EFFECT OF CLIMATIC CHANGE ON THE HARVEST OF THE KELP *MACROCYSTIS PYRIFERA* ON THE MEXICAN PACIFIC COAST

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ABSTRACT

The effect of sea temperature, sea level, upwelling, and wind speed on the *Macrocystis pyrifera* harvest was evaluated using historical harvest data for the western coast of the Baja California Peninsula, Mexico. The relationship between the environmental variables and harvest per unit effort (CPUE) was determined through correlation analysis for the period from 1956–1998. The effects of temperature, upwelling, and sea level were inverse, whereas the effect of wind speed was not significant. Multiple regression analysis showed that, of the variables studied, temperature best explained variations in *Macrocystis* harvest.

The giant kelp *Macrocystis pyrifera* (Linnaeus) C. Agardh is a member of the large brown algae (Phaeophyta) that are a conspicuous part of the marine environment. It is a subtidal species that attaches to solid or soft substrate, produces holdfasts that are either conical or low mounds. Because of the great size of individual plants, their trunk-like appearance in the water column, and the extensive surface canopies along the coastline, these subtidal habitats have been called forests (Foster and Schiel, 1985). Subtidal forests of *M. pyrifera* occur in many areas of the world, but is most widely distributed in the southern hemisphere. In the northern hemisphere, *M. pyrifera* commonly occurs from near Santa Cruz (central California) to Baja California (Foster and Schiel, 1985). Giant kelp is highly productive.

Macrocystis has been harvested since 1956 along the Pacific coast of Baja California and exported to the United States for the production of alginates. Recently, it has been sold in Mexico as meal and for abalone aquaculture (McBride, 1998). It is harvested by specially designed ships that cut the algae at an approximate depth of 1.2 m and transport it. Two ships participated in the harvest at the area of interest: EL CAPITÁN, from 1956–1966, (storage capacity of 300 t), and EL SARGACERO from 1967 to present, (storage capacity of 400 t). Ship operations were the same at all locations and did not change over the study period.

In spite of the importance of kelp, studies of variations in abundance or the size of harvest are few. Casas et al. (1985) and Hernández et al. (1989a,b; 1991) reported higher values of surface canopy and standing crop biomass in spring and summer. Corona (1985) found a higher harvest with less effort in spring and summer from data on kelp beds from 1978–1984. The first objective of this study is to analyze changes in the size of *M. pyrifera* harvest, the effort, and the catch per unit effort (CPUE) along the western coast of the Baja California Peninsula over the period of large-scale harvest, almost 43 yrs.

There is evidence that climatic changes have altered the productivity of marine ecosystems at several trophic levels (Polovina et al., 1994). The existence of causative relationships between the physical environment and biological productivity has been demonstrated (Polovina et al., 1995). In the California Current System and in other parts of the world, changes in climate have been shown to cause fluctuations in the number of small

pelagic fish (Southar and Isaacs, 1974; Lluch et al., 1989, 1991, 1992; Baumgartner et al., 1992; MacCall, 1996). Less is known about the effect of climate on benthic resources. In California, there is available information about the effect of environmental variables on the crab fishery (Wild et al., 1983; Bostford, 1986), abalone (Tegner, 1989, 1991; Davis et al., 1992), and sea urchin and kelp (North and Zimmerman, 1984; Dean and Jacobsen, 1984, 1986; Tegner and Dayton, 1987; Tegner et al., 1996). Tegner et al. (1996) compared data on the maximum canopy of the kelp forests and the size of the annual harvest of *Macrocystis* for California, and they chose harvest size as the most useful data to relate to environmental variables. They pointed out that harvest size was a reflection of changes in consumer demand and harvest productivity, as well as natural disturbances. This data has the advantage of integrating growth over a long period and has less subjectivity in its measurement.

