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Relationships between climate, growth and fisheries production in a commercially exploited marine fish

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Relationships between climate, growth and fisheries production in a commercially exploited marine fish

by

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Dedication

My research network is only half of my small army of supporters, friends and family that helped me get to this point today. I would like to extend a Texas sized thank you to all of my MSI friends, whom there are too many to name individually but you know who you all are, for all the love, laughs, and support that kept me sane the past few years. To my California friends who may not be physically with me but never truly left my side, including Judy and Jared Young, Dia and Kameran Neises, and Krista Rice. My California fishy family Sherri Charter, Bev Macewicz, Emily Gardner, and Stephanie Nehasil just to name a few. Lastly, my family, Marilyn, Mike, Brian and Jason who always believed in me, supported me and celebrated every accomplishment big or small. This one is not just for me but all of you.

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Abstract

Relationships between climate, growth and fisheries production in a commercially exploited marine fish

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Climate variability can affect fish populations and fisheries production in numerous ways, including inducing measurable fluctuations in fish growth, condition, and fisheries production. Unfortunately, mechanisms driving these linkages are poorly understood for most exploited species, which hinders effective management. The purpose of this study was to use the Gulf Corvina *(Cynoscion othonopterus)*, a heavily exploited marine fish in the Gulf of California, Mexico, as a model to investigate relationships between El Niño Southern Oscillation (ENSO) as measured by the Multivariate ENSO Index (MEI), sea surface temperature (SST), precipitation, drought as measured by the Palmer Drought Severity Index (PDSI), and river flow from the Morelos Dam with three parameters: adult fish condition, growth rate, and fisheries production. Adult fish condition was assessed by comparing annual variations in weight-length relationships of fish captured by the commercial fishery to each climate and environmental variable using an exponential model. Fish growth rate was measured using otolith chronologies for juveniles (years 0-2) and adult (years 3-10). Lastly, annual catch data from the commercial fishery was compared to each climate and environmental variable to examine relationships between climate and fisheries production. Results indicate that adult condition, juvenile growth rate and fisheries production are enhanced during El Niño conditions and increased SST. El Niño conditions during the birth year showed a positive relationship with fisheries landings at peak age of capture five years later, suggesting a possible linkage between juvenile recruitment, survivorship and future fisheries production. A weak positive relationship between river flow and growth rate in juveniles and adults was also found, which indicated that growth rate of both life history stages may be enhanced during strong El Niño years with high river flow. However, no relationship was found between precipitation and our parameters. Lastly, a positive relationship between decreased drought during the birth year and fisheries landings five years later indicated a freshwater influence on fisheries production. Our results indicate climate variability acting through El Niño events has a positive effect on growth, condition, fisheries production, and potentially juvenile recruitment suggesting the importance of both ocean climate variability and freshwater input on the Gulf Corvina.

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Introduction

Climate plays an important role in the productivity of a marine ecosystem, influencing plankton to forage species to apex predators (Hunt Jr *et al.*, 2002; Brander, 2007; Cheung *et al*., 2010). Fluctuations in fish production of the world's fisheries has been of great interest to the scientific community in recent years due to the emerging effects of changing climate (Brander, 2007; Cheung *et al*., 2010). The El Niño Southern Oscillation (ENSO) has been documented as a principal driver of inter-annual variability in fish population growth and individual fish growth for a number of species in the Eastern Pacific (Lehodey, 2006; Morrongiello *et al*., 2012). Changes in wind, rainfall, thermocline depth, and biological productivity due to ENSO have increased in frequency since 1990 due to anthropogenic climate change (Fiedler, 2002; Yeh *et al*., 2009). The added stressor of fishing intensity in combination with climate creates a situation in which highly exploited populations have a reduced ability to adapt or withstand climate-related changes (Hsieh *et al*., 2005; Brander, 2007; Planque *et al*., 2010).

Climate effects can affect fish condition, a parameter often used as an indicator of fish health (Rätz & Lloret, 2003; Macfarlane *et al.*, 2005; Ndjaula *et al*., 2013). Condition is often calculated as the deviation in the weight at a given length (Bolger & Connolly, 1989; Murphy *et al*., 1990) and can provide useful information about population ecology (Blackwell *et al.*, 2000; Froese, 2006) and ecosystem health (Murphy *et al.*, 1990). A variety of other analyses have been used to assess fish health such as Fulton's Condition Factor *(K)*, Relative Condition Factor *(Kn)*, and Relative Weight *(Wr)* (Fulton 1904; Le Cren 1951; Wege & Anderson 1978). Misuse of these analyses has become rampant in fisheries science mainly due to the difficulty in following their underlying assumptions necessary for correct interpretation (Cone, 1989; Froese, 2006). Recent reviews on methods to assess weight-length relationships in fishes recommend approaches that utilize ordinary- least squares regression (Cone, 1989; Froese, 2006). More recently, weight-length relationships for individual fish have been used as environmental indicators for fish populations (Marshall *et al*., 2004; Macfarlane *et al.*, 2005). For example, fish condition in juvenile Chinook Salmon *(Oncorhynchus tshawytscha)*, as represented by the slopes of regressions of weight-length relationships, increased during El Niño years, suggesting a positive influence of a warm temperatures on fish condition (Macfarlane *et al.*, 2005). Differences in climate regimes affect fish condition among populations. The condition of Adult North Atlantic Cod *(Gadus Morhua)* populations are lower in cold water habitats compared to populations in warm habitats, which may reduce their resilience to climate change and fishing pressure (Rätz & Lloret, 2003).

Climate variability affects other aspects of fish growth such as growth rate (Black, 2008; Rypel, 2009; Morrongiello *et al.*, 2012). Changes in otolith growth are tightly coupled with changes in somatic growth (Casselman, 1990; Campana & Thorrold, 2001). Therefore, fish chronologies of otolith growth-increment width can be used to infer the effects of climate variability (Boehlert, 1989; Lombarte & Lleonart, 1993). Water temperature is known to act as a regulator of incremental growth (Panella, 1971; Lombarte & Lleonart, 1993; Neuheimer & Grønkjær, 2012). In the central and northern California Current upwelling zone, growth increments in rockfishes *(Sebastes spp.)* are narrow during El Niño events which are characterized by warm temperatures and low upwelling (Woodbury, 1999; Black, 2009). In southern California, warm water has a positive influence on growth of a sciaenid species, White Seabass *(Atractoscion nobilis)* (Williams *et al.* 2007). Differences in climate-growth relationships have also been indicated between otolith chronologies generally from juveniles and adults reflecting changes in habitat and life history stages (Ong *et al.*, 2015).

Fisheries production and recruitment in the Eastern Pacific are strongly affected by climatic forcing (Beamish, 1993; Hollowed *et al.*, 2001; Galindo-Cortes *et al.*, 2010). In this region, ENSO events cause variations in Sea Surface Temperature (SST) (Fiedler, 2002; Lluch-Cota *et al*., 2007). More specifically, El Niño is linked to increased precipitation in terrestrial environments and warming water temperatures with decreased primary productivity in the California Current (Holmgren *et al*., 2001; Chavez *et al.*, 2002; Fiedler, 2002). In the North Pacific, increases in recruitment and year class strength during warm waters are triggered by El Niño events for many species such as Pacific Hake *(Merluccius productus),* Gulf of Alaska Walleye Pollock *(Theragra chalcogramma)*, and Gulf of Alaska Pacific Cod *(Gadus microcephalus)* (Hollowed *et al.*, 2001; Dutil & Brander, 2003). In the Gulf of California, Mexico, recruitment of juvenile Leopard Grouper *(Mycteroperca rosacea)* is negatively correlated with the Multivariate ENSO Index (MEI) due to reductions in the availability of juvenile habitat (*Sargassum spp.* beds) associated with warm El Niño years (Aburto-Oropeza *et al.*, 2010). Conversely, recruitment in the Yellow Snapper *(Lutjanus argentiventris)* is enhanced in the Gulf of California during El Niño years due to expansions in juvenile habitat (mangroves) in response to increased freshwater flow into coastal areas(Aburto-Oropeza *et al*., 2010). Therefore, depending on the fishery and the region in the Eastern Pacific, ENSO events may have different effects on fisheries production and recruitment.

The Colorado River Delta in the Upper Gulf of California is a region that is vitally important for estuarine and pelagic species (Fig. 1.) (Lluch-Cota *et al.*, 2007, 2010). The Delta is an inverse estuary, where its high evaporation rate exceeds any freshwater input from the Colorado River or rainfall (Lavín *et al.*, 1998). Damming of rivers for agricultural and livestock purposes results in little input of freshwater outside of the rainy season (Álvarez-Borrego, 1983). Consequently, the primary climatic events responsible for inter-annual variability in precipitation and river flow in the region are ENSO events (Herrera-Cervantes, 2010; Lluch-Cota *et al*., 2010; Páez-Osuna *et al*., 2016).

Biological productivity of commercially important fisheries in the Delta region have been linked to freshwater input. For example, studies of $\delta\ ^{18}O$ in otoliths, indicate that juveniles of Gulf Corvina *(Cynoscion othonopterus)* and Totoaba *(Totoaba macdonaldi)* seek out brackish estuarine nursery grounds created by fresh water inflow from the Colorado River (Rowell *et al*., 2005, 2008). Likewise, both species return to these areas to spawn as adults (Cisneros-Mata *et al*., 2008; Erisman *et al*., 2012). Additionally, increases in brackish nursery grounds due to increased freshwater input from river flow have been correlated with increased shrimp recruitment (Garcia, 1991; Galindo-Bect *et al*., 2000). However, a recent review paper by Brusca *et al.* 2017 argues there is a lack of evidence to support the importance of freshwater input to the productivity of the region. Historically, there have been extended periods of reduced or no river flow reaching the Upper Gulf of California from the Colorado River. Therefore, it's clear that ENSO is a driver of climate variability, but the local drivers mediating interactions between climate, ecosystem, populations and productivity continue to be debated.

The Gulf Corvina and its use of the Colorado River Delta as essential nursery and spawning habitat make it an excellent model to explore relationships between climate, growth, and fisheries production. Gulf Corvina are endemic to the Gulf of California (Robertson & Allen 2008). Other sciaenid fishes that occur in the region exhibit increases in growth rate with increased SST (Williams *et al*., 2007). Additionally, the foundation of Gulf Corvina research is based in well-documented life history characteristics, an understanding necessary for further analysis of growth (Román-Rodriguez, 2000; Gherard *et al.*, 2013). For example, Oxygen isotopes from natal otolith rings of Gulf Corvina indicate increased juvenile growth in brackish nursery grounds, which is thought to enhance juvenile survivorship of this euryhaline species (Rowell *et al.*, 2005; Perez-Velazquez *et al.*, 2014). Therefore, an increase in freshwater input via river flow and precipitation during El Niño events may lead to positive effects on this species. Characteristics of the fishery too have been documented, which includes serious concern over the sustainability of the fishery due a combination of size (gear) selectivity and high exploitation rates resulting in serious age truncation of the population (Gherard *et al.*, 2013; Erisman *et al.*, 2014). Fishery-induced age structure truncation has been shown to decrease a population's sustainability and increase variability, inevitably reducing the population's capacity to buffer against its environment (Hsieh *et al.*, 2006; Brander, 2007). Therefore the fluctuation of fisheries production with climate variability is of importance as well.

