Deep-sea Grenadiers and Climate Change

Danielle Fabian, Applied Marine and Watershed Science M.S.

California State University Monterey Bay

Mentor: Ken Smith
Summer 2017

ABSTRACT

Oceans display physical variability "over a range of vertical, horizontal, and temporal scales," (Brierley and Kingsford 2009) that influences factors such as larval dispersal, physiology, and nutrient availability (Lindegren et al. 2016). Such variability within all marine ecosystems is vulnerable to climate change. Changes in variability could ultimately lead to a loss of key prey species, which in turn could negatively impact remaining predators that not only play an important role within their ecosystems, but that are also deemed important in commercial fisheries (Brierley and Kingsford 2009). In order to predict and manage the consequences of increased greenhouse gasses (GHGs) and climate change, it is vital that we understand the interactions and feedbacks between marine systems and climate-related changes. Grenadiers are apex predators, playing an important role within their ecosystems; therefore, it is necessary to understand changes occurring over time in grenadier species abundance in order to protect the ecosystems they reside in. Many Grenadiers are benthopelagic; in which, the adult stages reside in the deep sea or on the seafloor, while the larvae are planktonic and reside in the upper water column (Allen et al. 2006). Larvae and juveniles are particularly susceptible to changes in ocean variability (Brierley and Kingsford 2009); therefore, monitoring changes occurring in all life stages of environmentally and economically important fish species with the change in climate and surface conditions is vital in order to protect and manage fisheries in the future. This paper focuses on the process of determining and altering my thesis project throughout the MBARI summer internship program, ultimately describing the finalized thesis plan that resulted as an outcome of multiple trials and error. The project focuses on studying correlations between changes in grenadier populations over time in relation to changes in climate and surface conditions. This study will involve conducting a time series benthic and midwater transect annotation to determine changes in grenadier abundance and size during a continuing 28-year time series at an abyssal station in the northeast Pacific (Sta. M). In addition existing NOAA databases will be examined to obtain grenadier abundance and size data for all life stages. The research question is the following: Does grenadier population structure change in relation to climate variables? Grenadier abundance data will be compared to physical variables relating to climate and surface ocean conditions. Cross correlation analyses will be used to determine relationships between changes in fish populations, at Station M and along the California coast, and changes in climate and surface conditions over time.

INTRODUCTION

Climate Change Affecting Physical Variability and Fisheries:

Since the mid-1800s, there has been a tremendous increase in carbon dioxide (CO_2) in the atmosphere due to the combustion of fossil fuels on a global scale. This rise in CO_2 has the potential to aggravate the greenhouse gas effect; an event that consists of CO_2 and other gases trapping solar heat within the atmosphere, warming the planet (Recent Global Warming 2002). Additional effects of the rise of anthropogenic greenhouse gases include: rising sea levels, rising global mean sea-surface temperatures (SST), increased ocean acidity, perturbed regional weather patterns, altered ocean circulation, changes in the extent of oxygen-deficient dead-zones, and changed nutrient loads (Brierley and Kingsford 2009). Marine biological processes are affected by such physical consequences, which could ultimately impact ecosystem services and threaten human food security (Brierley and Kingsford 2009). In order to predict and manage the consequences of increased greenhouse gasses (GHGs) and climate change, it is vital that we understand the interactions and feedbacks between marine systems and climate-related changes.

Oceans display physical variability "over a range of vertical, horizontal, and temporal scales," (Brierley and Kingsford 2009) that influences larval dispersal, physiology, nutrient availability, species migration, production, and biodiversity (Lindegren et al. 2016). Such variability among and within all marine ecosystems is vulnerable to climate change. The condition of larvae and juveniles, as well as the timing of reproduction and reproductive output, can be affected by variability as well (Brierley and Kingsford 2009). Particularly susceptible to changes in salinity, temperature, and pH, juveniles and larvae may not have the ability to survive elevated temperatures that their adult stages are capable of surviving. Similarly, if the hatching time of larval eggs does not coincide with food availability, survival rates may be affected. Changes in food availability could stem from temperature-driven phenological changes that could alter the timings of plankton blooms; ultimately leading to "breaks in the food chains and wholesale departures of prey species" (Brierley and Kingsford 2009). The loss of key prey species could negatively impact remaining predators that not only play an important role within their ecosystems, but that are also deemed important in commercial fisheries (Brierley and Kingsford 2009).