The second objective of this study is to show how the abundance of *M. pyrifera,* expressed as catch per unit effort (CPUE) is related to environmental variables, including sea surface temperature, sea level, upwelling index, and wind speed on the west coast of Baja California. It was also determinated which environmental factor best explains the variability in the abundance of *Macrocystis*.

METHODS AND MATERIALS

In Mexico, *M. pyrifera* is distributed along the western coast of the Baja California Peninsula from the border with the USA to Punta San Roque, Baja California Sur. However, the alga is harvested from Islas Coronado (32°15'N) to Arrecife Sacramento, Baja California (30°30'N) at 15 beds: Islas Coronados, Playas de Tijuana, Punta Mezquite, Salsipuedes, San Miguel and Sauzal, Bahía de Todos Santos, Punta Banda, Bahía Soledad, Santo Tomás, Punta China, Punta San José, Punta San Isidro, Punta San Telmo, Isla San Martín, and Bahía del Rosario (Fig. 1). This study encompasses all of these.

KELP HARVEST DATA.—Daily harvest records from 1956–1998 were provided by Products of the Pacific, S.A. de C.V. These contained the following information: harvest date, name of the bed, number of trips made by each ship, and harvest size mt (wet weight). In total, data were extracted from 3278 daily records.

The volume of the harvest per trip made by each ship, called harvest per unit effort (CPUE), served as an index of abundance of *Macrocystis*. To adjust for the difference in the storage capacity of the two ships, the data on harvest volume trip^{-1} was weighted in the following way:

Period	Storage capacity (t)	Harves volume/trip (t)	Weight factor
1967–98	400	364	1
1956–67	300	222	0.61

PHYSICAL PARAMETERS.—Sea surface temperatures (SST) were obtained from the data base of Reynolds and Smith (1994). The database contains monthly averages of SST (°C) from 1956–1992 for $2° \times 2°$ ocean quadrants. Records for latitudes 30°–32° N were selected. For the years 1993–1998, this information is available for $1° \times 1°$ ocean quadrants. For consistency, we averaged the monthly values from four quadrants. For years 1956–97, annual averages for the middle level of the sea (MLS) were obtained from the web page of the Sea Level Center of the University of Hawaii (http:lluslc.soest.Hawaii.edu/uhslc/data.html). For years 1956–98, the upwelling index (UI) for latitudes 28.5°–31.5°N was obtained from the upwelling index database of Bakun (1973), which maintains records for $3° \times 3°$ ocean quadrants. The upwelling index is expressed as $m^3 s^{-1} 100 m^{-1}$ of
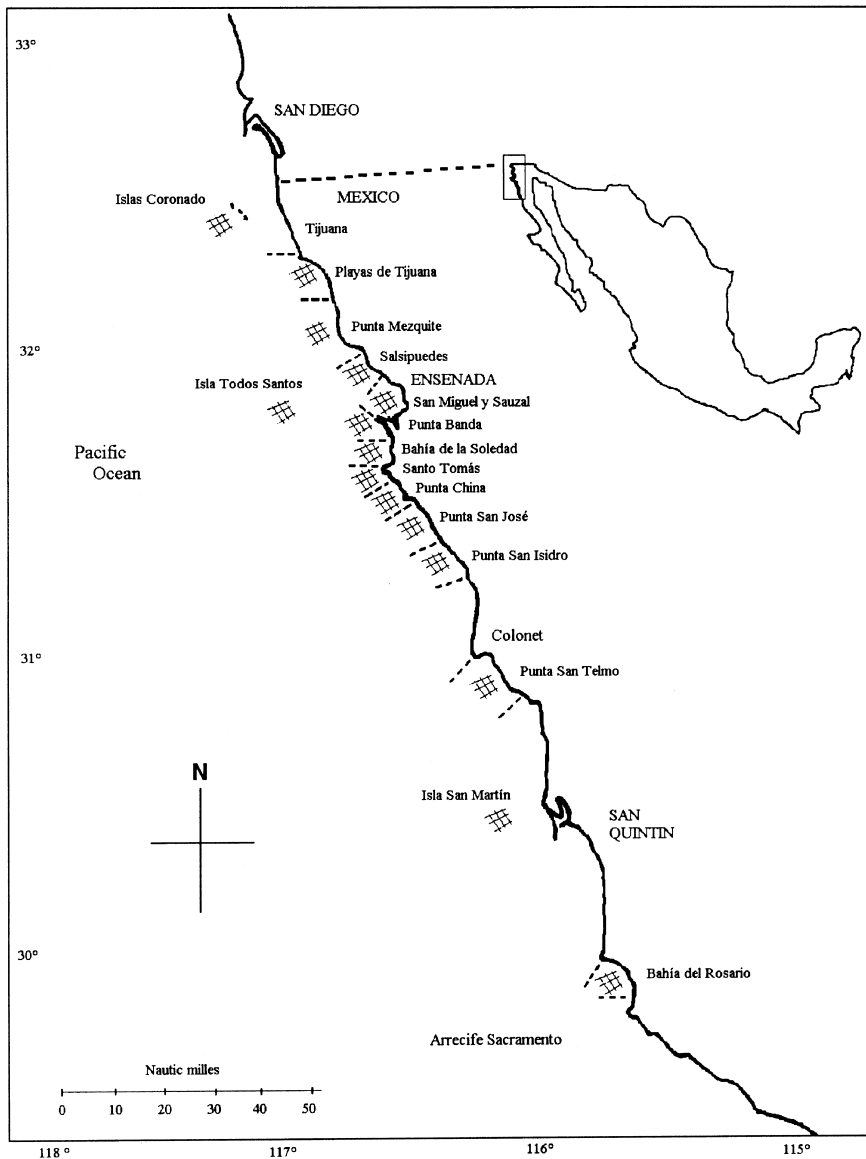
Figure 1. Distribution of the harvest beds of *Macrocystis pyrifera* along the Baja California Peninsula.