The objective of this study was to quantify relationships between climate, fish growth rate, fish condition, and fisheries production in the Gulf Corvina. Specifically, I tested for relationships between juvenile growth rate, adult growth rate, adult fish condition, and fisheries production with fluctuations in ENSO, Sea Surface Temperature (SST), precipitation, drought, and river flow. Currently, few fisheries management plans directly incorporate relationships between climate, environmental conditions, and fisheries production into stock assessments. The results produced by this study may be useful to fisheries management by providing insights on how population dynamics and potential fisheries production in the Gulf Corvina respond to fluctuations in climate and local environmental conditions. Managers could use this information to adjust harvest levels accordingly to avoid overfishing and maintain a sustainable fishery.

Materials and Methods

SPECIES BACKGROUND

Gulf Corvina grow to a maximum size of 1013 mm total length (TL) and 12 kg in body mass and can live to a reported maximum age of nine years (Román-Rodriguez, 2000; Gherard *et al.*, 2013). The average length and age at maturity for females is 295 mm TL and 2.3 years, respectively (Gherard *et al.*, 2013). Males reach sexual maturity at age two and 255 mm TL (Gherard *et al.*, 2013). Isotope analysis using $\delta\ ^{18}O$ indicated that juvenile Gulf Corvina seek out brackish nursery habitats in the Colorado River delta for the first two years of life with salinities that range from 26 ‰ to 30 ‰ (Rowell *et al.*, 2005). The specific juvenile diet is unknown, but adults are known to feed primarily on Pacific Anchoveta *(Centengralis mysticetus),* with the remaining diet consisting of various other fishes and shrimp (Román-Rodriguez, 2000).

FISH CONDITION

We investigated annual trends in length and weight from official fishery surveys conducted from 1997 to 2016. Fish were sampled randomly and opportunistically from commercial fishers at El Golfo de Santa Clara (Sonora) and El Zanjón (Baja California) during the days that the commercial fishery landed Gulf Corvina. Total length (TL) in millimeters and total weight (TW) in grams were recorded for each fish sampled. The sample size ranged from 38 to 2,057 per year and ranged in length from 550 to 850 mm TL (Table 1). Length and weight data measured for each fish collected from these surveys were conducted annually during peak fishing and spawning season (February-May) and were used to construct weight-length relationships.

Analysis of fish condition using length and weight data followed the suggestions and assumptions outlined in a review by Froese (2006). The length range chosen remained consistent with adult fish caught in the fishery (550-850 mm) and excluded outliers like juveniles and extremely old fish whose length and weight would not be representative of the population being studied. The consistent sampling of individuals during the same months each year (February – May) removed potential bias associated with seasonal changes in fish condition. Lastly, we assumed that sex was not a confounding factor for the condition analysis due to consistent sex ratios of 1:1 in landings surveys, similarities in growth patterns, length at maturity, and age at maturity between males and females (Gherard *et al.*, 2013; Erisman *et al.*, 2014).

A weight-length relationship was calculated for each year of data available using non-linear least squares regression analysis. This modeled relationship was created by minimizing the sum of squares and fitting the residuals to a best fit line. The best fit relationship was the allometric model for growth as indicated by weight (W) as a function of length (L), and a and b are parameters:

(1) $W = aL^{b}$

This allometric growth model is proposed as the preferred measure of weight-length relationships to indicate fish condition as a measure of fish health (Cone, 1989; Froese, 2006). The slope parameter b typically ranges from $2.5 < b < 3.5$ in fish with allometric growth (Hile, 1936; Froese, 2006). A value of b less than 3 indicates a decrease in condition and elongation in length and a value of b greater than 3 indicates an increase in condition and an increase in width with length (Hile, 1936). From this model, the value of b was generated for each year and used as a proxy for fish condition. From here, weight-length relationships will be referred to as condition in the text.

GROWTH RATE CHRONOLOGY OF JUVENILES AND ADULTS

Gulf Corvina sagittal otoliths were removed and dried whole after sampling, and then stored until further use. In total, 457 otoliths from fish ranging from 2 to 10 years old were collected during the period of 1997-2016 (Table 2). Otoliths were sectioned according to the methods established specifically for Gulf Corvina (Gherard *et al.*, 2013). Otoliths were first mounted on wood blocks with cyanoacrylate adhesive. A 0.5mm dorsal-ventral cross-section was made through the focus using a double-bladed Buehler IsoMet 1000 precision saw (Allen *et al.*, 1995). Sections were then mounted on a glass slide and submerged in water with a black background for viewing. Otolith sections were viewed using a Zeiss Stemi 2000-C microscope with a Zeiss Axiocam 105 color camera at 6.25x total magnification. Transmitted light with a polarized filter was used to enhance the contrast between opaque and translucent regions. Pictures were taken using the Zeiss program Zen 2 lite.

Images of otolith sections were then imported into Image-Pro Premier 9.1 x 64 to measure increment widths (Fig. 2). The software was calibrated to the image using the "Calibration" function. Once calibrated, measurements were made perpendicular to the growth increment along the same axis for each fish. A line was drawn as close to the focus as possible to the most distal increment using the "Line Profile" function. The most distal increment, however, was not included in the measurements due to potential incomplete formation of the annuli. A complete annuli was considered to be one opaque region to the end of the subsequent opaque region. Based on the year of collection and age of the fish, increment widths were back-calculated and assigned a ring of formation.

Once increments were measured, a chronology was generated (Black *et al.*, 2005). First age-related growth declines were created for years of formation (1-10) and fitting a negative exponential function to the data (Fig. 3). To do this measurement we organized with respect to age of formation. The mean was calculated for each age and the observed increment values, which were then divided by the age-specific mean. These standardized values were then averaged according to calendar year. Two chronologies were created, one for juveniles and one for adults. The juvenile growth rate chronology was created using first and second year of growth, operating under the assumption that after two years fish are sexually mature adults (Gherard *et al.*, 2013). Adult growth included rings formed during years 3-10. In order to maintain similar period in time series, the adult chronology and juvenile chronologies began with calendar year 1993 corresponding to the first year of sufficient sample size (n >20 increments).

FISHERIES PRODUCTION

The Gulf Corvina supports one of the most important commercial small-scale fisheries in the Gulf of California (Erisman *et al.*, 2012). It is currently listed as "vulnerable" by the American Fisheries Society and the Redlist of the International Union for the Conservation of Nature (IUCN) (Chao *et al.*, 2016). Gulf Corvina is prone to intense fishing pressure upon its spawning aggregations during peak periods of spawning (Erisman *et al.*, 2012). The modern Corvina fishery began in 1993, and from 1998 to present experienced consistent intense fishing effort, which generates an estimated 2,200 to 5,900 tons (Paredes *et al.*, 2010; Rodriguez-Quiroz *et al.*, 2010). The fishery generates an estimated of 2-3 million USD each year, which is second to only to the shrimp fishery in annual revenue (Rodríguez-Quiroz *et al.*, 2010). Gulf Corvina face intense fishing pressure over a relatively short fishing season in spring (February-May) consisting of 21-25 days, where the majority of fishing occurs in the 2-5 days before the new or full moon, creating an opportunistic fishing scenario for fishermen (Erisman *et al.*, 2012). The gear selectivity of the mesh gill nets used by the entire fishery and mandated by the Mexican government preferentially selects for age five adults (>550 mm in length), and the intense fishing pressure results in a population structure where few fish survive past age seven. Consequently, the reproductive activity of 2 to 3 year old adults are relied upon to support the productivity of the entire stock (Erisman *et al.*, 2014). We selected the period of 1998-2015 to assess fisheries production of the Gulf Corvina fishery. A lag of five years was used to assess the relationship between fisheries production and climate or environment at approximate birth year, i.e. five years prior to a fish entering the fishery.

CLIMATE AND ENVIRONMENT DATA COMPILATION

All measured and estimated data for fish condition, fish growth rate, and fisheries production were correlated with the Multivariate ENSO Index (MEI), the first principal component of six climate indicators in the tropical Pacific (Wolter & Timlin, 2011). The values were obtained from the National Oceanographic Atmospheric Administration website for MEI time series (www.esrl.noaa.gov). Monthly SST was chosen as an indicator of local climate; values were obtained from the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST1) (1870-now, 1º reconstruction) for the Sea of Cortez in the Eastern Tropical Pacific (28 ºN to 32 ºN, -115 ºE to -112 ºE). Precipitation, Palmer Drought Severity Index (PDSI), and river flow were the three variables used to test for freshwater input as an influence on growth and fisheries production. Monthly land precipitation data were retrieved from the 1901-2014 Climate Research Unit Time-Series Version 3.24 1º reconstruction of high resolution gridded data. The self-calibrating University Corporation for Atmospheric Research PDSI from 1850 includes evapotranspiration, precipitation, and soil properties, with positive numbers indicating wet conditions and negative numbers indicating dry conditions. Both precipitation and PDSI were averaged for the region (20 ºN to 60 ºN, 230 ºE to 300 ºE) values of SST, precipitation, and PDSI were extracted using KNMI Climate Explorer (http://climexp.knmi.nl). Lastly, river flow data were obtained from the Morelos Dam site (USGS 09522000) on the Colorado River closest to the United States/Mexico border (32.7 ºN, 114.7 ºW) using monthly values in ft3/sec.

DETERMINING RELATIONSHIPS BETWEEN CLIMATE, ENVIRONMENT, CONDITION, GROWTH RATE AND FISHERIES PRODUCTION

Linear correlations using Pearson's r were used to test for relationships between each parameter (juvenile growth rate, adult growth rate, fish condition, and fisheries production) and climate (MEI and SST) or (PDSI, precipitation, and river flow). First, each parameter was correlated with each of the monthly climate and environmental variables. Months with ($r \geq 0.30$) and significance $p < 0.10$ were then averaged together and correlated with each parameter. If none of the months were significant, then annual average was correlated with each parameter. The final step was to assess the correlation of the months or annual average (if applicable) for each relationship that had a spatial component (SST, precipitation, and PDSI) using KNMI Climate Explorer. Climate Explorer was used to create a correlation map with the gridded SST, precipitation or PDSI to show the spatial property of the climate-growth relationships. Pearson's r and ($p < 0.05$) were used to test for significant relationships.

