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Computational Analysis of Monterrey Sardine (Sardinops Sagax) Responses to Sea Surface Temperature (SST) and Chlorophyll-a (Chla) Variability in the Gulf of California, 1998-2015

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Abstract. This study employs advanced computational techniques to conduct a spatiotemporal analysis of monthly sea surface temperature (SST) and chlorophyll-a concentration (Chla) in the Gulf of California (GC) from 1998 to 2015. The analysis uses satellite imagery with 4 km resolution from AVHRR, MODIS-Aqua, and SeaWiFS sensors, which were processed through Idrisi Terrset 2020's geospatial modeling tools. Key computational methods include raster image processing, reclassification for precise geographic delineation, and statistical modeling using the Theil-Sen estimator and multiple linear regression techniques within the Earth Trends Modeler module. These methods enabled the generation of robust spatiotemporal models, correlations, and trend analyses of environmental variables like SST and Chla. Data on Monterey sardine (*Sardinops sagax*) catches, categorized by fishing zones, were also analyzed, revealing a declining trend, with sardine catches decreasing by 16.5 tons per month on average and dropping from over 60% of total small pelagic catches in 2007-2010 to just 2% in 2014-2015. The region of large islands (zones III, IV, and V) was identified as the most productive, contributing 44% to total sardine production. A significant negative correlation ($r = -0.81$) was found between SST and Chla, indicating that higher SSTs result in lower Chla concentrations. Monterey sardine catches also responded to environmental changes with a two-month lag, showing correlations of $r = -0.52$ with SST and $r = 0.57$ with Chla. The comprehensive computational approach, which included linear and nonlinear modeling, provided critical insights into the dynamics between environmental variables and sardine population trends, emphasizing the importance of ongoing monitoring and adaptive fisheries management in the face of climate change.

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Keywords. Gulf of California, SST, Chla, sardina Monterrey, sardinops Sagax.

1 Introduction

The Monterey sardine (Sardinops sagax) is a species of significant ecological and economic importance, with a wide distribution in temperate and cold waters across multiple oceans, including the Pacific, Atlantic, and Indian Oceans. It holds considerable commercial value, particularly in countries such as Mexico, Chile, and the United States, where it is predominantly utilized for producing canned sardines and fish meal [24, 3].

The species also plays a vital role in the marine food chain, serving as prey for predators such as seabirds, dolphins, and large fish like tuna [5]. However, fluctuations in the population dynamics of the Monterey sardine are often attributed to both environmental variability and the pressures of intensive fishing [2].

Given the significant variability in sardine populations, which are sensitive to climatic and oceanographic conditions, advanced computational methods are increasingly pivotal in studying and managing this species. In particular, machine learning algorithms and supercomputing techniques, such as principal component analysis (PCA) and Theil-Sen trend estimations, provide new ways to model and predict population dynamics.

These methods have been integral in the analysis of sea surface temperature (SST), chlorophyll-a concentration (Chla), and environmental patterns affecting the Monterey sardine in the Gulf of California (GC). The small pelagic fishery (PMP) in Mexico, particularly the Monterey sardine, is the largest in terms of volume. It encompasses a range of species under active management, including sardina crinuda (Opisthonema libertate) and mackerel (Scomber japonicus) [16]. Utilizing multivariate methods, such as PCA, allows for the detection of underlying patterns in fisheries data and environmental variables, which is critical for understanding the interaction between species distribution and environmental fluctuations. This analysis is enhanced by using supercomputing infrastructure, which processes large-scale satellite data, such as AVHRR and MODIS-Aqua imagery, to monitor SST and Chla variations with high spatial and temporal resolution.

The Gulf of California is a dynamic marine ecosystem, where oceanographic factors such as SST and Chla critically affect the abundance and distribution of Monterey sardine [18, 1]. SST and Chla data from satellite imagery were processed using machine learning models to uncover correlations between environmental conditions and species behavior, particularly during El Niño-Southern Oscillation (ENSO) events.

For instance, PCA was used to reduce the dimensionality of the complex environmental datasets, facilitating the identification of key drivers of change. Theil-Sen estimations, a non-parametric trend analysis technique, were applied to detect robust trends in SST and Chla over time, even in the presence of outliers or noise [14]. These computational techniques allowed for more accurate predictions of the response of sardine populations to ENSO phases and the potential long-term impacts of climate change on fisheries.

Studies have shown that during ENSO phases, particularly El Niño events, the Monterey sardine population tends to decline, with species such as sardina crinuda becoming more prevalent [21]. These findings are consistent with the work of researchers such as Silva and Yáñez [27], Lluch-Cota et al. [19], and Girón-Nava et al. [11], who have demonstrated strong correlations between ENSO-driven environmental conditions and the recruitment success of smaller pelagics.

Furthermore, this study highlights the importance of using high-performance computing (HPC) environments to process large datasets and execute complex models efficiently. The supercomputing resources at ACARUS, for instance, were instrumental in performing extensive spatiotemporal analyses, including calculating monthly indices of SST and Chla, as well as catch per unit effort (CPUE) of Monterey sardine. These computational methods are essential for providing insights into the spatial variability of fishing zones and the potential impacts of climate change on the ecosystem.