coast. For 1956–89, wind speed data (WS) for latitudes 30°–32° N were obtained from the COADS (Comprehensive Ocean-Atmosphere Data Set) database, which compiles monthly average wind speeds in ms^{-1} for 2° × 2° ocean quadrants.

The annual averages for cpue, SST, UI, WS, and MLS were calculated. These average values were used to calculate the annual anomalies for each of the variables using the following equations:

$$A_i = x_i - \bar{x}$$

$$\bar{x} = \frac{\displaystyle\sum_{i=1}^{n} Xi}{n}$$

where, A is the anomaly of the ith year, Xi is the ith annual value, x is the average value for the year i to n, n is the number of years.

Because the SST and MLS series had a long-term trend, this trend was eliminated through a linear fit. To eliminate the noise in the interannual variability in the graph representation, the series were smoothed by using running averages (Statsoft, 1999).

The relationships between abundance of *M. pyrifera* and the climatic variables were determined through correlation analysis using the anomalies of variables and harvest volume/trip values (Anderson, 1972). To identify the factor that explains most the variation in harvest volume/trip of *Macrocystis,* a multiple linear regression analysis was used (Zar, 1984).

RESULTS

In Baja California, kelp forests of *M. pyrifera* have been harvested since 1956 by the same company. Annual harvest have ranged from a low of 2980 t in 1983, to 44,250 t in 1989, with an average of 25,900 t (Fig. 2A). The history of the *Macrocystis* harvest reveals two major periods: 1959 to 1977, when the harvest increased to 44,000 t, and 1985–1997, when the harvest fluctuated around 32,800 t. Three large declines in harvest occurred in 1958, 1983, and 1998 (Fig. 2A), declines of 87%, 89%, and 79% with regard to the average value.