Results

FISH CONDITION, CLIMATE AND ENVIRONMENTAL VARIABLES

A total of 9,588 fish were used to determine annual variations in condition of Gulf Corvina during the study period of 1997-2016 (Table 1). Sample size ranged from 38 to 2,057 per each of the 14 years of collection (Table 1). Annual values of *b* ranged from 1.93 to 3.05 with a mean of 2.66 (Table 3). Two of the highest *b* values occurred during the historically large El Niño years of 1997 and 2015. MEI, SST, precipitation, PDSI, and river flow. Bi-monthly values of MEI for April-May had the strongest relationship with condition (r = 0.35), although the relationship was not statistically significant (p = 0.23) (Fig. 4). SST compared with monthly average of April-May was strongly correlated with condition, (r = 0.50, p = 0.07) (Fig. 5). Adult condition did not show a relationship with annual PDSI (r = 0.12, p = 0.70), and annual river flow (r = -0.13, p= 0.65).

GROWTH RATE CHRONOLOGIES AND THEIR RELATIONSHIPS WITH CLIMATE AND ENVIRONMENTAL VARIABLES

We created an otolith growth rate chronology for both juvenile and adult Gulf Corvina. The juvenile chronology was derived from 454 fish and approximately 875 increment width measurements from 1993 to 2013. The adult chronology was derived from 425 fish and 1,004 increment widths from 1993 to 2015 (Table 4). Growth rate as determined by each standardized chronology was then compared to the 5 variables (MEI, SST, precipitation, PDSI, and river flow). Juvenile growth rate compared to bi-monthly MEI averages showed a trend of December-January through May-June (Fig. 6). The spring MEI bi-monthly averages of January-February through April-May compared with juvenile growth rate was positively correlated (r = 0.47, p = 0.03), indicating a significant relationship (Fig. 7).

Adult growth rate showed no relationship with monthly or annual MEI ($r = 0.21$, $p = 0.34$). SST compared with juvenile growth rate had the strongest relationship with the winter months of January and February (Fig. 8). When the mean SST of these two months was taken, a positive relationship was found between SST and juvenile growth ($r = 0.37$, $p = 0.10$) (Fig. 9, Fig. 10). Adult growth rate showed no relationship with annual SST ($r = 0.02$, $p =0.92$) or annual PDSI ($r= 0.31$, $p = 0.16$). Juvenile growth rate showed no relationship with annual PDSI ($r = 0.03$, $p = 0.91$). Juvenile growth rate showed no relationship with annual precipitation ($r = 0.16$, $p = 0.48$) and adult growth rate showed no relationship with annual precipitation ($r = -0.21$, $p = 0.34$). Juvenile growth rate compared to monthly river flow of the Morelos Dam showed a positive relationship with months January, February, November and December for the same year ($r = 0.45$, $p = 0.04$) (Fig. 11). When these months were averaged, a positive relationship was found between river flow and juvenile growth rate ($r = 0.45$, $p =0.04$) (Fig. 12). Adult growth rate compared to monthly river flow of Morelos Dam had the strongest monthly relationship with the months of March through June (Fig. 13). When these months were averaged together, a positive relationship was found between river flow and adult growth rate ($r = 0.46$, $p = 0.03$) (Fig. 14).

FISHERIES PRODUCTION AND THE RELATIONSHIP WITH CLIMATE AND ENVIRONMENTAL VARIABLES

Mean MEI for the months May-June through November-December during the birth year showed a positive relationship and fisheries production five years later ($r = 0.66$, $p < 0.01$) (Fig. 15, Fig. 16). SST showed a similar relationship to the regional climate signal indicated by MEI (Fig. 17). The months with the strongest relationship between SST and future fisheries landings (5 years later) were April-December ($r = 0.65$, $p < 0.01$) (Fig. 18, Fig. 19). To compare drought conditions at birth with fisheries production five years later, monthly PDSI was tested and a relationship with all months of the year except for June (r = 0.29) was found (Fig. 20). Mean PDSI for the months of September-December had a positive relationship with future fisheries production (r = 0.51, p = 0.03) (Fig. 21). No relationship was found between annual river flow and fisheries production five years later (r = -0.19 and p = 0.45).

Discussion

To our knowledge, this study is the first to investigate relationships of climate variability, environmental variables and indicators of freshwater input with life history specific growth rate chronologies, adult fish condition, and fisheries production in a single species. Such relationships with climate and the environment can have meaningful implications for fisheries management. We found that adult condition, juvenile growth rate and fisheries production in the Gulf Corvina increased during El Niño years. Moreover, relationships with SST, indicated a positive influence of warm water on fish condition, juvenile growth rate and fisheries production. However life history stage may play an important role in the sensitivity of Gulf Corvina growth rate to a changing climate, because only a relationship with river flow was detected for adult growth rate, and no effects of climate or SST were observed. As an attempt to tease out mechanisms for environmental effects, precipitation, drought and river flow were tested with fish condition, growth rate and fisheries production five years after birth. A relationship with increased juvenile growth rate and increased river flow was found. Likewise, increased fisheries production five years later compared with a measure of drought (PDSI), indicated that increased freshwater input at birth year is associated with increased catch of Gulf Corvina five years later. These results suggest the importance of both ocean climate variability and freshwater input to recruitment, growth, and fisheries production in the Gulf Corvina.

Climatic and environmental conditions associated with El Niño impacts the Gulf Corvina and the fishery in a variety of ways. The fishery may benefit from faster juvenile growth rates during El Niño events, through increased survival rates of juveniles that results in increased fishery recruitment rates and landings five years later. Juvenile growth rate is often correlated with increased survivorship as a driving force for future fisheries production (Beamish, 1993; Sogard, 1997). Increased survival and recruitment of Gulf Corvina could increase fisheries production at peak age of capture, age 5, when fish are most likely to enter the fishery. Therefore, annual harvest quotas may be adjusted in response to climatic conditions which could allow for predicted responses of the population and volumes of fish available to the fishery. Increased adult condition during El Niño years also has the capacity to benefit the fishery. El Niño years could mean an increase in the amount of fish per kilogram sold for the same amount of effort therefore, producing an increase in revenue for fishers. From a conservation standpoint, fewer fish could be caught for the annual quota, because they are at higher weights during El Niño years.

Fish condition is the manifestation of physical, biological and environmental impacts experienced during a period of a fishes life and is also strongly affected by food availability (Lankford & Targett, 1994; Marshall *et al.*, 2004; Macfarlane et al., 2005). Adult fish condition of Gulf Corvina was correlated with MEI and SST levels during the spring months. According to the only diet study on Gulf Corvina, Pacific Anchoveta *(Centengraulis mysticetus),* is the primary food source of adult fishes, particularly during the months surrounding the spawning season (Román-Rodriguez, 2000). This species is an integral part of the food chain in this region, and increases in stock biomass of Pacific Anchoveta have been reported during El Niño years (Sánchez-Velaso *et al.*, 2000; Mellink, 2003; Páez-Osuna *et al*., 2016). Therefore, increased densities of the major prey source of adults may explain seasonal increases in adult condition during El Niño years. Increased fish condition in warmer climates has been documented in several other species such as adult Rockfish *(Sebastes spp.),* adult North Atlantic Cod *(Gadus morhua)*, and Chinook Salmon *(Oncorhynchus tshawytscha)* (Lenarz *et al.*, 1995; Rätz & Lloret, 2003; Macfarlane *et al.*, 2005). For example, increased condition in Cod populations of the northeast and west Atlantic was attributed to the warmer temperature regimes of their environment compared to the decreased condition of cod populations in cold waters of the northwest Atlantic (Rätz & Lloret, 2003). These studies report that food availability with changing environmental conditions and increased SST may be coupled with increased condition in fish.

Growth rate chronologies developed from hard parts (e.g. shells, otoliths, etc.) are a huge resource for long-term ecological datasets and have the capability to help determine the impact of climate on marine and freshwater environments (Morrongiello *et al.*, 2012). The separation of otolith chronologies into life history phases is a relatively new method first documented by Ong *et al*. (2015) for a marine fish in northwest Australia. Similar to that study, we generated otolith chronologies separated into two life history phases, juvenile and adult growth. In this study, juvenile growth rate increased during warmer winters associated with El Niño conditions. These results are consistent with many other studies that have found positive relationships between juvenile growth rate in fishes and increased SST associated with El Niño conditions (Macfarlane *et al.*, 2005; Williams *et al.*, 2007; Sogard, 2011; Ong *et al.*, 2015). The increase in juvenile growth rate with warming climate conditions, especially during the winter, is important because juveniles of temperate fish species are better able to combat starvation and temperature extremes during the winter (Sogard, 1997). Understanding the factors that create favorable conditions for growth and survival during El Niño events is critically important for maintaining stable populations of Gulf Corvina in response to ongoing, intense fishing pressure and anticipated changes to climate and environmental conditions.

The El Niño atmospheric teleconnection is represented by an anomalous warming in the eastern equatorial Pacific Ocean (Yeh *et al.*, 2009). El Niño is the strongest in the Gulf of California during the winter when wind-driven upwelling is disrupted along the east coast of mainland Mexico (Herrera-Cervantes *et al.*, 2007). In the Gulf of California, the ecological response to ENSO events is not homogenous and primary production abundance specifically in the upper region, can be variable (Herrera-Cervantes *et al*., 2010; Páez-Osuna *et al.*, 2016). Secondary production abundance in the region can also be atypical. For example, zooplankton assemblage structure was altered during the strong 1982/1983 El Niño which created an influx of tropical-subtropical waters, yet total abundance of zooplankton did not decrease (Jimenez-Perez & Lara-Lara, 1988; Lavaniegos & Lara-Lara, 1990). The combination of food available for juveniles and growth under the thermal maxima threshold (Pörtner, 2002) has the potential to create optimal circumstances for increased growth in Gulf Corvina. A laboratory experiment using Weakfish *(Cynoscion regalis)*, a close relative of the Gulf Corvina, showed juveniles in suitable estuarine habitats have increased feeding and growth rates at elevated temperatures (Lankford & Targett, 1994). Therefore, it is reasonable to speculate that warm temperatures and zooplankton productivity during El Niño conditions in the Upper Gulf of California enhances food availability, which leads to increased growth rate in juveniles.