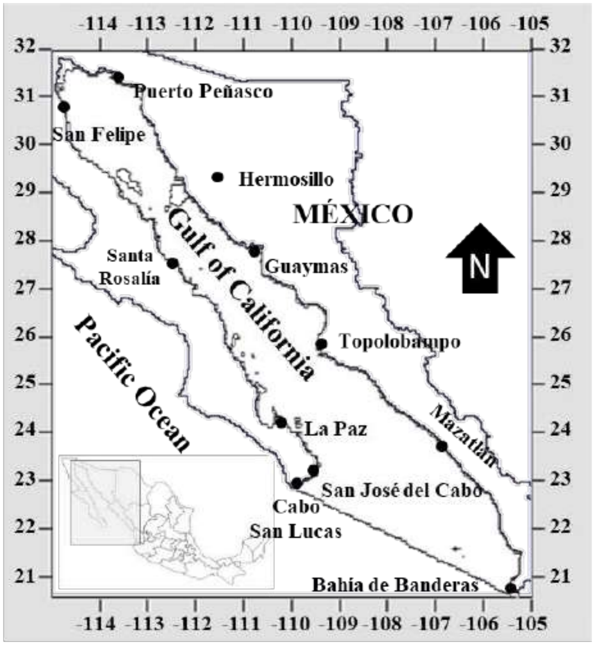


Fig. 1. Study area. Gulf of California, with a margin of 12 km away from the coast

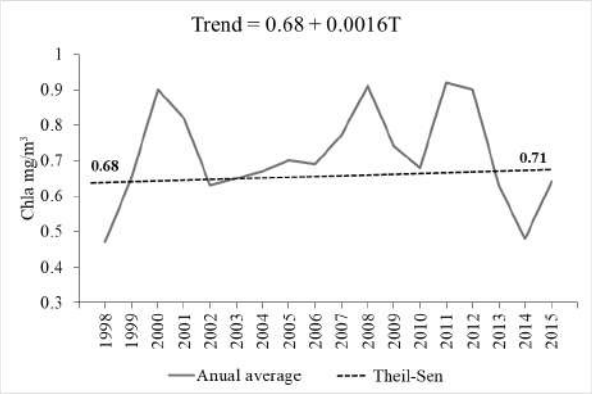


Fig. 2. Annual average Chla and its trend 1998-2015

The role of environmental variability in shaping sardine populations is further emphasized by researchers such as Cisneros-Mata et al. [4] and Herrera-Cervantes et al. [15], who have analyzed long-term data on fisheries and environmental factors in the GC.

By employing machine learning techniques, such as regression models and time-series analysis, the study provides a more comprehensive understanding of how fluctuations in SST and Chla drive changes in sardine abundance, particularly in response to climate events like ENSO.

Advanced computational methods, including machine learning and supercomputing, are indispensable tools for analyzing the complex interactions between environmental variables and species dynamics. The application of PCA, Theil-Sen trend analysis, and spatiotemporal modeling has significantly improved our ability to monitor, predict, and manage the Monterey sardine population in the GC.

These computational insights are critical for ensuring the sustainable management of this vital resource in the face of climate change.

2 Materials and Methods

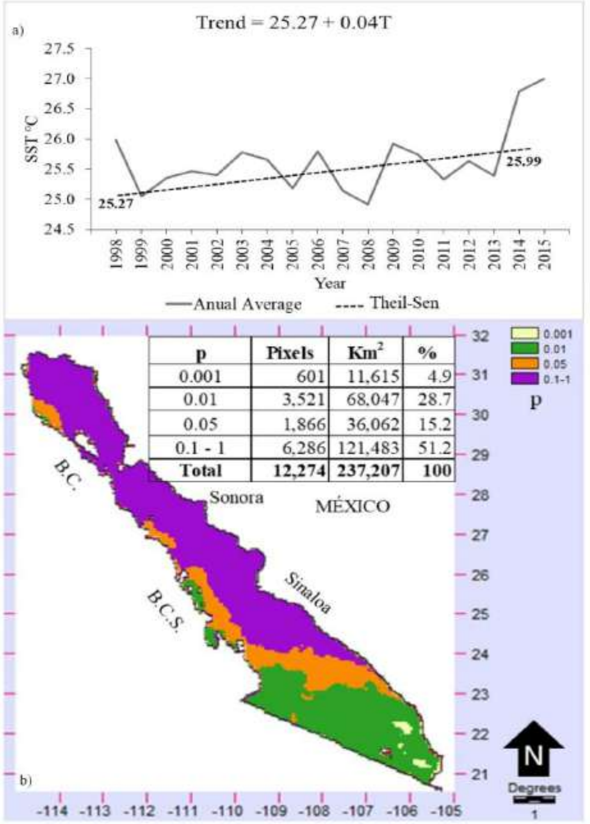
2.1 Study Area

The GC is one of the five most productive and most biodiverse seas in the world [9], with more than eight thousand species of marine fauna that inhabit it, of which it is estimated that more than nine hundred species are fish [12]. It has an average width of 200 km and 1,500 km long. It borders the states of Sonora and Sinaloa to the east and the Baja California peninsula to the west. In the south, the GC is in open communication with the Pacific Ocean [25]. The study area (Fig. 1) covers an area of 237,207 km², with a margin of approximately 12 km outside the coastline to avoid the effect of overestimation due to turbidity and terrestrial influence, characteristics of shallow areas [20].