SST from 1956–98 had an average value of 17.4°C, with a minimum of 16.3°C in 1975 and a maximum of 19.3°C in 1998. There were cool periods in 1956–57, 1960–66 and 1969–76. Warming periods occurred in 1958–59, 1981–84, and a very pronounced one from 1992–98. In this last year, the SST was the warmest in 43 yrs (Figs. 2B,3A). For the period 1956–97, MLS varied, on average by 2.03 cm, with a minimum of −67.6 cm in 1964 and a maximum of 107.2 cm in 1984. MSL had negative anomalies in 1960–76 and 1988–90. Positive anomalies occurred in 1958–59, 1982–84, and 1990–97 (Figs. 2C,3B).

The average value for the UI from 1956–98 was 122 $m^3 s^{-1}$, with a minimum of 67 m^3 s^{-1} in 1966 and a maximum of 169 $m^3 s^{-1}$ in 1971. There were three periods of negative anomalies: 1965–69, 1985–87 and 1992–93. Positive anomalies occurred in 1956–59, 1970–75, 1980–84 and 1989–91 (Figs. 2D,3C). From 1958–90, the average wind speed was 22.2 $m^3 s^{-1}$, with a minimum of 17.5 $m^3 s^{-1}$ in 1967 and a maximum of 29.9 $m^3 s^{-1}$ in 1987. Clear negative anomalies occurred in 1959 and 1966–70. Positive anomalies occurred in 1971–75 and 1982–89 (Figs. 2E,3D).