Grenadier and Focal Species:

Grenadiers, of the family Macrouridae, are the most common benthic fish in the deep sea. The Macrourids generally have low recovery rates, and species that are commercially exploited may be overfished, resulting in a fishery collapse within a short time period (Large et al. 2003). In addition to being the most common benthic fish of the deep sea, grenadiers are important apex predators making it critical to understand changes in population structure over time. Many grenadiers, including the four focal species of this research project, are benthopelagic. The adult stages reside in the deep sea or on the seafloor, while the larvae are planktonic and reside in the upper water column (Allen et al. 2006). The following are brief descriptions of the grenadier focal species included within this project:

Coryphaenoides acrolepis:
C. acrolepis is a benthopelagic mid-slope grenadier species that is significantly more abundant than any other slope species (Cohen et al. 1990). This species is a target species in commercial fisheries. It is a non-migratory species that resides in the North Pacific at a depth range of 400-1800 meters (Cohen et al. 1990). Due to its economic importance, it is necessary to monitor potential changes in abundance of this species over time to avoid over fishing.

***Coryphaenoides armatus*:**
C. armatus is a deep-slope upper continental rise grenadier species found in all the world's oceans, at depths between 800 and 4,000 meters (Cohen et al. 1990). This species is known to grow slowly; potentially living up to 75 years of age. Abundance of *C. armatus* is likely driven by migration in response to variation in food availability (Drazen et al. 2012; Bailey et al. 2006). *C. armatus*, although of no interest to fisheries, is often caught as by-catch and is difficult to differentiate from *C. acrolepis.*

Coryphaenoides yaquinae:
C. yaquinae is a rough abyssal grenadier species that dominates and is confined to the abyssal plains encompassed within the Pacific Ocean (Jamieson et al. 2012). Although preferring deeper depths, the species is known to inhabit a depth range of 3400 to 5800 meters (Wilson and Waples 1983). *C. yaquinae* is closely related to *C. armatus,* and the two species are almost indistinguishable from one another based on physical characteristics alone (Jamieson et al. 2012). While generally bathymetrically segregated, the two species co-exist on the Pacific continental margin between the 3400-4300 meter depth ranges (Jamieson et al. 2012).

Coryphaenoides leptolepis:
C. leptolepis is commonly referred to as the "Ghostly Grenadier", and is listed as Least Concern because the species has no known predators and resides outside the range of fisheries. It is a bathydemersal species, inhabiting a depth range of 610-4000 meters, and can grow to 62 centimeters in length. *C. leptolepis* is native to the northeast and eastern central Pacific, as well as the western central, eastern central, northwest, and northeast Atlantic. Due to a lack of commercial importance and depth range, very little is known about *C. leptolepis* (Iwamoto 2015).

For my internship this summer, the goal was to establish a thesis project for my Master's at CSU Monterey Bay. While I originally thought that this would be a relatively straight-forward process, many road blocks occurred forcing several changes to my project through the internship. That being said, this paper elaborates on the evolving process of selecting my final project and not on the data ultimately required for a research paper.