The interaction between fisheries production and changing climate is a topic that has been heavily studied for many overfished fish populations and one that is relevant to the heavily fished Gulf Corvina (Beamish, 1993; Planque *et al.*, 2010; Britten *et al.*, 2016). Due to the severe age truncation and high gear selectivity of the Gulf Corvina fishery, it was possible to lag fisheries production to therefore create a level of predictability of previous climate and environment (Gherard *et al.*, 2013; Erisman *et al.*, 2014). Specifically, I found that monthly MEI and SST have a strong positive relationship with fisheries production five years later. This result suggests the importance of a juvenile "critical" period for susceptibility to climate. Therefore, El Niño conditions at birth increase the availability of fish to the fishery five years later. Drivers for increased survivorship of recruits may include a combination of increased growth due to increasing SST, food available necessary for growth and habitat availability. Chinook Salmon off California showed increases in juvenile condition and growth rate due to the combination of increased SST during the 1998 El Niño event and associated increases in zooplankton blooms (Macfarlane *et al.*, 2005). Therefore, increases in abundances of zooplankton were speculated to increase the opportunity of greater small fish abundances as a food source for Chinook Salmon juveniles (Macfarlane *et al.*, 2005). In the Gulf of California, the decrease in *Sargassum spp*. habitat availability for juvenile Leopard Grouper *(Mycteroperca rosacea)* is associated with warming SST during El Niño years and a decrease in nutrient availability (Aburto-Oropeza *et al.*, 2010). The effect of increasing strengths of El Niño on nursery habitat results in decreased recruitment of juveniles and therefore decreased future catch of adults in the fishery (Aburto-Oropeza *et al.*, 2010). Alternatively, Yellow Snapper *(Lutjanus argentiventris)* juvenile abundances in mangrove nursery habitat increase during El Niño conditions due to increased fresh water inflow and nutrient input (Aburto-Oropeza *et al.*, 2010). Increased adult catch in fisheries landings four years later was found, suggesting a positive effect of climate on recruitment and fisheries production (Aburto-Oropeza *et al.*, 2010). Therefore, habitat quality, food availability and increased growth, may all be important drivers of fisheries production of Gulf Corvina during El Niño years.

Juvenile growth rate showed the strongest response to warming regional climate as indicated by MEI and SST, although adult growth rate embodied a different response. El Niño conditions are commonly associated with negative effects on growth in adult fishes (Lenarz *et al.*, 1995; Woodbury, 1999; Black, 2009). However, we found no relationship between MEI, SST, and adult growth rate. This finding suggests that adult growth rate for the Gulf Corvina may be minimally affected by annual variations in regional climate and water temperatures. While climate and water temperature are important drivers of changes in fish growth, other environmental factors like freshwater input can also be drivers of change. We found that both juvenile and adult growth rate increased in response to increased Colorado River flow from the Morelos Dam. Both seasonal and inter-annual variation of freshwater inflow have been found to affect growth rate of fishes, although the effect on the juvenile life history phase has been the more commonly documented link between freshwater and growth rate (Rowell *et al.,* 2005; Gillson, 2011; Morrongiello *et al.*, 2014). Specifically for Gulf Corvina juveniles, the increase in freshwater input from the Colorado River is attributed to increased estuarine brackish habitat quality (Rowell *et al.*, 2005). The relationship between adult growth rate and freshwater input has been documented in several other species elsewhere. Adult growth rate in the Australian Mangrove jack *(Lutjanus argentimaculatus)* increased with increased freshwater input through rainfall (Ong *et al.*, 2015). Another estuarine species inhabiting dry tropical estuaries, the Barramundi *(Lates calcarifer)* also showed a positive relationship between adult growth rate and freshwater input (via river flow) within the same year (Robins *et al.*, 2006). A possible mechanism for this increase in adult growth rate with an increase in freshwater input was suggested by Ong *et al.* (2015), who argued that the decrease in salinity may reduce metabolic costs and allow for more energy allocation to growth.

To date, many studies indicate the benefit of freshwater input to the Upper Gulf of California habitat on species and coastal ecosystems in the region (Galindo-Bect *et al.*, 2000; Dettman *et al.*, 2004; Glenn *et al.*, 2007). Among these studies, fisheries production of fish and invertebrates is said to increase with increased freshwater inflow (Galindo-Bect *et al.*, 2000; Rowell *et al.*, 2005, 2008) as well as the expansion of critically important nursery grounds for many estuarine species including the Gulf Corvina (Rowell *et al.*, 2005; Glenn *et al.*, 2007). Despite the published support for the benefits to freshwater input to the Upper Gulf of California, this topic has been hotly debated (All, 2006; Brusca *et al.*, 2017). One of the main sources of contention is whether overflow from the Colorado River ever reaches the Sea of Cortez (All, 2006; Glenn *et al*., 2007). The alternative argument is that the extremely high oceanic productivity of the region is the larger driving force for the success of the region's resources (Brusca *et al.*, 2017). The Upper Gulf of California is said to have experienced long periods of minimal freshwater input and elevated salinities, similar to the current circumstances today (Brusca *et al*., 2017). Therefore, many of the studies citing the importance of freshwater input from the Colorado River to the region are actually based more in speculation then scientific evidence (Brusca *et al.*, 2017). The majority of freshwater input to North West Mexico is through the North American monsoon, which is responsible for 70% of annual rainfall and 80% of surface runoff (Douglas, 1995; Anderson *et al.*, 2000). Therefore, climate variability such as ENSO events are crucial for determining freshwater input (Holmgren *et al.*, 2001; Páez-Osuna *et al*., 2016). The results of this study provide more convincing evidence to the influence of oceanic variability on fish growth and fisheries production. However, some evidence as to the benefits of freshwater input, primarily during very strong El Niño events, is provided and may be relevant to expand on in future research dealing with impacts of freshwater on fish growth of both juvenile and adult fish. We provide one of the few if not only, studies to give evidence to the important linkage between the broader impacts of climate variability and environmental drivers on a biological resource of great economic value in the Gulf of California.

This study links climate variability, local environment and freshwater indicators with fish growth rate, fish condition and fisheries production in one model system. Gulf Corvina has been shown to respond positively to inter-annual climate variability in which adult condition, juvenile growth rate, and fisheries production are increased due to El Niño conditions. We also provide some evidence to the effect of freshwater input on life history specific growth rate and fisheries production. Therefore, both juvenile and adult growth rate are positively influenced by an increase in river flow from the Colorado River. The information gained from this study and others like it that use model systems to explore the effects of climate variability on fish and their fisheries, are highly valuable to fisheries managers. Currently very little information like this exists and in fact more information for an ecosystem-based management approach linking climate with fisheries research has been requested by several sources (Lluch-Cota, 2000; Páez-Osuna *et al*., 2016; Brusca *et al.*, 2017). We not only provide a methodological framework for future research on other species, but we provide information that gives predictive power for future management of fisheries in response to climate variability which is severely lacking in the literature to date.

		Total Length (mm)		Total Weight (g)		
Year of collection	(N)	Min	Max	Min	Max	Sample Months
1997	147	560	860	1850	8800	February, March, April
1998	38	565	815	650	7200	March, April, May
1999	125	558	920	1500	8500	February, March, April
2004	39	595	720	1158	3410	March, April
2005	609	560	795	703	2045	March, April
2006	449	559	929	1390	3575	March
2009	1569	578	853	203	5680	March, April, May
2010	2057	592	1013	235	11950	March, April
2011	663	588	850	1360	4540	March, April
2012	1543	570	830	1087	5980	March, April
2013	189	551	798	1490	4670	March, May
2014	830	570	890	1270	8710	February, March, April
2015	1230	570	1000	1650	10260	February, March, April
2016	100	565	763	1455	3750	March
Total	9588					

Table 1. Summary of data used for analysis of fish condition in the Gulf Corvina according to year of collection, sample sizes for each year (N), minimum and maximum length of fish sampled, minimum and maximum weight of fish sampled, and the months sampled.

Year of Collection	Average of TL (mm)	(N) Samples
1997	670.67	31
1998	669.32	42
1999	704.54	30
2000	664.50	20
2003	630.22	23
2004	589.17	6
2005	653.06	17
2006	655.82	18
2007	658.36	26
2008	712.73	15
2009	709.90	30
2010	655.79	24
2011	531.52	25
2012	630.48	31
2013	601.48	29
2014	714.13	30
2015	711.53	30
2016	704.67	30
Total	659.33	457

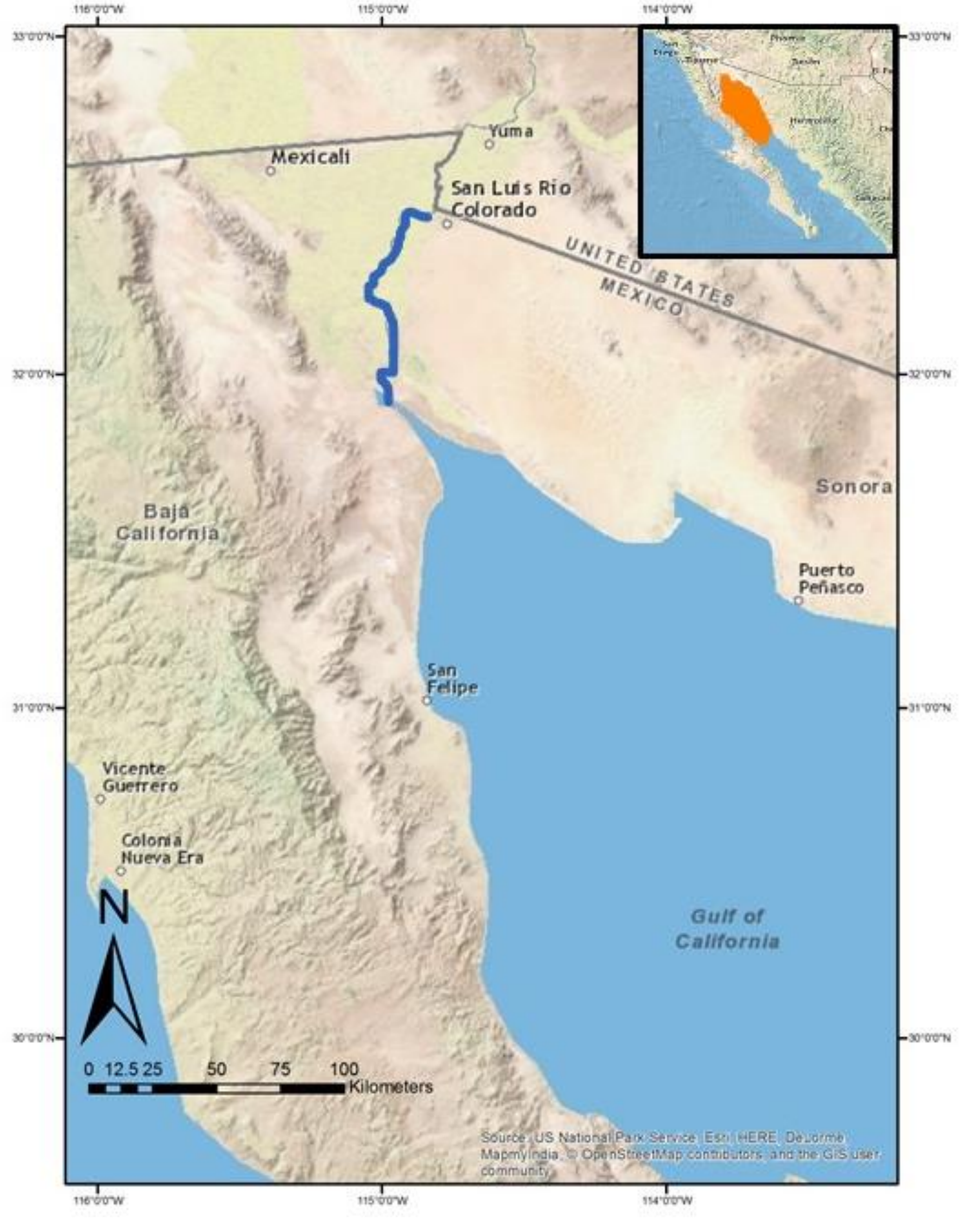
Table 2. Summary of data used for analysis of annual growth rate in the Gulf Corvina according to year of collection, the average length, and the number of otolith samples (N).