Correlation analyses indicated an inverse relationship between the size of CPUE and SST ($r^2 = -0.46$; P < 0.05; Fig. 3A); MLS ($r^2 = -0.48$; P < 0.05; Fig. 3B), and UI ($r^2 = -0.35$, P < 0.05; Fig. 3C). The relationship between cpue and WS was not significant ($r^2 = 0.006$, P > 0.05; Fig. 3D). The results obtained by multiple regression analysis (SST: −0.45; MLS: −0.02; WS: −0.03 with r = 0.46, P < 0.10) indicate that changes in SST best explain the variation in harvest volume trip^{-1} of *M. pyrifera.*
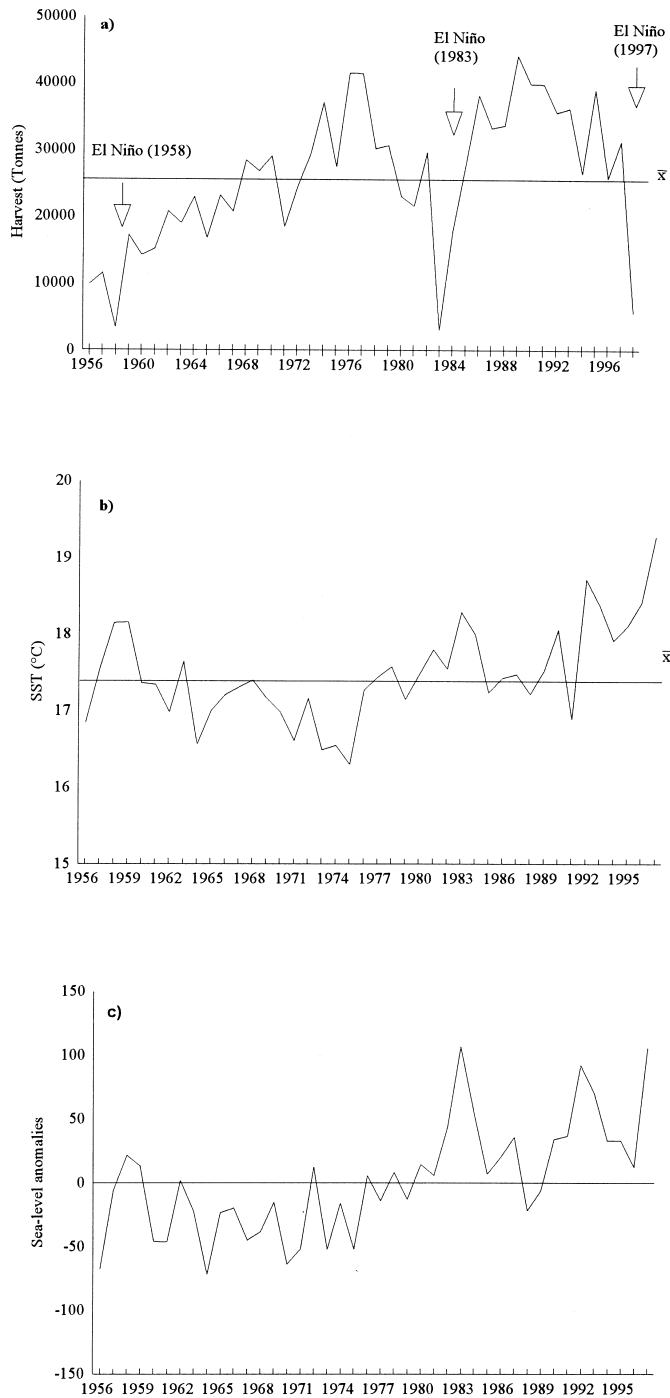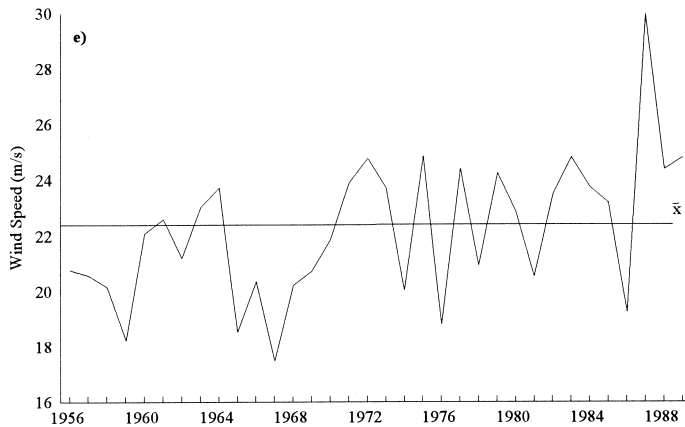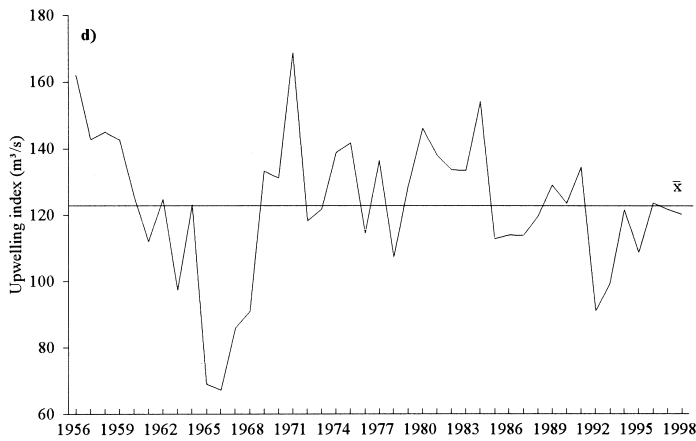
Figure 2. Data series of a) Harvest volume of *Macrocystis pyrifera*, b) Sea surface temperature, c) Middle anomaly level sea, *(on following page)* d) Upwelling index , and e) Wind speed.

Discussion

The fishery of *M. pyrifera* does not show signals of overexploitation, since it is at a stage where effort increases correspond to harvest increases and the CPUE has remained almost constant from the beginning of the collecting period until the present.

The harvest volume per trip is a reasonable indicator of the abundance of *Macrocystis* because approximately 60% of the algal biomass is represented by the surface canopy and about 95% of the production is in the upper 1 m of the water column, with a maximum cutting depth of 1.2 m. Furthermore, harvesting techniques and the ships have remained similar over the period of study, so the volume of each harvest is comparable throughout this study.

