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Relationship between environmental variables and temporal variation in body size and abundance of *Euthynnus lineatus*

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Introduction

Sea surface temperature (SST) is one of the most important oceanographic parameters for studying skipjack habitat in the tropical region (Lehodey et al., 1997; Bertignac et al., 1998; Mugo et al., 2010; Zainuddin, 2011; Zainuddin et al., 2017). However, the association observed in tunas with ocean thermal structures cannot be explained by SST per se, but also involves other mechanisms linked to the temperature of the tuna.

highly productive areas in search of food and aggregations such as frontal zones, eddies or upwellings (Barkley et al., 1978; Laurs et al., 1984; Brill et al., 1994; Santos, 2000; Castro et al., 2017; Garcés et al., 2023). Additionally, previous studies of chlorophyll-a (Chl-a) concentration and SST, using satellite data, have allowed to predict skipjack feeding areas and their possible habitats or migration routes in the ocean (Polovina et al., 2001; Zainuddin et al., 2008).

The black skipjack, *Euthynnus lineatus* **(Kishinouye, 1920),** is an epipelagic species distributed in the Pacific at tropical and subtropical latitudes, mainly in waters with surface temperatures exceeding 20 °C (Forsbergh, 1989). *E. lineatus* does not undergo large-scale migrations, as its movements are more associated with continental shelves (FAO, 1994). This behavior explains why it constitutes one of the main fishery resources exploited by artisanal fisheries in coastal communities in the southern Mexican Pacific (Ortega-García & Lluch-Cota, 1996). The largest catches of black skipjack *(E. lineatus)* in Mexico correspond to the coastal strip located between Puerto Escondido and areas surrounding the bays of Huatulco, Oaxaca (Fig. 1).

The artisanal skipjack fishery on the southern coast of Mexico constitutes an activity that significantly impacts the economy of coastal communities, both regionally and nationally (DOF, 2023). The capture of *E. lineatus* occurs year-round; however, there are few studies related to temporal variations in abundance and with any phase of its life cycle or fishery at the national level. González & Ramírez (1989) mention that the coastal coastline of Oaxaca is one of the main spawning and breeding areas for skipjack during the winter months. On the other hand, Ayala-Duval et al. (1988) observed that, due to its oceanographic characteristics and high productivity, the Oaxaca coast is a center of biological activity that is expressed in a high migration of large fish for feeding and breeding purposes.

Fiedler & Bernard, (1987) documented that scombrids have a high relationship to feeding areas according to temperature and chlorophyll conditions.
However, Ortega-García & Lluch-Cota (1996) reported a three- to five-month difference between peak tuna abundance and pigment concentrations. Therefore, the objective of this study was to explore the short-term relationship between oceanographic variables (e.g., SST and Chl-a) and the abundance and body size (length-weight ratio) of *E. lineatus* off the coast of Oaxaca from October 2022 to October 2024.

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Materials and methods

Study area

The study region is located south of Mexico in the Pacific Ocean, mainly along the coastal shore of Oaxaca, and belongs to the northwestern end of the Gulf of Tehuantepec **(Fig. 1).** The fishing area is characterized by a very narrow continental shelf (4-6 km) and a steep slope, reaching depths greater than 5000 m near the coastline **(Lara-Lara et al., 2008).** The study is based on the coastal fishery for black skipjack by the artisanal fishery of Puerto Ángel, Oaxaca, and the marine limit is determined by the spatial dynamics of the fleet that operates at a distance between 1 and 7 nautical miles from the coast **(Fig.** 1).

The climate's seasonality is mainly marked by two seasons: a dry season, which runs from November to April, and a rainy season, which runs from May to October.
During the dry season, the Tehuano winds, a cold air mass from North America, cause a rise in the thermocline in the Gulf of Tehuantepec, resulting in intense upwelling of nutrient-rich waters **(Lavín et al., 1992; Fiedler, 2002).** During this season, the direction of the coastal current is primarily determined by the southward-flowing California Current **(Kessler, 2006).** When the Tehuano winds decrease and circulation is reestablished in the Gulf of Tehuantepec and adjacent waters, the Costa Rica Coastal Current exerts a greater influence on the area, leading to a lower thermocline and the presence of warmer (30°C) and less productive surface waters **(Hernández-Becerril et al., 2015).**