Year of collection	*a*	*b*	*b* p < 0.05	0.95	95% (-)
1997	9.23E-06	3.01	< 0.01	3.27963	2.746573
1998	0.000519	2.42	< 0.01	3.376902	1.467649
1999	0.000367	2.45	< 0.01	2.72631	2.183386
2004	8.03E-06	3.01	< 0.01	3.571339	2.453226
2005	0.000153	2.44	< 0.01	2.579908	2.289352
2006	0.008134	1.93	< 0.01	2.093524	1.763224
2009	9.41E-05	2.61	< 0.01	2.775087	2.453357
2010	7.66E-06	3.02	< 0.01	3.109407	2.938971
2011	0.000211	2.50	< 0.01	2.662042	2.344972
2012	3.27E-05	2.80	< 0.01	2.908722	2.685049
2013	0.000125	2.59	< 0.01	2.76496	2.415462
2014	0.000125	2.59	< 0.01	2.76496	2.415462
2015	6.64E-06	3.05	< 0.01	3.157896	2.933733
2016	4.19E-05	2.75	< 0.01	3.037317	2.470574

Table 3. Annual adult fish condition model parameters *a* and *b* values, standard error for *a* and *b,* significance for *b*, and 95% confidence intervals for *b*.

	Year of formation (years)	Chronology time series	Total number of increment widths	Number of otoliths
Juvenile Chronology	0-2	1993-2013	875	454
Adult Chronology	3-10	1993-2015	1004	425

Table 4. Juvenile and adult Gulf Corvina chronologies according to their year of formation, the chronology time series generated from when the years of formation occurred, the total number of increment widths, and the number of otoliths used in the generation of each chronology.



Source: US National Park Service, Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community

Figure 1. Map showing the Upper Gulf of California, including the Colorado River Delta that lies between Baja California and mainland Mexico. Inset map shows the entirety of the Sea of Cortez, and orange indicates the species range of Gulf Corvina. .

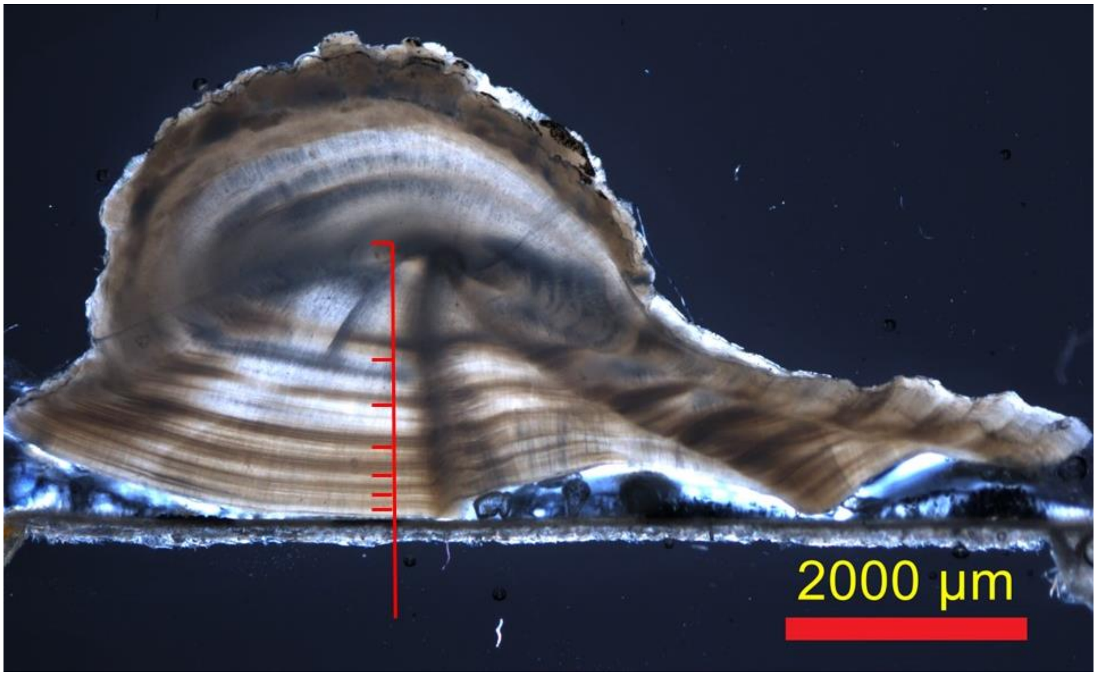


Figure 2. Cross section of sagittal otolith of a Gulf Corvina. The section was taken from an individual that was six years of age and 814 mm TL.

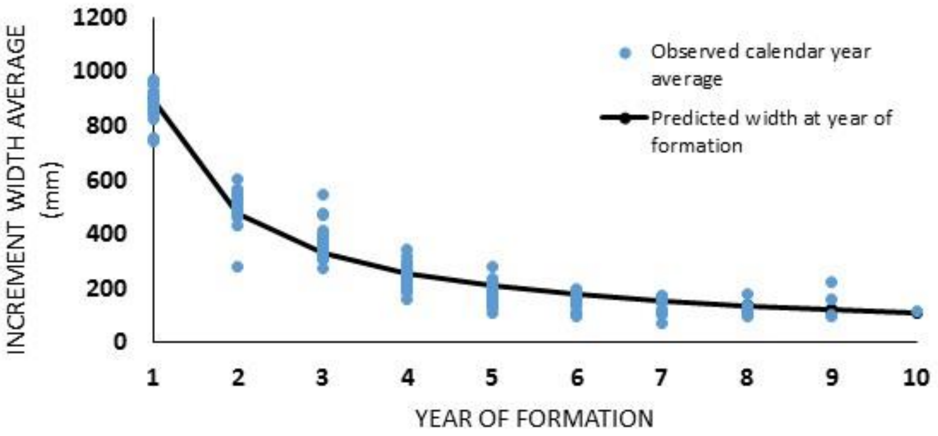


Figure 3. Growth rate analysis required standardization of increment widths to remove individual fish replication. Each ring of formation contained multiple points that are an average of increment widths for each calendar year that growth was formed. Due to varying ages of fish and rarity of older fish, fewer observed data points exist for year of formation 8+.

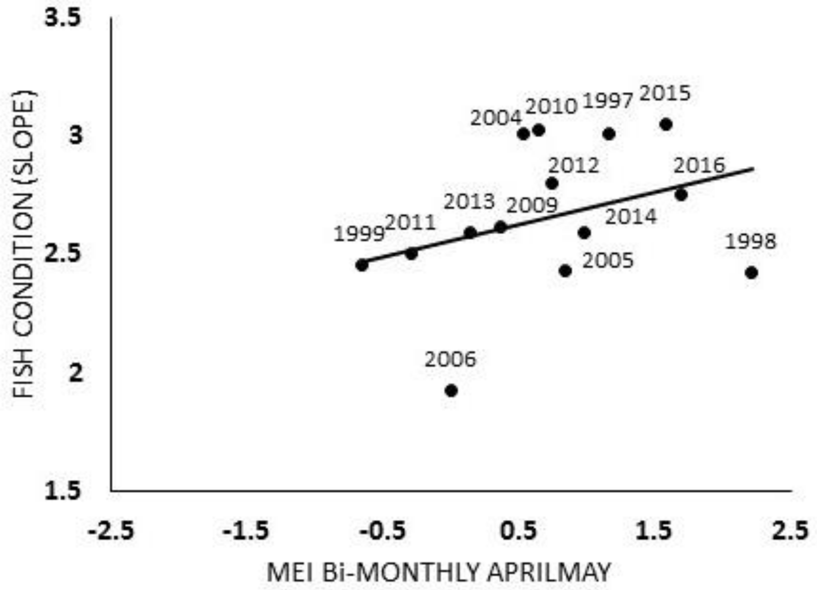


Figure 4. Annual adult fish condition as determined by the slope for each year *b* versus bi-monthly Multivariate ENSO Index (MEI) value for April-May (1997-2016) (r = 0.35, p = 0.23, n = 14, df= 12).

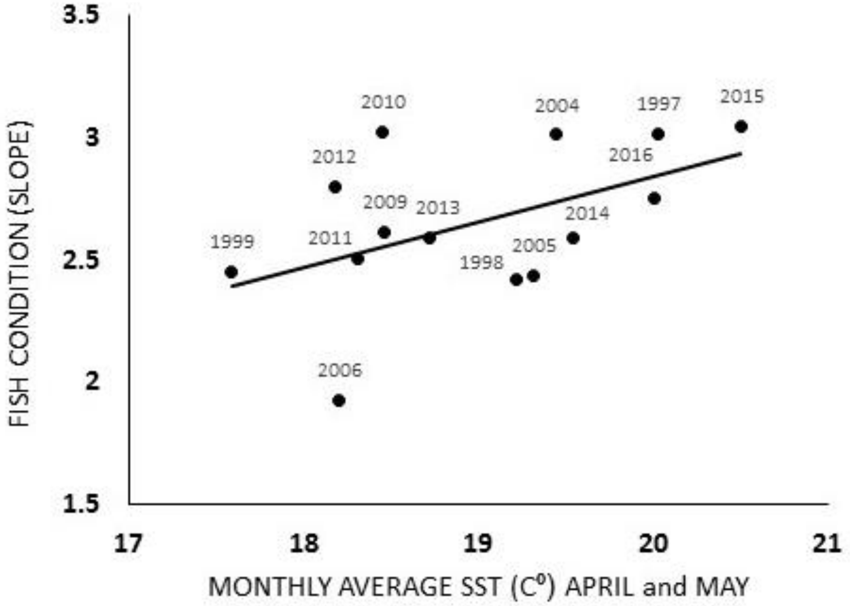


Figure 5. Annual adult fish condition as determined by the slope *b* for each year versus the monthly average of SST April and May (1997-2016) (r = 0.50, p = 0.07, n = 14, df = 12).