The periods of cooling and warming of the SST found during over 43 yrs are consistent with those found by Smith (1995) for 1940–1983 at the Scripps Institution of Oceanography pier in La Jolla, California.
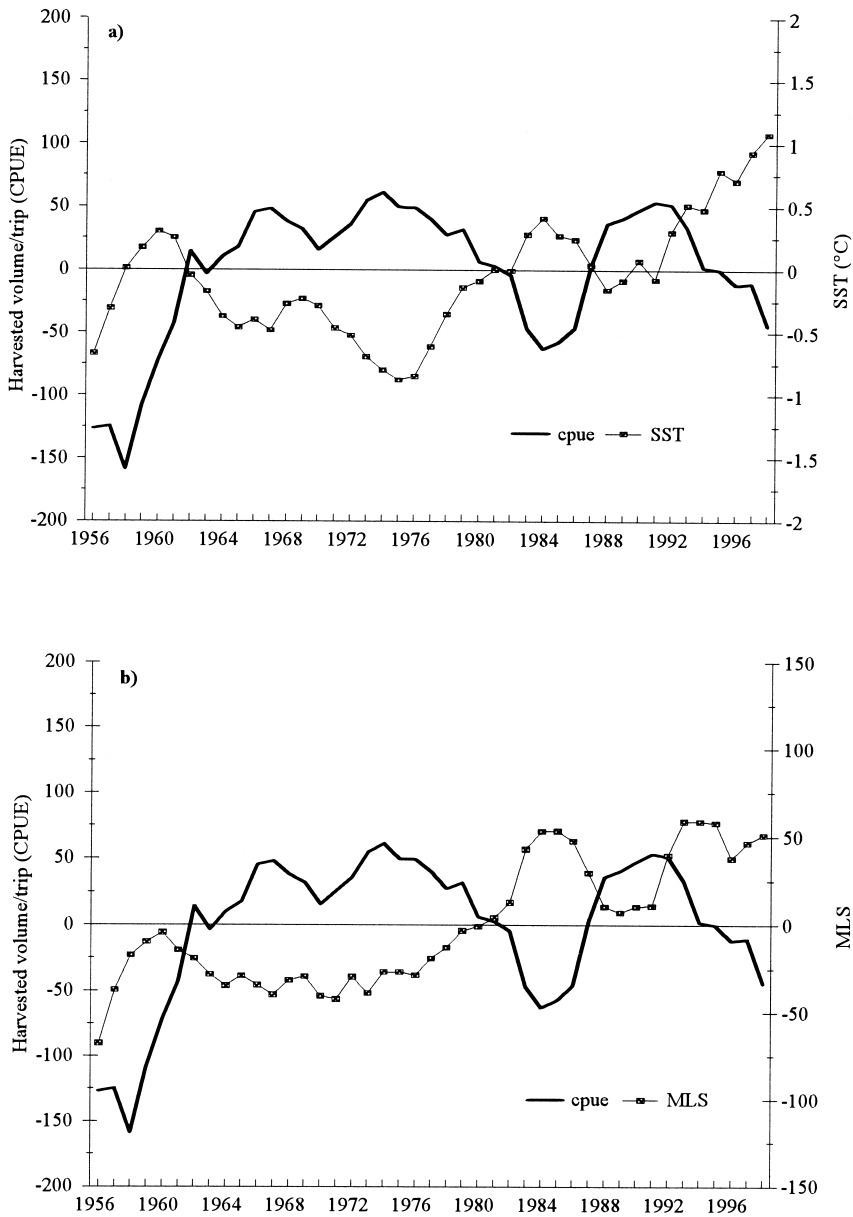
Figure 3. Correlation of harvest volume/trip of *Macrocystis pyrifera* with a) Sea surface temperature (SST), b) Middle level sea (MLS), *(on following page)* c) Upwelling index (UI), and d) Wind speed (WS). The heavy line represents the harvest volume/trip and the thin line represents the environmental variable.