During the rainy season, there is a natural contribution of nutrients to the sea due to the drainage of rainwater into the marine environment, which increases the amount of organic matter and nutrients, mainly in the coastal zone **(Martínez-Santos 2014; Cabrera-Núñez, 2016).** Surface circulation during this season is governed by the Costa Rican Coastal Current, with a northward flow that carries low-salinity, nutrient-rich waters along the Oaxacan coast **(Lavín et al., 1992; Kessler, 2006).** In the coastal zone, the thermocline occurs between 10 and 15 meters deep, where the mixed layer is very shallow and favors abundant fish resources **(Araico-Gonzáles, 2012).**

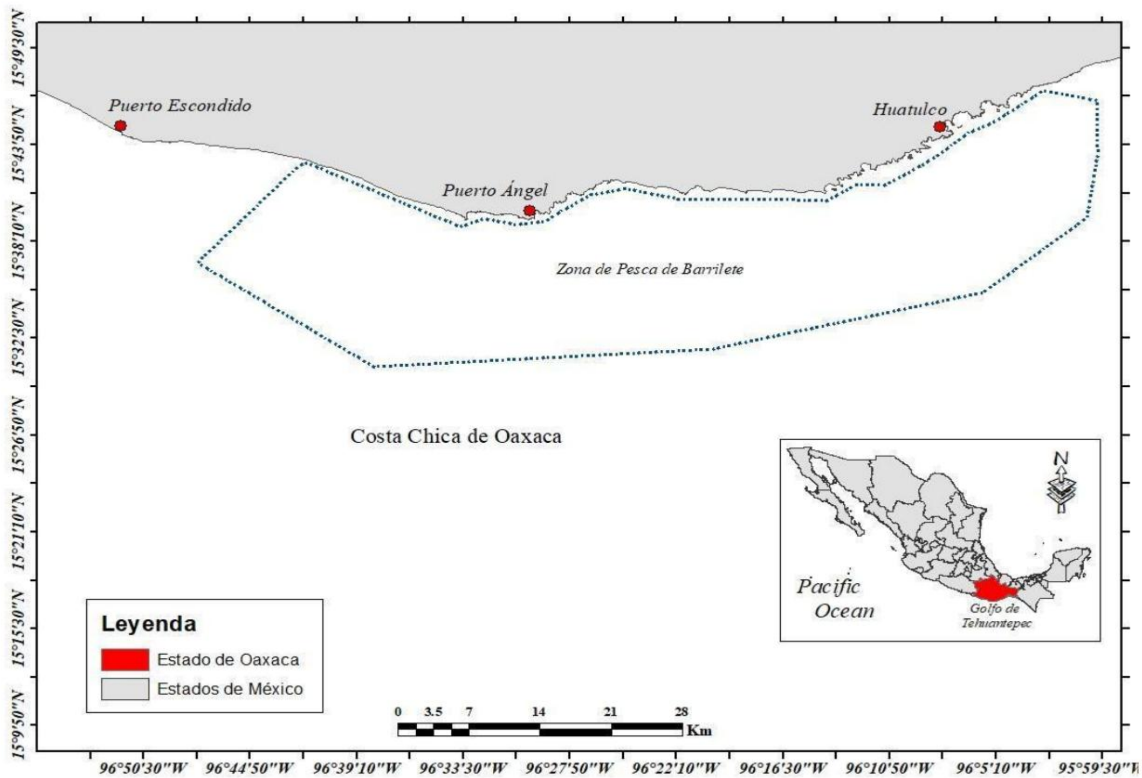

Figure 1. Location of the study area on the small coast of Oaxaca, Mexico. The dashed line indicates the fishing area of the Puerto Ángel artisanal fishing fleet.

Sea surface temperature and chlorophyll a concentration

This study used satellite data with monthly temporal resolution during October 2022 - October 2024. The Sea Surface Temperature (SST) data used for this study were derived from the Level 4 Multi-scale Ultra-high Resolution (MUR) Foundation Temperature version 4.1 produced by the Group for High Resolution Sea Surface Temperature (GHRSST) and were taken from the PODAA-JPL web site (https://podaac.jpl.nasa.gov/dataset/MUR-JPLL4- GLOB-v4.1). The MUR SST is a global monthly analysis gridded at a 0.01° × 0.01° horizontal resolution. The feature resolution of the MUR SST analysis is an order of magnitude higher than most existing analysis products and is of sufficient quality along the coastal and open ocean to study the small-scale feature **(Scales et al., 2015; Mill et al., 2015; Chin et al., 2017; Vázquez et al., 2017; Abhishek and Sil, 2019).**

On the other hand, the chlorophyll-a (Chl-a) data used were derived from the Moderate Resolution Imaging Spectroradiometer in Water (MODISA) Level 3 Standard Mapped Image and were taken from the PODAA-JPL website (https://oceandata.sci.gsfc.nasa.gov). The Chlorophyll-a Aqua/MODIS is a global monthly analysis gridded at a 0.04° × 0.04° horizontal resolution.