2.2 Data

Time series of satellite images with monthly averages of SST and Chla were used, with a spatial resolution of 4 km, for the period 1998-2015 (216 months), from the AVHRR, MODIS-Aqua, and SeaWiFS satellites, as detailed in Heras-Sanchez et al. [14].

The data for the Multivariate El Niño Southern Oscillation Index (MEI) were obtained from the National Oceanic and Atmospheric Administration (NOAA). Additionally, monthly series of catches



p	Pixels	Km^2	%
0.001	601	11,615	4.9
0.01	3,521	68,047	28.7
0.05	1,866	36,062	15.2
0.1 - 1	6,286	121,483	51.2
Total	**12,274**	**237,207**	**100**

Fig. 3. a) Annual average SST and its trend and b) Spatial significance of the SST trend , 1998-2015

(in tons) of minor pelagics and Monterey sardines for the entire GC and fishing effort by the Gulf and by fishing area were included. These data were collected by the Regional Aquaculture and Fisheries Research Center in Guaymas (CRIAP-Guaymas), part of the National Fisheries Institute (INAPESCA). The landing statistics for PMP are reported in the statistical yearbooks issued by the National Aquaculture and Fisheries Commission (CONAPESCA), which also include the composition of the main species landed in the most important ports of the GC, such as Guaymas and Yavaros in Sonora. This information is available at[1].

2.3 Data Processing

For the processing of satellite images, it was necessary to utilize high-performance computing infrastructure due to both the size of the original images and the complexity of the analyses. The SST and Chla imagery were processed using Idrisi Terrset 2020 [17], converting the data into raster format for comprehensive spatio-temporal analysis.

The attributes of these images were standardized, and the study area, defined by its geographical coordinates (latitude 20.61° N to 32.02° N and longitude -114.98° W to -104.98° W), was appropriately cropped. For accurate analysis, the images were reclassified by assigning a value of zero to pixels representing mainland and islands, effectively excluding these areas from the dataset.

Key statistical metrics, including monthly spatio-temporal averages, maxima, minima, standard deviations, standardized anomalies, and annual averages, were calculated for each image and across the entire temporal series. These calculations provided a robust framework for analyzing trends and patterns within the dataset.

The regionalization of the eleven small pelagic fishing zones within the Gulf of California (GC) was delineated using data provided by CRIAP-Guaymas. This regionalization reflects the operational zones of the sardine fishing fleet, excluding the upper Gulf and the southern coasts of Baja California Sur.

Utilizing the CRIAP-Guaymas data, a comprehensive monthly catch series for Pacific Mackerel (PMP) and Monterrey sardine within the GC and each of the eleven defined fishing zones was constructed. Basic statistics for these datasets were computed, and monthly indices were derived. Further, the catch per unit effort (CPUE) for Monterrey sardine in each fishing area was estimated based on the total catch data from the GC and the fishing effort per area.

This CPUE calculation was instrumental in determining the total production per fishing area, using the following formulas:

$$CZ = \frac{CG}{VG} \times VZ, \tag{1}$$

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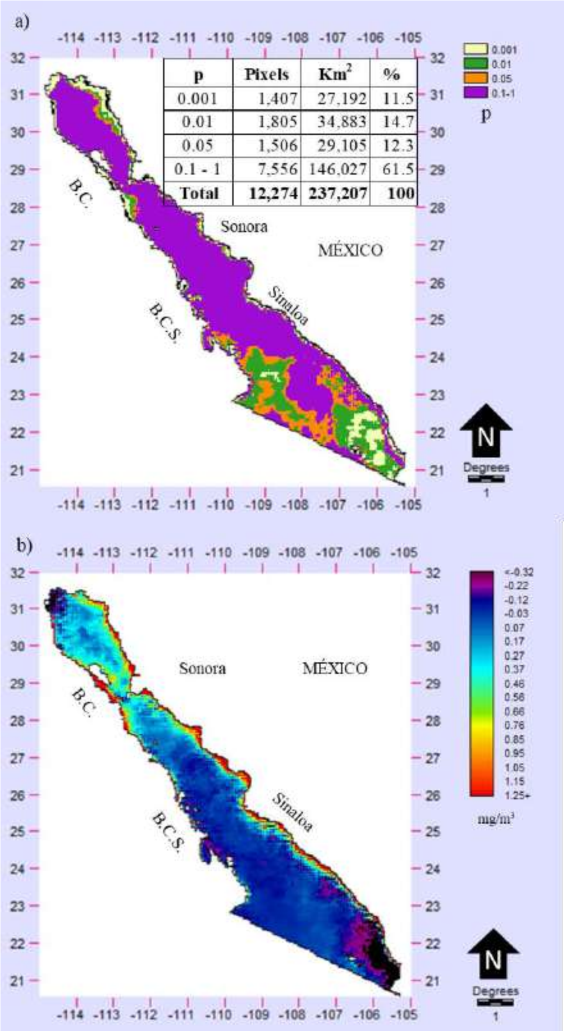
[1] https://www.gob.mx/conapesca/documentos/anuario-estadistico-de-acuacultura-y-pesca



p	Pixels	Km²	%
0.001	1,407	27,192	11.5
0.01	1,805	34,883	14.7
0.05	1,506	29,105	12.3
0.1 - 1	7,556	146,027	61.5
Total	**12,274**	**237,207**	**100**