Positive anomalies in the CPUE between 1964 and 1975 correspond to a decrease in the SST. The low temperatures during this period coincide with a Regime Change (Mantua et al., 1997). Beginning in 1976, the SST increased coincidently with a decrease in the harvest volume of *Macrocystis*, with both peaking in the mid-1980s. In 1988–89, during
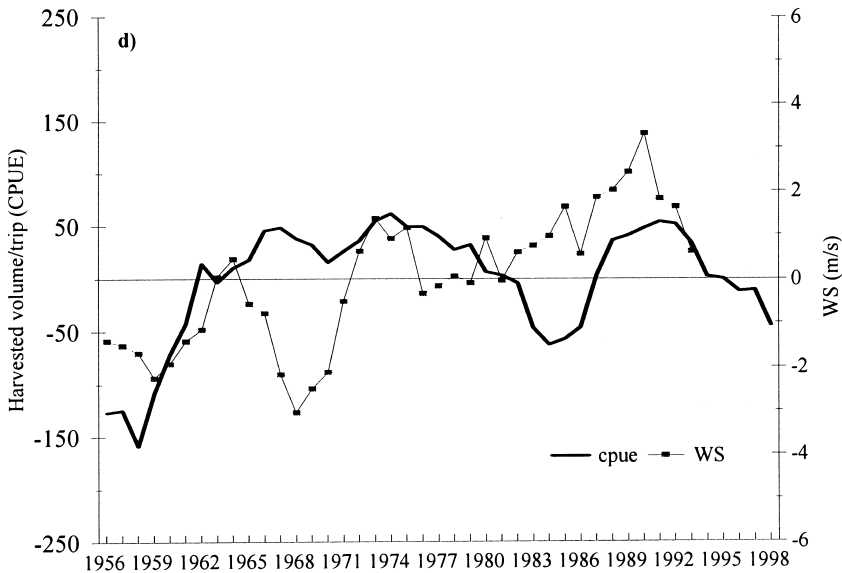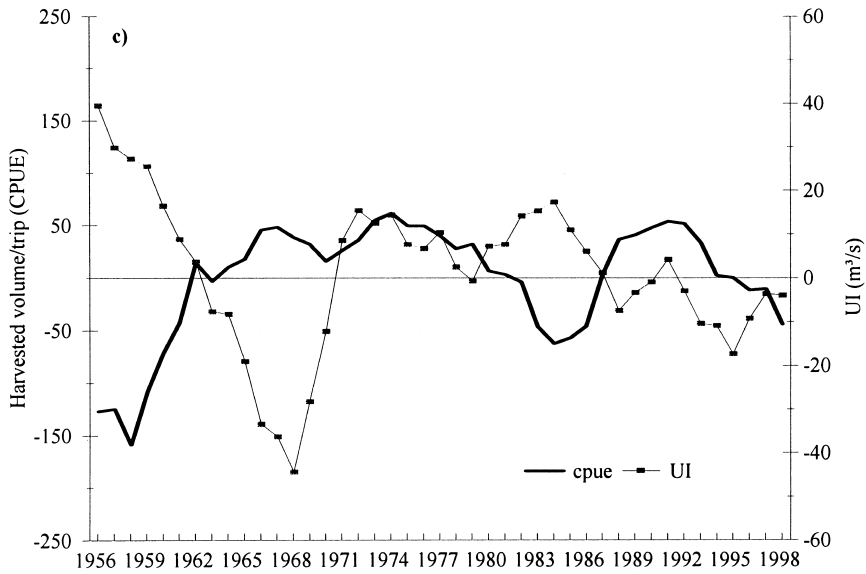
a La Niña cooling period, the maximum CPUE occurred. Finally, since the beginning of the 1990s, a strong warming trend is apparent, with a concomitant decrease in the CPUE. North et al. (1993) related the maximum annual canopy area of the algal bed of California from 1967–89 to the maximum and minimum quarterly temperatures and to the number of warm and cool days per year. They found that the former explained 34% of the variability in canopy area and the latter to 46%.