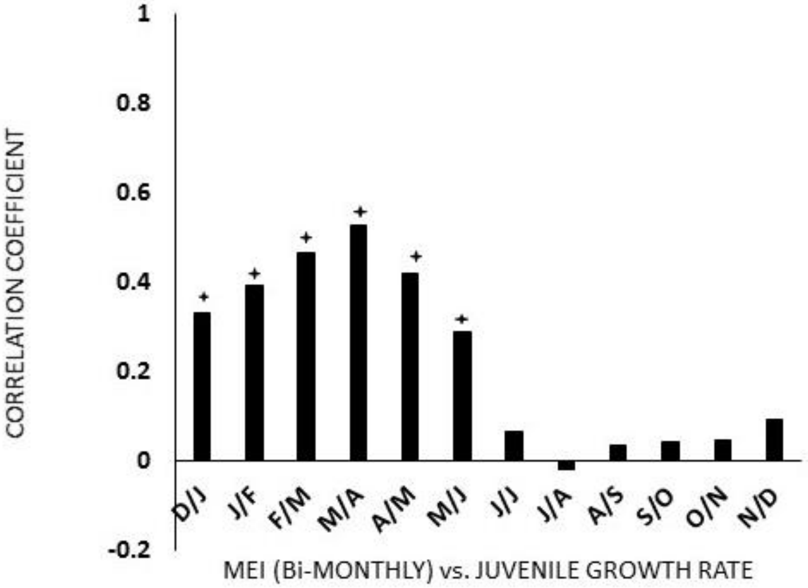


Figure 6. Bars indicate correlation coefficients of the relationship between juvenile growth rates (1993-2013) versus bi-monthly Multivariate ENSO Index (MEI) values of the same years. The plus signs (+) indicate months that have a correlation coefficient of $r \geq 0.30$.

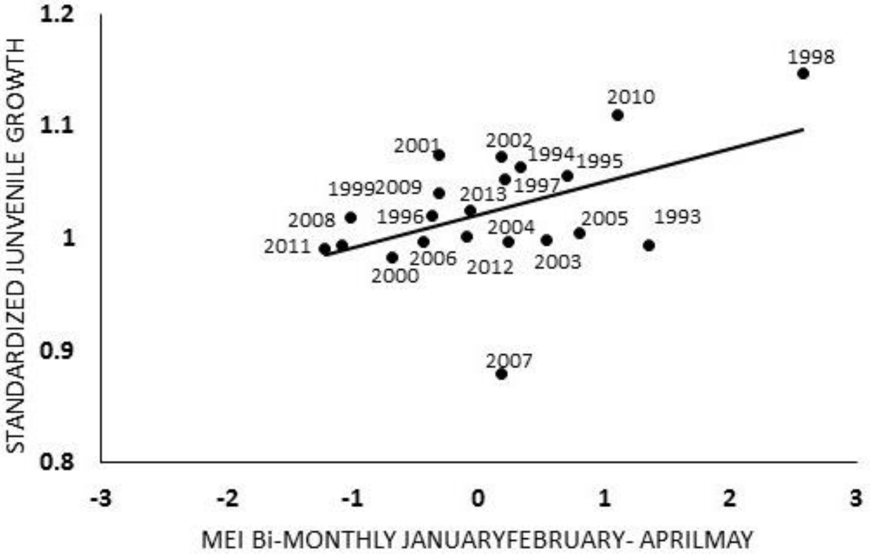


Figure 7. The relationship between juvenile growth rate (1993-2013) versus Multivariate ENSO Index (MEI) bi-monthly average for January-February through April-May (r = 0.47, p = 0.03, n = 21, df =19).

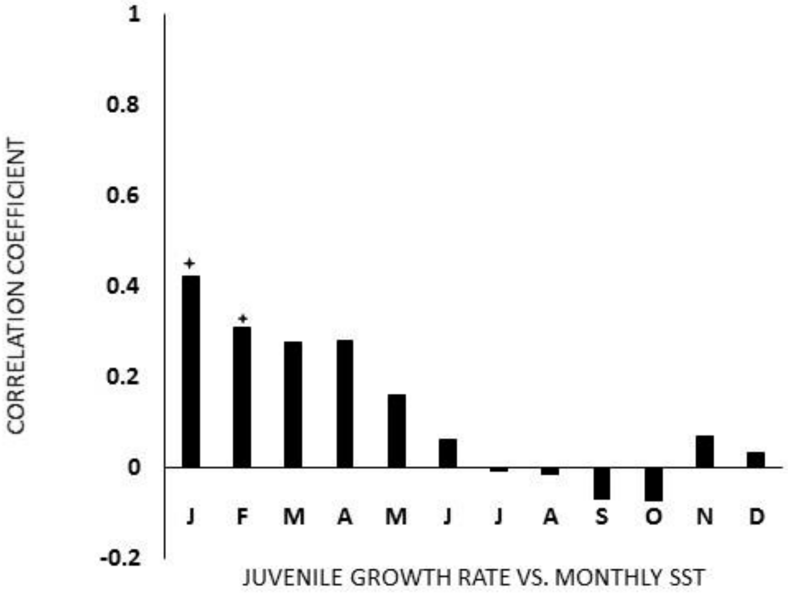


Figure 8. Bars indicate correlation coefficients of the relationship between juvenile growth rates (1993-2013) versus monthly Sea Surface Temperature (SST) values of the same years. Plus signs (+) indicate months that have a correlation coefficient of r ≥ 0.30.

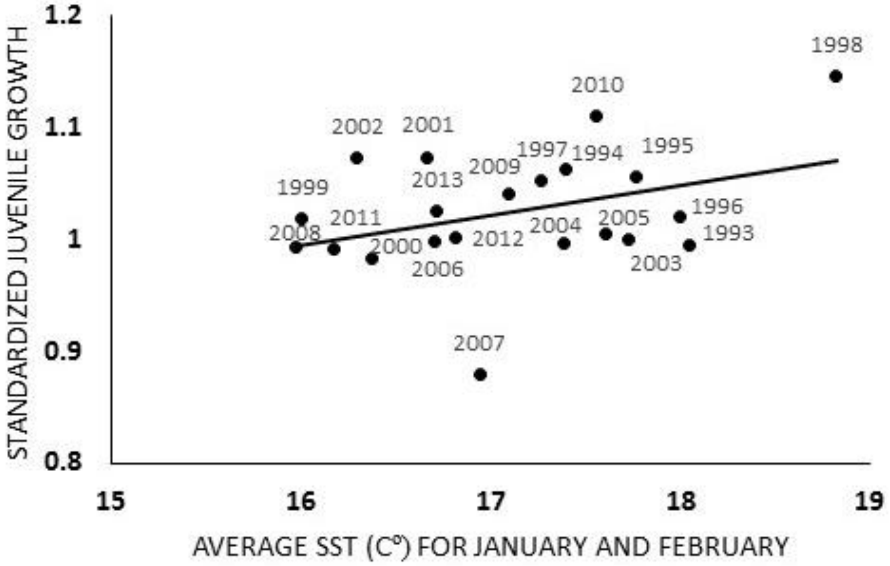


Figure 9. The relationship between juvenile growth rate (1993-2013) versus sea surface temperature (SST) monthly average for January and February (r = 0.37, p = 0.10, n = 21, df = 19).

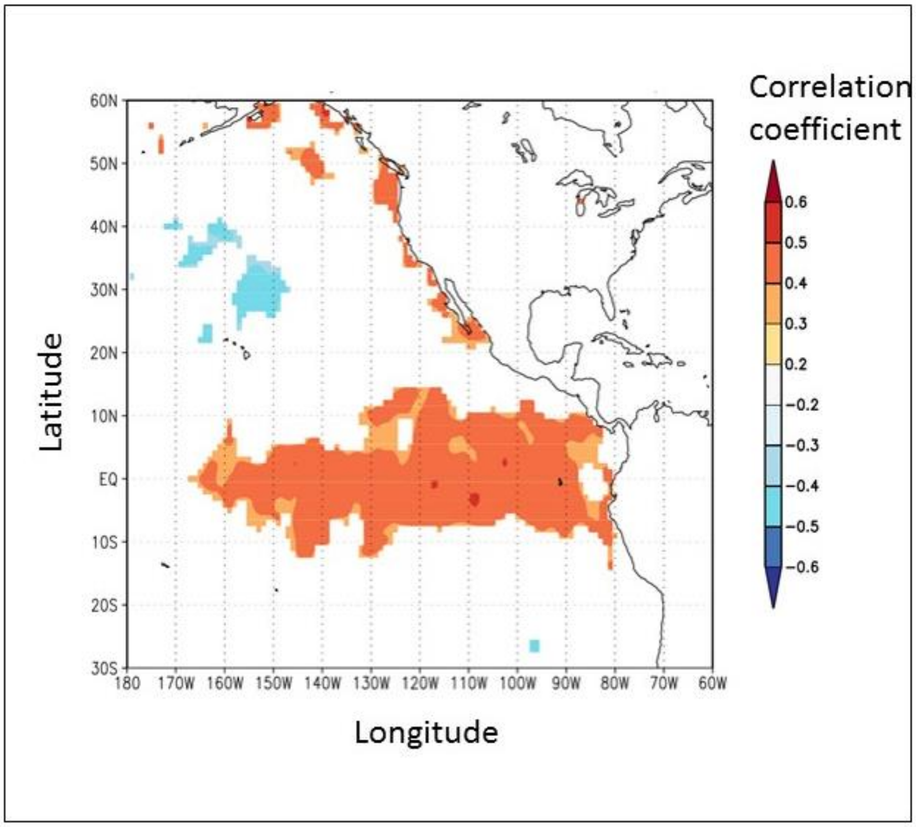


Figure 10. Map of spatial correlation of juvenile *Cynoscion othonopterus* chronology with sea surface temperature (SST). Averaged January-February (1993-2013) SST from the (HadISST1) 1870-now 1º reconstruction for the Sea of Cortez north of the Midriff islands was correlated with the juvenile Gulf Corvina chronology (1993-2013). Warmer colors indicate positive correlations, and cooler colors indicate negative correlations. The map was created using KNMI Climate Explorer (Trouet & Oldenborgh, 2013).