Fig. 4. a) Spatial significance of the Chla trend, and b) Spatial trend of Chla in the Gulf of California, 1998-2015

$$CPUEZ = \frac{\sum_{i=1}^{n} CZ}{\sum_{i=1}^{n} VZ}. \tag{2}$$

The estimated Monterrey sardine catch for each fishing area (CZ) and the total catch for the entire Gulf (CG) were analyzed. The total number of trips where Monterrey sardines were caught for the entire Gulf (VG) was recorded, and the ratio CG/VG provided the catch per unit effort (CPUE) for the entire Gulf. The number of trips per fishing area (VZ) where Monterrey sardines were caught was also noted. The CPUE for each fishing area (CPUEZ) was determined for the period 1998-2015, with CZ and VZ values accumulated over the 216 months of the study period.

Spatio-temporal analyses included estimating linear trends (using the least squares method) and Theil-Sen trends for SST, Chla, PMP, and Monterrey sardine series. The CPUE served as an indicator of the population density of the Monterrey sardine. The Theil-Sen method, a robust non-parametric technique, was utilized to analyze trends and seasonality in geostatistical and time series data, providing a median trend line resistant to outliers or extreme values (Neeti and Eastman, 2011). Trends were validated with four confidence levels as part of the spatial analysis.

The Earth Trends Modeler module in Idrisi Terrset 2020 [17] was employed, using multiple linear regression techniques to develop spatio-temporal models for the Gulf of California (GC). These models illustrated the spatial connection between monthly mean series of environmental variables (SST and Chla).

Monthly series of SST and Chla images, along with tabular data on PMP and Monterrey sardine captures, were used to generate indices of monthly averages. These indices were correlated to analyze relationships between variables, employing various modules of Idrisi Terrset 2020 and applying least squares correlation.

Additionally, spreadsheets were utilized to create scattergrams and linear graphs, perform trend analysis, and conduct linear correlation of the study variables. This facilitated comparison of results obtained with the spatio-temporal indices and models generated using Idrisi Terrset 2020 modules[17]. Scatter plots of SST/Chla were used to analyze ecological conditions in the GC fishing areas during the study period. For each fishing zone, monthly catches of Monterrey sardine in tons were estimated based on the CPUE for the GC and the fishing effort per fishing zone.

3 Results

The annual averages of the GC SST showed values with regular fluctuations between 25 and 26 ° C, except for the years 2014 and 2015, when the average was 26.7 and 27 ° C respectively (Fig. 3).

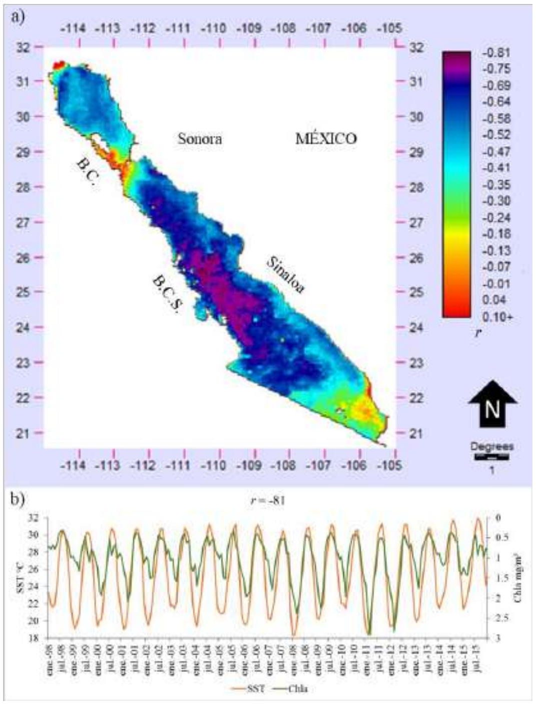


Fig. 5. SST/Chla linear model of the Gulf of California, 1998-2015. a) Spatial correlation and b) temporal correlation with inverted Chla signal

The average SST of the GC was 25.4 (± 1.4) ° C and with a cumulative increase of 0.72 ° C for the period 1998-2015, equivalent to 0.04 ° C annually, with a confidence level of 95%.

The significance of the spatial analysis of the SST trend for the study period indicated that 48% of the space covered by the study area, equivalent to 151,724 km², presented an estimated trend with a confidence level of at least 95%, which can be seen in Fig. 3a.

Additionally, 28.7% of the study area has an estimated trend with a 99% confidence level, while 4.9% exhibited an exceptionally high confidence level of 99.9%.