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Field methods

The catch data and morphometric samples were obtained from artisanal fishing in Puerto Angel, Oaxaca **(Fig.** 1), during the period from October 2022 to October 2024. Samples were obtained weekly and the fish analyzed were randomly collected from different vessels. The sample size was based on the abundance of the fishing fleet since the fishing gear used in this fishery is trolling and handline. In general, the catches of the fleet correspond to an average distance of 5-7 miles from the coast and the fishing trips last approximately two hours of work per day.

The specimens were sampled at the beach, in a fresh whole state without discrimination of sex. For each organism, the furcal length (Lh) was measured following the recommendations of the FAO (1982) and the measurements were recorded to the nearest cm. The total weight of the organism (Pt) was measured with a 5-kilogram capacity clock scale, to the nearest 10 grams. Furthermore, the monthly and annual catch data for skipjack in the state of Oaxaca were obtained from the Aquaculture and Fisheries Statistical *(https:// www.gob.mx/ conapesca/ documentos/ anuario-estadistico-de-acuacultura-y-pesca).*

Data management and statistical analysis

Data were recorded monthly over a two-year period (October 2022–2024). Abundance and body size values for organisms (weight and length) were incorporated into a QR working matrix. Data on abiotic variables (sea surface temperature and chlorophyll a concentration) were collected from satellite images. A Kruskal-Wallis (KW) analysis was performed to determine whether there were significant differences in the variability of abundances, weights, and sizes of organisms during the analyzed period. Multiple correlations were performed between environmental variables and abundance, weight, and length values to determine the possible relationship and influence of abiotic variables on biotic variables.

Results

Environmental conditions

In general, it was observed that, for the coast of Oaxaca, the monthly average of the SST It ranged between 27.21 (December 2022) and 31.08 °C (June 2023). Analysis of the surface temperature expressed as temperature anomalies shows that during the sampled period, 4 phases were recorded, two cold and two warm **(Fig.** 2). The first cold phase (C23) was recorded from October 2022 to April 2023, reaching anomalies less than -2 °C during the month of February 2023. C23 was longer in duration and intensity compared to the second cold phase (C24), which was recorded from November 2023 to April 2024, with thermal anomalies that did not reach -1.5 °C **(Fig.** 2).

Regarding the warm phase, it was observed that the first phase (H23) was recorded during the months of April-November 2023, while the second warm phase (H2024) was observed during the months of May-October 2024 **(Fig.** 2). H23 recorded the maximum temperatures

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anomaly values (1.8°C) observed throughout the period analyzed, which were recorded at the beginning of the phase (June-July). H24, in addition to showing lower intensity in anomaly values, recorded its maximum values (1.3°C) near the end of the warm period (August-September).

For its part, the monthly average of the temporal variation of the concentration of chlorophyll *a (Chl-a)* fluctuated around 0.32 mg/m3 throughout the period analyzed **(Fig.** 2). The maximum Chl-a value was recorded in December 2022 (0.93 mg/m3), while the minimum was during May, June and September 2023 (0.09 mg/m3). In general, it was observed that the seasonal variation of Chl-a showed an inverse pattern to the SST anomalies, with the exception of the period from November 2023 to May 2024 where low Chl-a values were recorded associated with negative SST anomalies **(Fig.** 2).