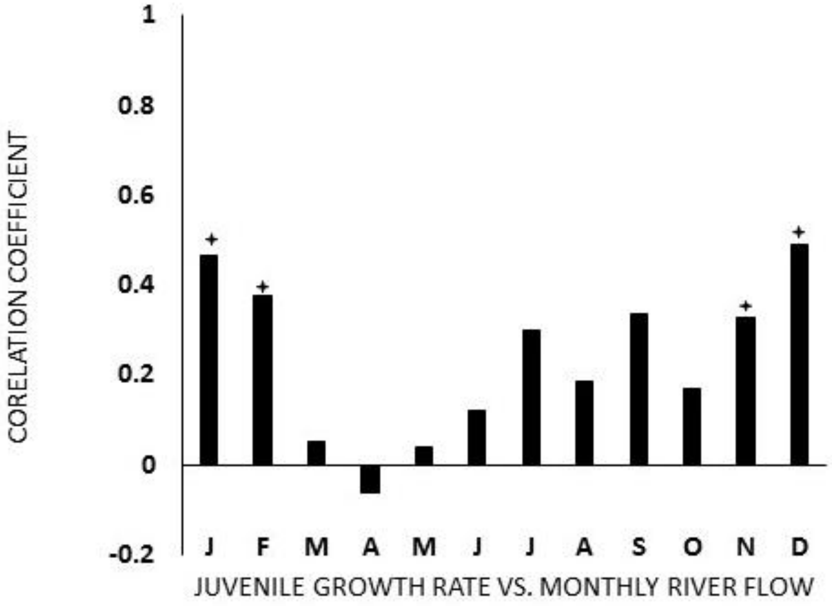


Figure 11. Juvenile Growth Rate (1993-2013) versus monthly averaged river flow (ft^3/s) from Morelos Dam January-December (1993-2013). Plus signs (+) indicate months that have a correlation coefficient of $r \geq 0.30$.

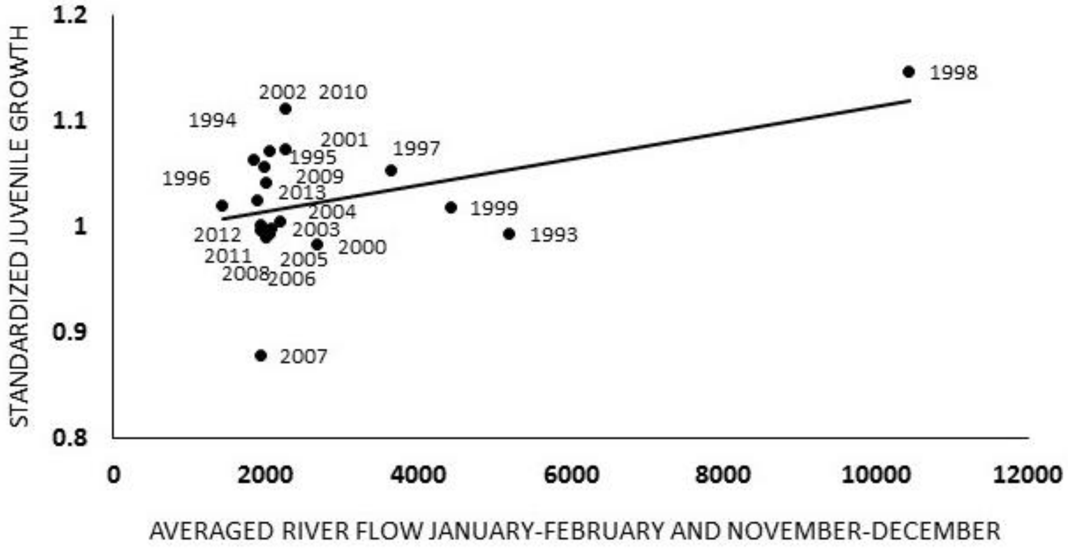


Figure 12. The relationship between juvenile growth rate (1993-2013) and river flow from Morelos Dam (ft^3/s) for January-February and November-December of the same year (r = 0.45, p = 0.04, n = 21, df = 19).

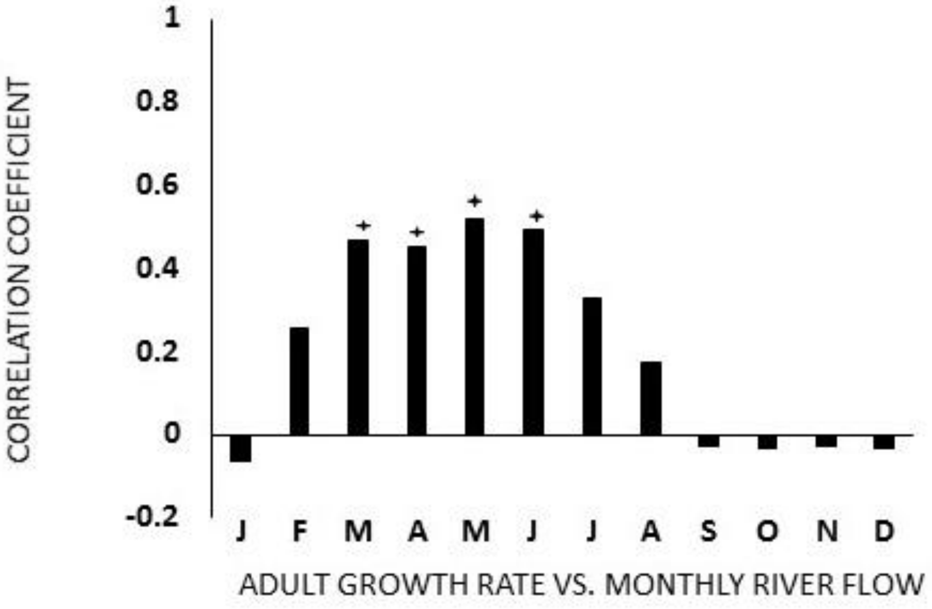


Figure 13. Bars indicate adult growth rate (1993-2015) versus monthly averaged river flow from Morelos Dam (ft^3/s) for March-June (1993-2015). Plus signs (+) indicate months that have a correlation coefficient of $r \geq 0.30$.

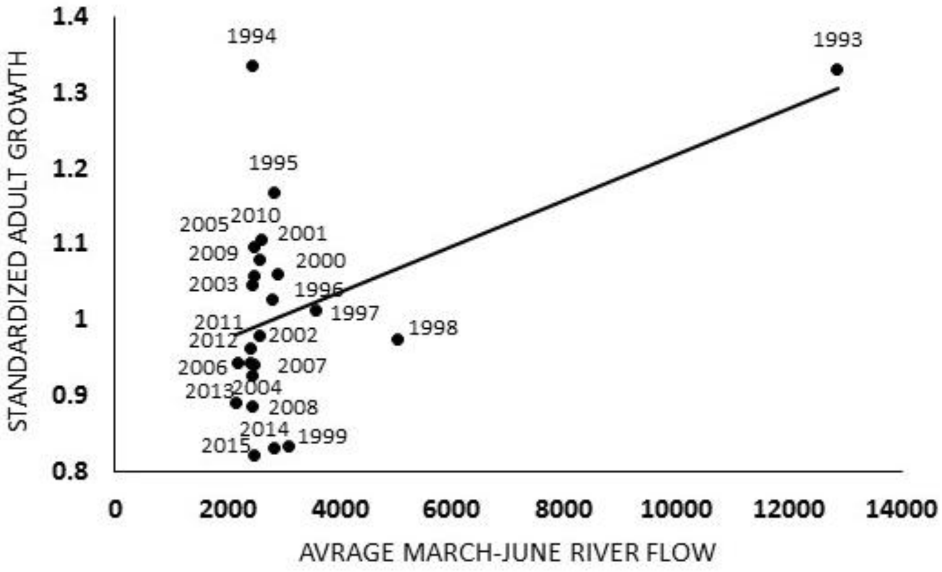


Figure 14. The relationship between adult growth rate (1993-2013) versus river flow from Morelos Dam (ft^3/s) for March-June (r = 0.46, p = 0.03, n = 23, df = 21).

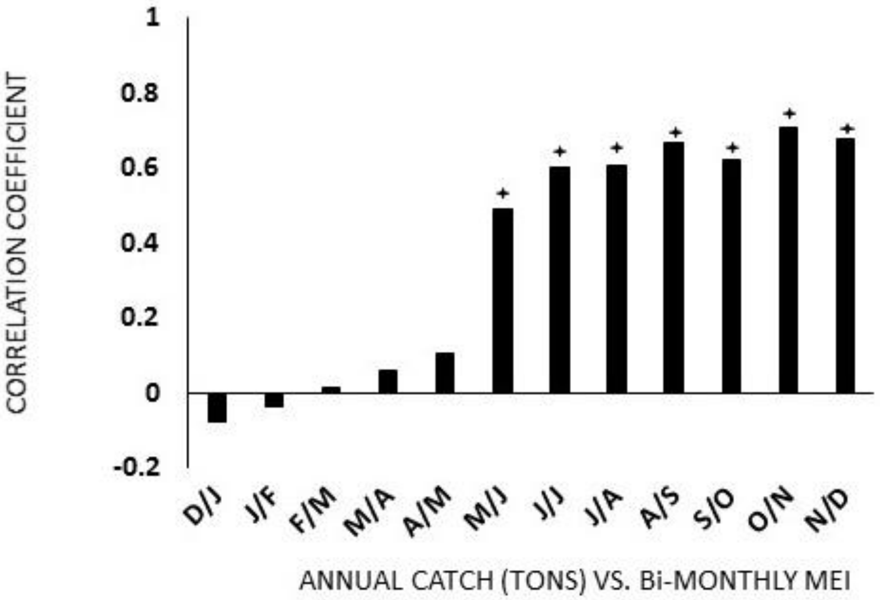


Figure 15. Bars indicate fisheries production (1998-2015) versus monthly average Multivariate ENSO Index (MEI) for May-June through November-December five years prior. Plus signs (+) indicate months that have a correlation coefficient of r ≥ 0.30.

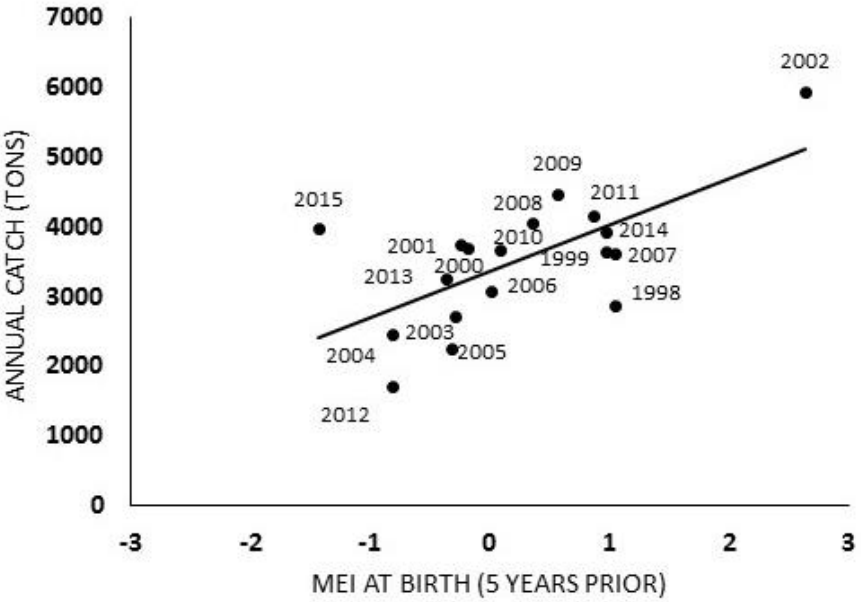


Figure 16. Fisheries production (1998-2015) correlated with bi-monthly MEI months for May-June through November-December five years prior. ($r = 0.66$, $p < 0.01$, $n = 18$, $df = 16$).