Within this 48%, a substantial portion, representing 28.7% of the study area, displayed an even higher confidence level of 99% (green areas, $p = 0.01$). These regions were characterized by a robust and consistent trend in SST over the study period. Additionally, a smaller portion, accounting for 4.9% of the study area, exhibited an exceptionally high confidence level of 99.9% (beige areas, $p = 0.001$).

These areas experienced the most pronounced and statistically significant SST trend among all the analyzed regions. The remaining 52% of the study area exhibited either no significant trend or a trend with a lower confidence level. These areas, depicted as white and yellow in Figure 3b, were primarily located in the central and western portions of the study area.

The absence of a significant trend in these regions suggests that SST in these areas remained relatively stable over the study period, or that the available data was insufficient to detect a discernible trend. The average Chla was estimated at 0.95 (± 0.82) mg/m³, with a cumulative increase for the entire series of 0.03 mg/m³, equivalent to 0.0016 mg/m³ annually, with spatial and temporal variations (areas with increases and decreases in Chla, and temporal fluctuations) (Fig. 2).

Based on the spatial analysis of the Chlorophyll-a (Chla) trend, 38.5% of the Gulf of California (GC) exhibited significant changes with a confidence level of at least 95%, encompassing an area of 91,180 km². These areas were primarily located along the continental coast, at the gulf's entrance, and in isolated regions of the peninsular coast (Fig. 4).

The coast of Nayarit, the gulf's entrance, Bahía de La Paz, and the northwestern portion of the upper gulf coast experienced a negative trend ranging from 0.03 to 0.5 mg/m³. In contrast, the coast of Sonora, Sinaloa, and the peninsular area near the large islands exhibited significant increases ranging from 0.07 to 1.25 mg/m³ (Fig. 4). In the GC, there is a strong inverse spatial correlation between SST and Chla, being greater at the mouth and middle part of the gulf (Fig. 5a). The maximum spatial correlation (r = -0.81, p ¡ 0.05) occurs on the western coast of the entrance to the gulf, where the highest temperatures correspond to the lowest concentrations of Chla.

There are two distinct regions: the area of the large islands, which registers the lowest SST of the GC (22.4 ± 4.9 ° C) and an average Chla of 1.49 (± 0.83) mg/m³, and the southern zone (entrance of the gulf off the coast of Nayarit), which records the highest SST (28 ± 2.6 ° C) and an average

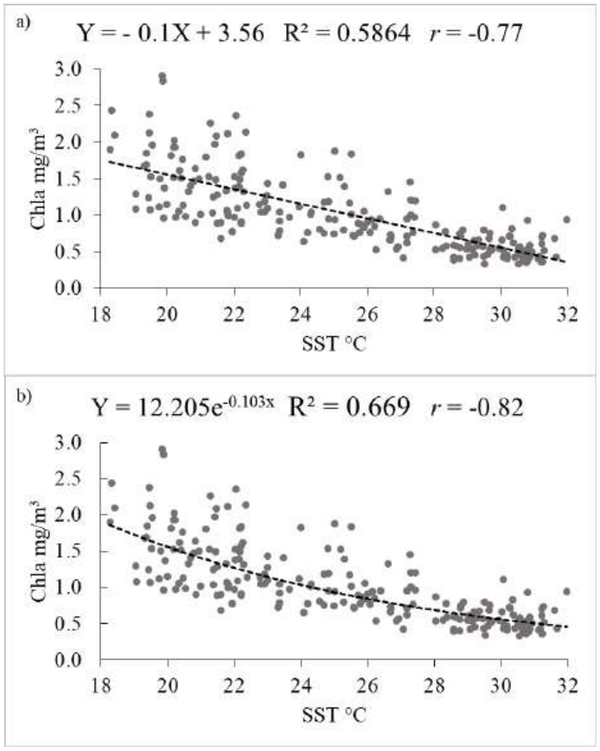


Fig. 6. Trend and temporal correlation of SST and Chla in the Gulf of California, 1998-2015. a) linear method and b) exponential method

Table 1. Spatio-temporal variation of SST and its relationship with Chla variability, by SST ranges

SST Range	SST (°C)	Chla (mg/m^3)	Time %
<26°C	42%	0.99	46%
24°C - 26°C	35%	1.24	12%
>24°C	23%	2.31	42%

Chla of 0.24 (± 0.14) mg/m³ (Fig. 5b). Over time, the monthly averages of SST and Chla are equally correlated with r = -0.81 (p ¡ 0.05); the months with the highest temperature correspond to the lowest concentration of Chla and vice versa. Regularly during warm periods, the SST and Chla signals have a stronger correlation, as seen during warm periods when the SST peaks and Chla reaches its minimum values.

Cold periods, such as in 2011 and 2012, recorded the highest Chla values in the series, corresponding to the lowest SSTs (Fig. 6).

In the period 1998-2015, SST recorded average values higher than 26°C in 42% of the GC, corresponding to an amplitude in the Chla signal of 0.99 mg/m³. In the transition range of cold-warm conditions ($SST > 24°C$ and $\leq 26°C$), a greater Chla signal amplitude of 1.24 mg/m³ was observed 12% of the time, covering 35% of the GC. SST lower than 24° C was observed in 23% of the GC for 42% of the time, with a more unstable Chla signal (amplitude of 2.31 mg/m³) (Table 1).