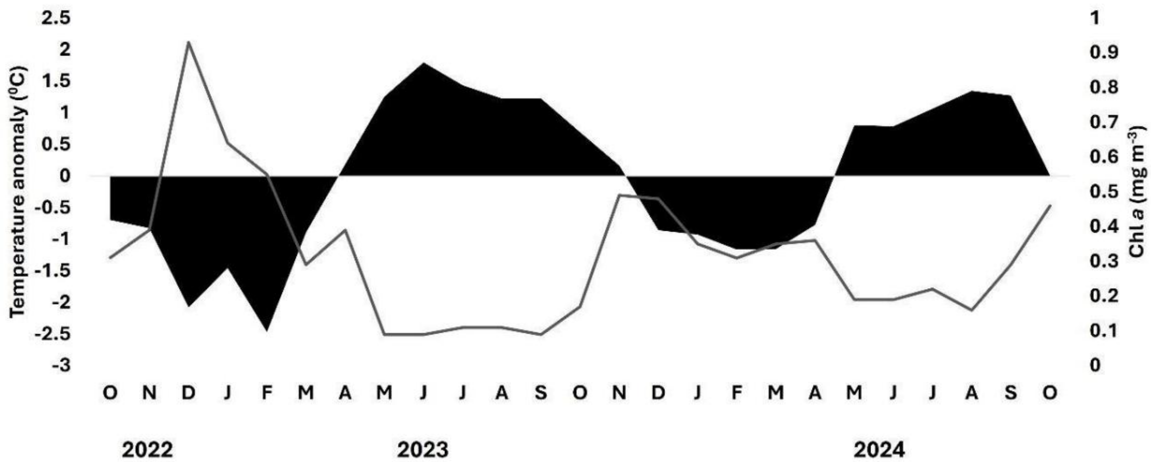

Figure 2: Chlorophyll *a* concentration (grey line) and sea surface temperature anomalies (black areas) off the coast of Oaxaca.

Abundance and length-weight relationship

For this study, morphometric measurements of furcal length *(Fl)* and total weight *(TW)* were recorded for a total of 1,967 and a monthly average of 105 *E. lineatus* organisms. between the months of October 2022 and 2024 (Table 1).

The monthly average fork length of *E. lineatus* ranged between 44.86 (± 4.6) and 49.55 (± 1.67) cm, recorded in July 2024 and March 2023 respectively (Table 1). The statistical analysis of the *Lf* showed significant differences for the *Lf* (KW, H = 122.39, P < 0.05) between the different seasons of the year, except spring/winter. For its part,

The monthly average of the total weight of the analyzed *E. lineatus* organisms ranged around 1.71 kg. The lowest values of the monthly average were recorded in the months of June and July 2024 (1.51 kg), while the highest value was observed in April 2023 (1.98 kg) **(Table** 1). Additionally, significant differences were observed for Pt (KW, H = 85.13, P <0.05) between all seasons of the year, except for summer and autumn.

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Table 1: Monthly average furcal length and total weight of *E. lineatus* specimens Captured off the coast of Oaxaca from October 2022 to October 2024. Monthly catch of *E. lineatus* reported for the state of Oaxaca in the Statistical Yearbook of Aquaculture and Fisheries (CONAPESCA). Season = Season of the year; A = autumn; W = winter; Sp = spring; Su = summer; * = data not available.

Year Month	Season	Mean length (cm)	Length SD (cm)	Mean weight (kg)	Weight SD (kg)	Captures (Ton)
October 2022	TO	45.417	1927	1,633	0.155	28.9
November 2022	TO	45,979	3.252	1,840	0.474	106.8
2023 February	W	48,444	2.751	1,664	0.275	36.8
March 2023	W	49.553	1,672	1,561	0.178	47.4
April 2023	Sp	48,633	3.074	1986	0.372	55.2
2023 May	Sp	48.163	1,673	1942	0.239	115.1
June 2023	Sp	48,459	2.544	1,848	0.281	56.6
July 2023	His	47.241	2.251	1,701	0.251	230.5
August 2023	His	45,962	2.676	1,596	0.214	37.8
2023 September	His	47,535	2.589	1,773	0.305	41.4
October 2023	TO	45,735	2.967	1,641	0.274	37.7
2024 February	W	48,356	2.925	1955	0.362	*
2024 March	W	49.018	4.512	1959	0.428	*
April 2024	Sp	45.206	4.343	1,633	0.339	*
2024 May	Sp	46,863	3.288	1,725	0.301	*
June 2024	Sp	46,887	3.342	1,513	0.240	*
July 2024	His	44,864	4.609	1,515	0.348	*
August 2024	His	46.418	2.454	1,559	0.121	*
2024 September	His	47,415	4.026	1,674	0.224	*
October 2024	TO	46.302	3.408	1,644	0.226	*

The fork length frequency histogram of *E. lineatus* **(Fig. 3A)** showed that sizes 44–50 cm were the most abundant (1,708 organisms). In addition, a low frequency of organisms with fork length greater than 50 cm (191 organisms) and of organisms smaller than 42 cm (100 organisms) was observed.

The frequency histogram of total weight shows a distribution centered around 1.7 kg **(Fig.** 3B). In addition, a lower abundance of *E. lineatus* weighing more than 2.0 kg (199 organisms) was observed.

