplankton biomass, measured as chlorophyll a concentration, of surf water at the longer beaches of southern Africa.

Biomasa del fitoplancton medida como concentración de clorofila a, en el agua de la zona de rompiente a lo largo de las playas de Sudáfrica.

At sandy beaches where human impacts are minimal, large coastal aquifers can provide nitrogen to maintain a surf diatom standing stock level proportional to the magnitude of the nutrient supply. While surf energy is the major force controlling the presence or absence of surf diatoms (Lewin et al. 1975, Talbot et al. 1990), nutrients may well control their standing stocks.

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