3.1 Monterrey Sardine Catch Analysis

The projected catch of Monterrey sardine accounted for approximately 50% of the total small pelagic fishery in the Gulf of California (GC) during 1998-2015. The annual data regarding Monterrey sardine catch, other small pelagics, and total small pelagics are presented in Fig. 7. Notably, in 2008 and 2009, the Monterrey sardine catch represented 92% and 91% of the total small pelagic catch, respectively, whereas it decreased to only 1% and 2% in 2014 and 2015.

During El Niño events (e.g., 2014-2015), the population of Monterrey sardine decreased significantly, allowing other opportunistic small pelagic species to dominate. Conversely, during La Niña events (e.g., 2008-2009), there were optimal seasons for Monterrey sardine, with higher catch volumes.

The basic statistics and correlations between the variables studied for the entire Gulf of California (GC) and individual fishing areas for the period 1998-2015 can be consulted in Tables 2 and 3. On average, the CPUE-Mty (Catch Per Unit Effort for Monterrey sardine) for the entire Gulf was 136.4 tons per fishing trip, with a total accumulated production of 2,807,915 tons over 20,580 fishing trips.

These figures were obtained under average ecological conditions of SST (25.4 ± 4 ℃) and Chla (1.01 ± 0.53 mg/m^3) for the period (Table 2). The correlation between SST and Chla was r = -0.81, SST/CPUE-Mty was r = -0.49 (+2 months), and Chla/CPUE-Mty was r = 0.49 (+2 months) (Table 3). The Monterrey sardine population showed similar delayed responses of 2 months

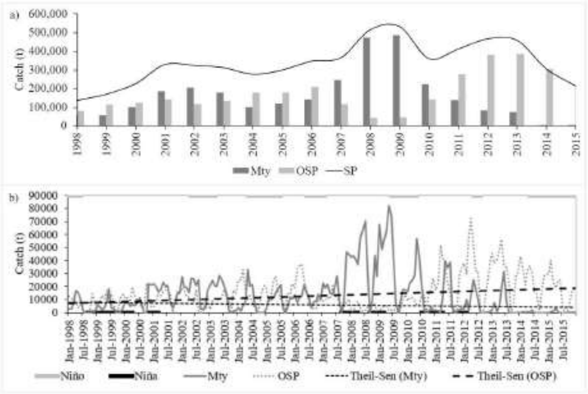


Fig. 7. Gulf of California, annual catch of Monterrey sardine (Mty), other small pelagics (OSP) and total small pelagics (SP), 1998-2015

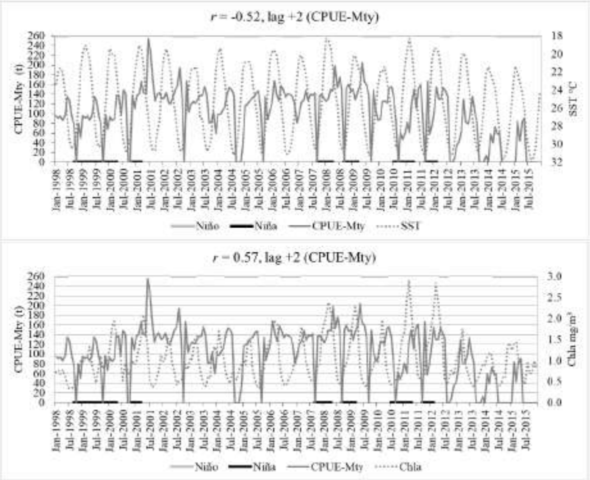


Fig. 8. Gulf of California, Monterrey sardine catch (Mty) and other minor pelagics (OSP), 1998-2015, trend lines and ENSO events

to both environmental variables. The region of the large islands (zones III, IV, and V) was the most productive, accounting for 44% of the total Monterrey sardine production, followed by the middle region (zones VII and VIII) with 30%. Zone IV had the highest CPUE-Mty in the large islands region (142.5 t/trip), but with a lower fishing effort (2,428 trips) than other zones. The area of Ángel de la Guarda Island (Zone IV) had an average Chla of 1.71 ± 0.89 mg/m^3 and SST of 22.7 ± 5.0 ℃, with a correlation of r = -0.41 (SST/Chla) and a 2-month lag in CPUE-Mty response (Tables 2 and 3).

Zone III, located north of Shark Island, had a CPUE-Mty of 138.8 t/trip with average SST of 23.3 (± 5.3) ℃ and Chla of 2.55 (± 1.85) mg/m^3. Although the fishing effort (2,828 trips) was greater than in Zone IV, the cumulative catch was lower (392,427 t). The SST/CPUE-Mty lag was 3 months, and the Chla/CPUE-Mty lag was 2 months (Tables 2 and 3). Zone V had the greatest fishing effort (3,887 trips) and highest production (515,900 t).

The SST/Chla correlation was r = -0.67, with no lag in the CPUE-Mty response, and an average CPUE-Mty of 132.7 t/trip (Tables 2 and 3). Zones VII and VIII, located at similar latitudes, showed inverse SST/Chla correlations but differed significantly in their CPUE-Mty.