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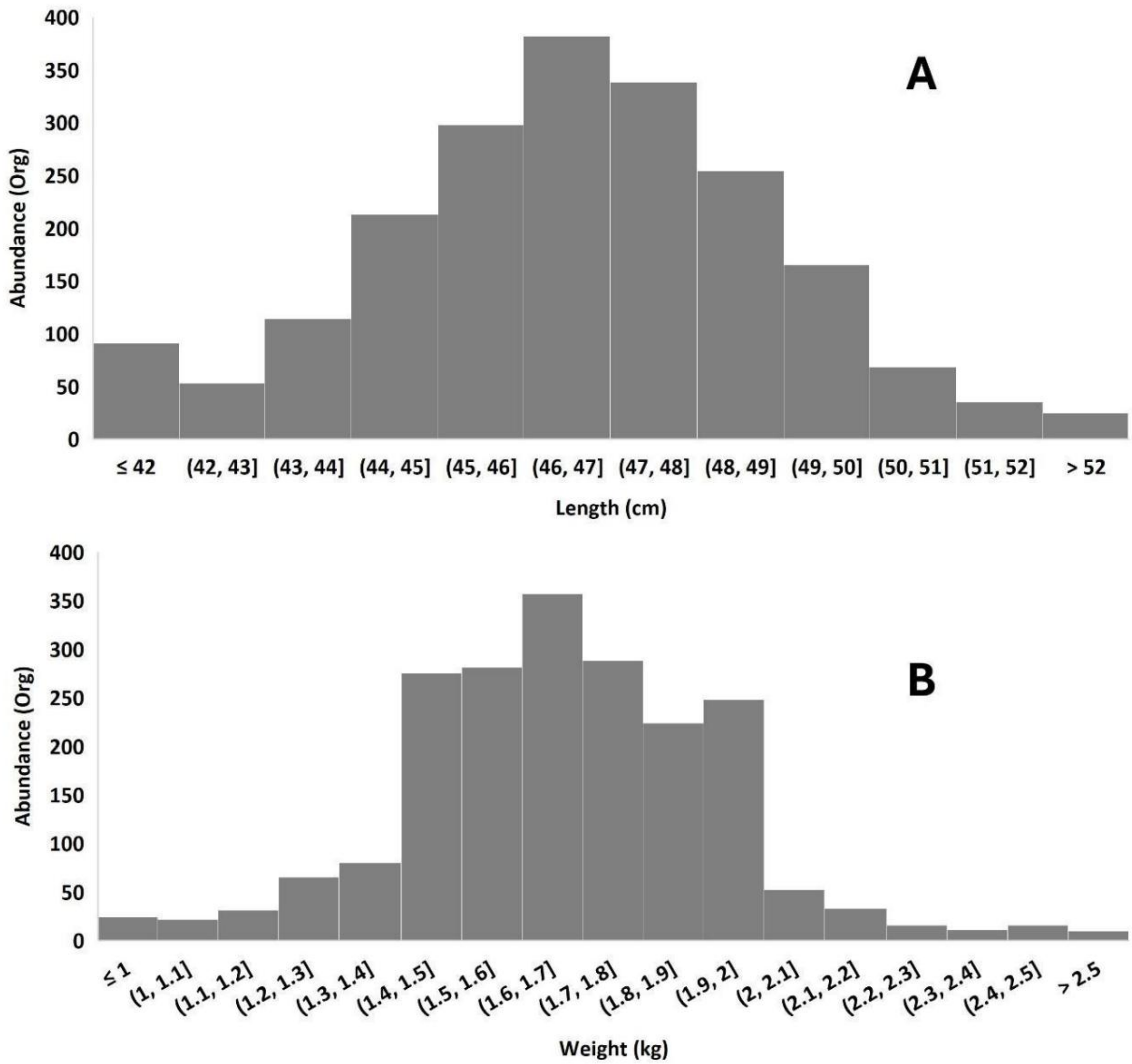

Figure 3: Frequency histograms of furcal length (A) and total weight (B) of *E. lineatus* Captured during the period October 2022–October 2024 on the coastal shore of Oaxaca, Mexico. Org=number of organisms.

The correlation between weight and length of *E. lineatus* was statistically significant *(P<0.05).* The rest of the correlations were not statistically significant *(P>0.05)* **(Table** 2). The temporal variation in length shows an increase in body size in the months of February and March of 2023 and 2024 **(Fig.** 4). This pattern recorded for length is also reflected in the body weight of *E. lineutus,* which presents high average values in the months of March and April of 2023 and 2024 respectively **(Fig.** 4). When comparing the catch volumes with the length and weight data, no relationship was observed between the months with larger body sizes and larger catches **(Fig. 4).**

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Table 2: Correlation values between environmental variables, length and weight of *E. lineatus* captured from October 2022 to October 2024 on the coastal shoreline of Oaxaca, Mexico.