METHODS

Attempt #1: *C. acrolepis* and *C. armatus* Study

Both *C. acrolepis* and *C. armatus* are known to have pelagic larvae, which is ultimately the intermediate tie between the surface and the seafloor in determining what is happening between species. Changes is surface water conditions are probably affecting these species, and such species changes could ultimately affect fisheries. Aside from their larvae being at risk due to changes in physical variability within the oceans, the adults may also be at risk from fishing. Fishing effort is going deeper with increasing depletion of economically important species in shallow water. These two species overlap on the slope and are difficult to distinguish (Ken Smith, pers. comm.). It is necessary to monitor changes occurring in both species to protect and manage the grenadier fisheries in the future; otherwise, accidental misclassification may result in fishermen wrongly assuming that the target species', *C. acrolepis*, population abundance is thriving, when in reality, it may be declining at a rapid rate. This could result in overexploitation and collapse of fisheries, which in turn, could negatively affect local communities as a whole.

My original thesis project was to be focused on studying correlations between changes in *C. acrolepis* and *C. armatus* populations over time in relation to changes in climate and surface conditions. Abundance and size data for all life stages would be collected from all fisheries sources available on the two species. Databases include the following sources: National Marine Fisheries Services (NMFS) databases; Cal Fish and Game; Monterey Bay Aquarium Research Institute (MBARI); National Oceanic and Atmospheric Administration (NOAA): Southwest Fisheries Science Center (SWFSC), Northwest Fisheries Science Center (NWFSC), and Alaska Fisheries Science Center (AFSC); Oregon State University; CalCOFI/LTER; Scripps Institute of Oceanography, University of Washington, and California Academy of Sciences. The life stages of the two species to be included in the study were as follows: eggs, larvae, juveniles, and adults. Very little research has been conducted on these species, making it difficult to find information concerning their sex and fecundity.

Attempt #2: Macrourids and Pacific Hake

Although my original thesis plan looked promising, given the available databases, I had to make adjustments to account for a lack of data on the species *C. armatus*. While there was a large quantity of data available for *C. acrolepis*, the commercially important species, very little data has been collected on *C. armatus;* likely due to the fact that it has not been deemed economically important. Due to a lack of data, the focus of the thesis project had to be switched to focusing on all Macrourids with pelagic larvae in databases previously mentioned. After searching through all of the databases, I was faced with another road block. There were data available on various Macrourid species; however, there was a large quantity of data available for only one or two life stages of the listed species, and very little on the other life stages. Due to this, I decided to include Pacific Hake in my study because it is one of the most commercially important fish species and data is available on the species for all life stages within the majority of the databases I searched through. Pacific Hake is a ground fish with pelagic larvae like the Macrourids, making the species a perfect candidate for the study.

Attempt #3: Methodological Issues in Data Collection

Out of the various databases I searched, only two sources had long time-series information on all fish species, limiting my data sources from eleven to two. The two sources, both provided by NOAA, are the data server ERDDAP and the data warehouse FRAM (refer to the References section for links to both sources). ERDDAP had enough data on various Macrourid species and Pacific Hake to continue pursuing an altered thesis study. However, throughout the process of extracting datasets from the two sources, I came across a 2007 NWFSC Summary Report stating "the spatial coverage of the SWFSC survey during the 1983-2000 period is largely inadequate to index pre-recruit abundance for most species, particularly where coast wide assessment areas are used in population modeling" (Hastie and Ralston 2007). Since all of the data available on ERDDAP and FRAM were collected through the SWFSC survey, 17 years' worth of the data could not be used in its present form. A contact informed me that SWFSC is working to adjust the data so that it can be used in the future. However, for the time being I decided to focus on resources available through MBARI.