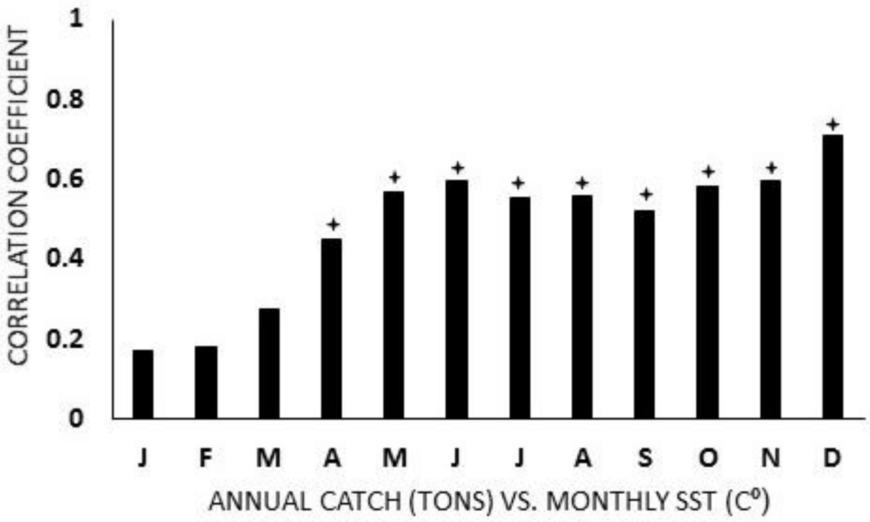


Figure 17. Bars indicate fisheries production (1998-2015) versus monthly average sea surface temperature (SST) May-December five years prior. Plus signs (+) indicate months that have a correlation coefficient of r ≥ 0.30.

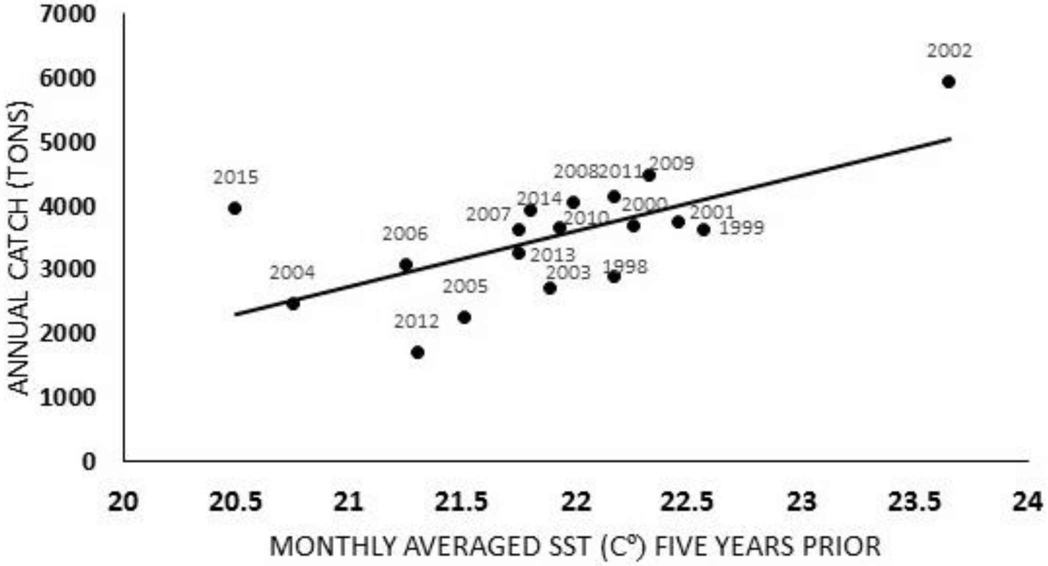


Figure 18. The relationship between fisheries production (1998-2015) versus averaged sea surface temperature (SST) for April-December five years prior ($r = 0.65$, $p < 0.01$, $n = 18$, $df = 16$).

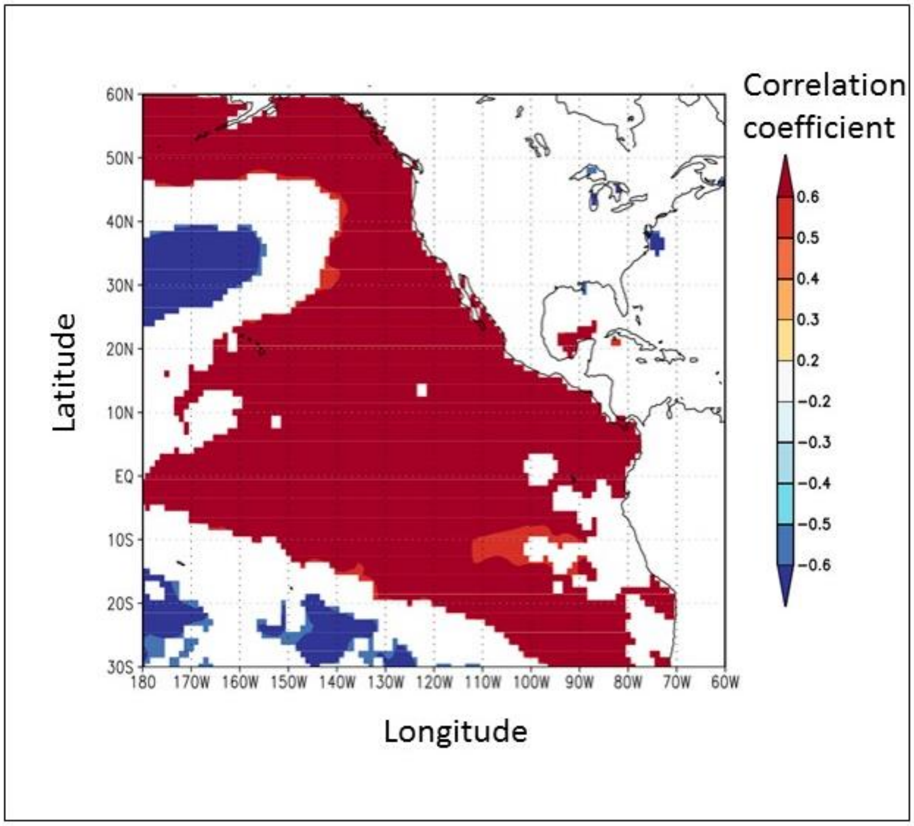


Figure 19. Map of spatial correlation of *Cynoscion othonopterus* fisheries production with Sea Surface Temperature (SST). April-December averaged SST from Hadley Centre Sea Ice and Sea Surface Temperature (HadISST1) 1870-now 1º reconstruction for the Sea of Cortez north of the Midriff islands was correlated fisheries production of Gulf Corvina five years later (1998-2015). Warmer colors indicate positive correlations and cooler colors indicate negative correlations. The map was created in KNMI Climate Explorer (Trouet & Oldenborgh, 2013).

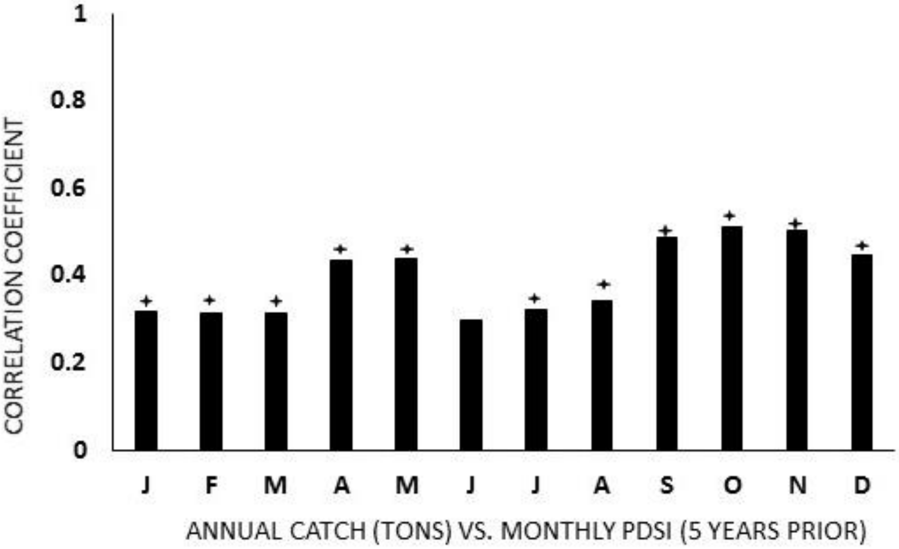


Figure 20. Bars indicate fisheries production (1998-2015) versus Palmer Drought Severity Index (PDSI). Plus signs indicate months that have a correlation coefficient of r ≥ 0.30.

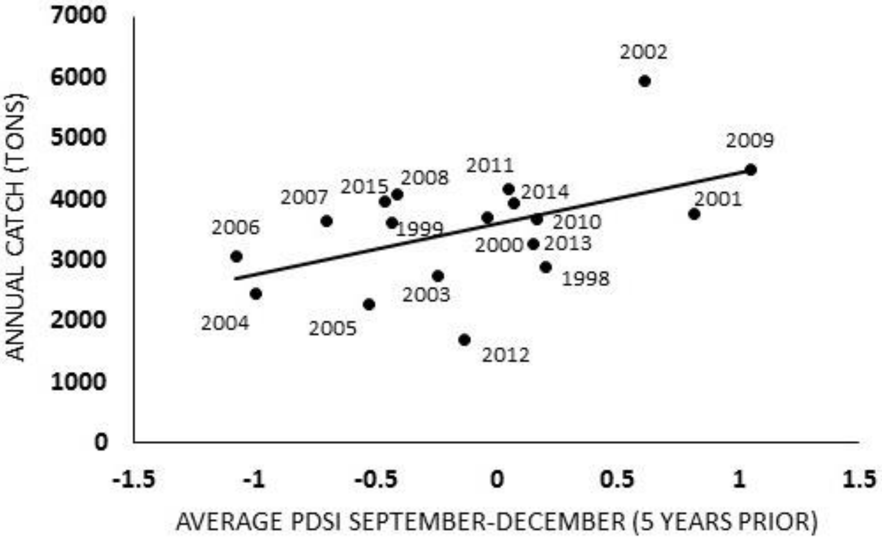


Figure 21. The relationship between fisheries production (1998-2015) and peak PDSI at birth for the months of September-December (1993-2010) (r = 0.51, p=0.03, n = 18, df = 16).

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