Zone VII had a CPUE-Mty of 123.4 t/trip, with a cumulative catch of 382,331 t and fishing effort of 3,099 trips, under average conditions of SST 24.5 ± 5.2 ℃ and Chla 1.87 ± 1.52 mg/m^3. The SST/Chla, SST/CPUE-Mty, and Chla/CPUE-Mty correlations were r = -0.63, r = -0.39, and r = 0.36, respectively (Tables 2 and 3).

Zone VIII, with the highest CPUE-Mty in the GC (152.1 t/trip), had a fishing effort of 3,186 trips and a cumulative production of 484,452 t. The SST/Chla, SST/CPUE-Mty, and Chla/CPUE-Mty correlations were r = -0.75, r = -0.31, and r = 0.43, respectively, with no significant lag (Tables 2 and 3).

Zones VI, IX, and X showed varied productivity and environmental conditions, with Zone VI recording a CPUE-Mty of 141.1 t/trip and lower correlations of SST and Chla with CPUE-Mty. Zone IX, located in the Yavaros region, recorded a CPUE-Mty of 128.1 t/trip, with significant correlations between SST/Chla (r = -0.72), SST/CPUE-Mty (r = -0.57), and Chla/CPUE-Mty (r = 0.42) (Tables 2 and 3). Finally, Zones I, II, X, and XI, located in the upper GC and southern areas, had fewer fishing trips and lower cumulative production. Environmental variables in these zones showed varying correlation and lag times, with SST/Chla correlations of r = -0.77 in Zone XI and weak correlations with CPUE-Mty (Tables 2 and 3).

Table 2. Statistics of SST, Chla and CPUE of Monterrey sardine from the Gulf of California and its fishing areas, 1998-2015

Gulf/Fishing zone	**Sea Surface Temperature (℃)**				**Chla concentration (mg/m³)**				**Monterrey sardine**		
	Min	**Max**	**Mean**	**Std. dev**	**Min**	**Max**	**Mean**	**Std. dev**	**Cumulative catch (t)**	**Cumulative trips**	**CPUE (t/trip)**
Golfo	18.3	32.0	25.4	4.0	0.33	2.91	1.01	0.53	2,807,915	20,580	136.4
ZONE I	15.5	31.6	23.4	5.1	0.57	1.65	1.16	0.16	90,251	677	133.3
ZONE II	15.5	31.6	23.2	4.9	0.33	8.44	1.56	1.10	2,072	16	129.5
ZONE III	15.3	31.8	23.5	5.0	0.51	13.14	2.55	1.85	392,427	2,828	138.8
ZONE IV	15.0	30.7	22.7	5.6	0.61	5.49	1.71	0.89	345,993	2,428	142.5
ZONE V	14.8	32.2	23.1	5.0	0.34	7.13	1.87	1.32	515,009	3,887	132.7
ZONE VI	15.5	31.3	23.3	5.0	0.34	7.13	1.57	0.83	217,981	1,545	141.1
ZONE VII	16.0	32.2	24.2	4.7	0.32	3.70	1.87	1.52	381,383	3,099	123.4
ZONE VIII	16.1	32.2	24.2	4.7	0.36	3.16	1.63	0.96	484,452	3,186	152.1
ZONE IX	16.4	32.2	25.1	4.9	0.30	8.37	1.90	1.55	318,316	2,484	128.1
ZONE X	16.8	32.3	25.7	4.6	0.57	9.53	2.09	1.55	46,188	361	127.9
ZONE XI	17.7	32.1	24.8	4.3	0.17	3.53	0.93	0.63	9,255	69	134.1

This table (3) illustrates the relationship between general ecological conditions, based on the averages of sea surface temperature (SST) and chlorophyll-a concentration (Chla), and the accumulated capture volume of Monterrey sardine for the period 1998-2015. The center of the bubble represents the ecological conditions, while the size of the bubble indicates the accumulated catch volume.

During this period, the Monterrey sardine was predominantly concentrated around the area of the large islands, which corresponds to fishing zones III, IV, and V. Additionally, notable concentrations were also found in the middle portion of the Gulf of California, particularly in zones VII and VIII.

4 Discussion

The results of this study reveal significant patterns in the response of the Monterrey sardine to environmental variations in the Gulf of California (GC). The relationship between sea surface temperature (SST), chlorophyll concentration (Chla), and the distribution of this species provides valuable insights into its ecology and population dynamics.

The distinct behavior of SST and Chla in the regions of the large islands and the entrance to the Gulf, which exhibit lower variability, aligns with findings reported by Heras-Sánchez et al. [13].

They identified Region 1 at the Gulf's entrance as having the least variable SST and Chla. Similarly, Álvarez-Borrego and Lara-Lara [28] and Soto-Mardones et al. [26] noted that the region around the large islands maintains constant tidal mixing throughout the year, fostering high productivity even in adjacent areas.