The effects of high temperatures in the Pacific waters of Baja California Peninsula during the El Niño years were evident in the harvest and CPUE registered in 1958, 1983, and 1998, amounting to under 5000 t yr^{-1}. During El Niño events, changes in both distribution and abundance of *M. pyrifera* have been described at some localities of California for 1958 and 1983 (Tegner and Dayton, 1987) and for Baja California Peninsula for 1983 and 1998 (Hernández, 1988; Ladah et al., 1999). During El Niño, high temperatures and low nutrient concentration results in wide-spread mortality of the giant kelp forest (Gerard, 1984; Tegner and Dayton, 1987, 1991; Tegner et al., 1996).

Increases in sea temperature may reduce the *Macrocystis* population by limiting the availability of nutrients. A strong negative correlation was noted between temperature and nitrate availability (Gerard, 1982; Zimmerman and Kremer, 1986). When nitrate concentration falls below 1 µM, as it does off the coast of southern California at approximately 15.5°C (Zimmerman and Kremer, 1984) and off Bahía Asunción, Baja California Sur at 18.5°C (south of the distribution of this species) (Hernández et al., 2001) growth rate of *Macrocystis* declines. Large-scale disappearances may be explained because canopy growth is supported by transfer of nitrogen from lower parts of the plant that are bathed in water with higher nitrate concentrations (Jackson, 1977). If the lower parts of the plants cannot transfer enough nitrogen to the surface, then the canopy dies back and individuals succumb, probably because of low nitrogen reserves (Gerard, 1984).

In addition to limiting nitrates, and thereby causing *Macrocystis* to die off, high temperatures also inhibit successful recruitment of new algal cells to the beds. Thus, the population cannot recover until the temperature decreases (Jackson, 1977). At the southern limit, Ladah et al. (1999) suggest that microscopic stage of *M. pyrifera* survived the stressful conditions during the ENSO, possibly in a dormant state.

The decline in the CPUE when MSL was higher than normal may, in fact be caused by increased SST. Large positive anomalies in the MLS occur during periods in which the thermocline is at a greater depth, and at the same time, when SST is higher. The pattern of response of CPUE to changes in MLS is similar to that previously described for temperature changes.

Upwelling of deep-sea water normally brings to the surface a rich supply of nutrients that can benefit marine organisms. The surprisingly inverse correlation found between UI and *Macrocystis* abundance may be explained as follows. Some periods (1958–59 and 1980–84) with high upwelling values also had elevated SST. A similar phenomenon was documented by Hayward (1997) for both the California and Peruvian Currents in the mid-1970s. Under these circumstances, nutrient enrichment may not occur because the combination of increased temperature and coastal wave activity cause thickening of the mixed layer. This prevents Ekman pumping reaching the nutrient-enriched waters, which under these conditions would be deeper than normal (Shkedy et al., 1995).

Furthermore, the upwelling values used in this study were estimated for large 3° × 3° oceanic quadrants. *Macrocystis* beds would normally occupy only a small portion of such a quadrant, being restricted to small rocky coastal zones where nutrients are available from runoff and from benthic sources stirred up by vigorous water movements (Tegner et al., 1996). Also, there are generally sufficient nitrogen levels in the beds of *Macrocystis* in coastal waters off southern California (Dohrman and Palmer, 1981), therefore nutrient deficiencies likely prevail only during periods of extreme sea warming, such as those caused by El Niño (Dean and Jacobsen, 1986). These observations can be extended to the beds off Baja California.

From the factors considered in this study, SST is the one variable that explains most of the changes in the abundance of *M. pyrifera*. As a result of this species' sensitivity to temperature (it is temperate affinity), it grows better in cool regimens (Tegner and Dayton, 1987). Its low tolerance to variations in temperature were evident during the El Niño 1982–83 and 1997–98, when this species disappeared from its normal distribution range in the Baja California Peninsula.

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