	R	R2	*P*
Length/Temperature	-0.213	0.045	0.365
Length/Chl *a*	0.086	0.007	0.715
Length/Weight	0.550	0.303	0.011
Weight/Temperature	-0.143	0.020	0.545
Weight/Chl *a*	0.078	0.006	0.742

The *E. lineatus* catch data for the state of Oaxaca published in the Statistical Yearbook of Aquaculture and Fisheries (CONAPESCA) cover only the period from October 2022 to October 2023 (Table 1). The catch volume reported for July 2023 (230.5 ton) stands out, which, compared to the following months, is double the catch volume (November 2022 = 106.8 ton; May 2023 = 115.1 ton).

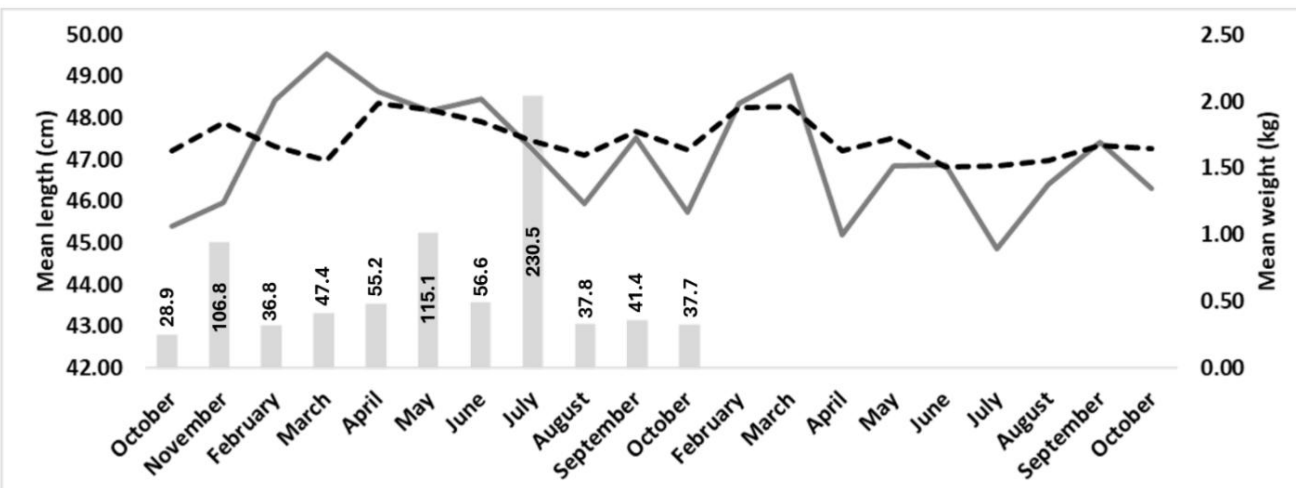

Figure 4: Relationship between length (line) and weight (dashed line) of *E. lineatus* captured during the period from October 2022 to October 2024 on the coastal shoreline of Oaxaca, Mexico. Monthly catches in tons of *E. lineatus* from the state of Oaxaca, obtained from the statistical yearbook of Acuaculture and Fishing (bars).

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Considerations

SST anomalies along the Oaxaca coast showed marked seasonal variations, ranging from negative to positive. Negative SST anomalies were generally observed between October and March, while positive anomalies were recorded between April and September.

A statistically significant correlation *(P<0.05)* was observed between the weight and length of *E. lineatus.* The temporal variation in length shows an increase in body size in the months of February and March of 2023 and 2024, which coincides with the anomalies negative anomalies recorded in this study. Meanwhile, a decrease in skipjack lengths was observed during periods of positive anomalies. This pattern recorded for length is also reflected in the body weight of *E. lineutus,* which presented high average values in the months of March and April of 2023 and 2024, respectively.

The frequency histogram of *E. lineatus* fork length **(Fig. 3A)** showed that sizes 44-50 cm were the most abundant, and a low frequency of organisms smaller than 42 cm (100 organisms) was also observed, indicating that the skipjack fishery in Oaxaca catches organisms above the first maturation size (40 cm). The frequency histogram of total weight also shows a distribution centered around 1.7 kg **(Fig.** 3B), although a lower abundance of *E. lineatus* larger than 2.0 kg was observed .

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