This continuous exchange and strong vertical mixing contribute to the observed stability in SST and Chla. In contrast, the coastal areas of southern Sonora and northern Sinaloa experienced increases in Chla concentration, likely due to upwelling systems driven by northwest winds during winter and nutrient-rich discharges from shrimp farms [22, 6]. These factors, combined with upwelling efforts, modify local ecosystems and enhance nutrient availability [28].

Consistent with previous research[23, 8], our results confirm that SST significantly influences the distribution of the Monterrey sardine. During El Niño events, characterized by warmer SSTs, the sardine population shifts towards northern latitudes in search of more favorable temperature conditions [15, 10]. Heras-Sánchez et al. [14] also reported a similar trend, noting an extended warm period in the second subperiod (2007-2015) compared to the first (1998-2006), which could affect species distribution and abundance.

Regarding Chla, our findings support the hypothesis that the Monterrey sardine responds to variations in primary productivity, especially

Table 3. Linear correlation between the monthly averages of the environmental variables and the monthly CPUE of Monterrey sardine. Gulf of California and its fishing areas, 1998-2015

Gulf /Fishing zone	SST/Chla r	SST/CPUE-Mty r	Chla/CPUE-Mty r
Golfo	-0.81	-0.49 (+2 CPUE-Mty)	0.49 (+2 CPUE-Mty)
ZONE I	-0.57 (+1 Chla)	-0.33 (+1 CPUE-Mty)	0.34
ZONE II	-0.59 (+1 Chla)	-0.15 (+1 CPUE-Mty)	0.09
ZONE III	-0.56 (+1 Chla)	-0.33 (+3 CPUE-Mty)	0.27 (+2 CPUE-Mty)
ZONE IV	-0.41 (+2 Chla)	0.43 (+1 CPUE-Mty)	-0.27 (+1 CPUE-Mty)
ZONE V	-0.67	-0.28	0.29
ZONE VI	–	0.34	0.15
ZONE VII	-0.75	0.01	0.36
ZONE VIII	-0.31 (+3 CPUE-Mty)	0.43 (+3 CPUE-Mty)	–
ZONE IX	-0.72	-0.57 (+1 CPUE-Mty)	0.42 (+2 CPUE-Mty)
ZONE X	-0.68	-0.43	0.23
ZONE XI	-0.77	0.20 (+3 CPUE-Mty)	0.20 (+3 CPUE-Mty)

in coastal zones. High Chla concentrations correlate with higher sardine densities, indicating that phytoplankton-rich areas serve as favorable feeding habitats [28, 1, 11].

However, the relationship between Chla concentration and sardine abundance varies with season and local oceanographic conditions, highlighting the complexity of this interaction. Heras-Sánchez et al. [14] observed seasonal trends in Chla, with increases during cold conditions and decreases during warm conditions, impacting the sardine population.

Our study confirms that the Monterrey sardine population declines during El Niño events, as reported by Martínez-Zavala et al. [21], with opportunistic species like crinuda and largemouth sardines becoming more prevalent.

This finding aligns with the work of Silva and Yáñez [27], Lluch-Cota et al. [19], Arreguín-Sánchez et al. [1], and Girón-Nava et al. [11], who found strong correlations between environmental conditions influenced by ENSO events and the recruitment success of smaller pelagics. Girón-Nava et al. [11] noted significant effects on the Monterrey sardine population during the 2014-2015 El Niño event due to changes in SST and Chla concentration.

Heras-Sánchez et al. [13] identified 12 regions in the GC based on SST and Chla distribution, noting that the upper Gulf region, including the large islands and Sonora coast, had lower average SST and higher Chla concentrations but greater variability. This study's results corroborate these findings, with fishing areas in these regions exhibiting similar behavior, showing high variability in the upper Gulf and Sonora coast, which gradually changes towards the outer Gulf.

This study also highlights that the fishing zones around the large islands and the central coastal areas of the Gulf have the highest accumulated catches of Monterrey sardine, in line with Nevárez-Martínez et al. [23], who indicated species concentration in the central-northern GC.

Other researchers, such as Cisneros-Mata et al. [4], suggest that recruitment of Monterrey sardine is related to environmental variability and density-dependent factors.

In the context of long-term climate variability, our observations underscore the importance of considering environmental variability and climate phenomena like ENSO when assessing the impact of climate change on marine ecosystems. El Niño events can intensify changes in temperature and productivity in the GC, potentially affecting the long-term distribution and abundance of Monterrey sardine and other species [7].

5 Conclusion and Future Work

This study contributes to our understanding of the ecology and population dynamics of the Monterrey sardine and other minor pelagics in the Gulf of California, considering SST, Chla concentration, and the environmental effect of ENSO events. It is shown that the distribution and abundance of the Monterrey sardine species respond to pulses of primary production, which showed a high spatial and temporal correlation with the SST of the Gulf of California.

The results obtained with the data from small pelagic fisheries indicate a great impact on the populations of the Monterrey sardine during warm periods intensified by El Niño events. Conversely, during La Niña events, the populations increased in response to lower SSTs and higher Chla levels. For the period 1998-2015, the Monterrey sardine population exhibited a downward trend of 16.5 t/month, and other minor pelagic species took advantage of this opportunity to become more abundant, with an increase of 54 t/month.

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