Attempt #4: Finalized Thesis Project - MBARI Time-Series Study

Due to previously mentioned data collection issues, efforts were redirected towards collecting Macrourid adult fish count data from a continuing 28-year time series study conducted independently by the Smith lab at MBARI. The data used for the preliminary thesis study was collected at Station M, an area located in the abyssal NE Pacific approximately 200 km off Point Conception and 4000 m deep. A number of autonomous long-term instruments have been deployed on the seafloor at Station M to collect various types of data. The following instruments are currently deployed at Station M: 2 sediment traps floating 600 meters above the bottom of the seafloor (mab) and 50 mab, a time-lapse camera, a sedimentation event sensor, and a benthic rover. The sediment traps collect particulate matter that falls through the water column, eventually reaching the seafloor. The traps collect sinking material at 10-day intervals with a rotating carousel of 21 bottles. Once recovered for ten these bottles are taken back to the lab where the contents are analyzed for carbon. The time-lapse camera takes a picture of the seafloor every hour, and has done so since 1989. The sediment event sensor collects and takes a picture of sediment samples at 50 mab every 3-4 hours and is used to measure fluorescence and content of the material (detritus, fecal pellets, etc.). The benthic rover moves along the seafloor within the study site, taking images of the seafloor every few days to look at animal communities and florescence, and also makes sediment community oxygen consumption (SCOC) measurements. Satellite imagery is also used to estimate chlorophyll in surface waters above

Station M. The ROV, the Doc Rickets, a remotely operated vehicle (ROV), is also deployed on cruises at various time intervals throughout the time-series to conduct video transect surveys of the seafloor within the study site. All of the instruments being used simultaneously at Station M throughout the time-series study complement each other to give a holistic picture of the sediment community at Station M to observe changes over time.

The focal species for the study include the three Macrourid species present at Station M, including *C. armatus, C. yaquinae*, and *C. leptolepis*. Due to the difficulty in distinguishing between the three species in the time-lapse camera images, the three focal species were grouped together into a single category, as opposed to counting individuals separately by species. The research question was the following: Does population density of Macrourid populations at Sta. M change in relation to climate variables? Fish density data would be compared to physical variables relating to climate and surface conditions to determine potential correlations between changes in fish populations at Station M. The physical variables used in the study include the following: sea surface temperature (SST), particulate organic carbon flux (POC flux), chlorophyll (Chl), export flux from the euphotic zone (EF), sediment community oxygen consumption (SCOC), Northern Oscillation Index (NOI), Multivariate Ocean Climate Indicator (MOCI), Multivariate ENSO Index (MEI), Southern Oscillation Index (SOI), and North Pacific Gyre Oscillation (NPGO). All physical variables used in the data analysis were previously averaged to obtain weekly averages to compare to weekly averaged fish count data using cross correlation analyses.

MBARI's software VARS (Video Annotation and Reference System) was used to analyze the benthic and water column Macrourid population abundance at Station M. VARS allows for annotation at any level of detail, including measurements of individual animals and comments on behavior and color. The VARS software stores all of the data and annotations within the system (Linda Kuhnz, pers. comm.). Species density can be determined by visually counting the number of individuals present in each image over each time sequence. The number of fish present per hour (i.e. per image) is averaged over each week. Due to limited time, only a section of the time-series data was analyzed, which consisted of collections from November 2014 to June 2016. Only the bottom 75% of each 20 m^2 image was included in the sample area, due to insufficient lighting in the remaining area. To ensure that 75% of each image was included, a line was permanently placed across the screen using the VARS software.

RESULTS

Once fish counts were obtained, the data were plotted alongside the previously mentioned physical data to visually determine possible trends between fish counts and the physical variables (Figs. 1(A) & 1(B) in Appendix). Although the fish density and physical parameters changed over time, there appeared to be no obvious trend. This could mean the sample size was insufficient to determine any patterns over this short time sequence or that additional lags between fish density and surface conditions need to be employed. Often times when lags are taken into account, patterns emerge that would otherwise go unnoticed. An example of this can be seen when comparing POC flux to fish abundance on the seafloor. Without accounting for a lag, a correlation between POC flux (food supply) and fish abundance would not necessarily be observed because organic material takes time to fall through the water column before settling on the seafloor. The grenadiers that ingest the epibenthic fauna and infauna feeding on this material would appear only after the organic material reached the seafloor, which occurs sometime after the increase in POC flux that begins at the surface.

To account for time lags between variables, cross correlations between the fish count and physical variable data will be run to determine any potential relationships between changes in fish population abundance and changes in climate and surface conditions over time. Due to time limitations, there was only enough time to run a cross correlation between export flux and fish counts. Results from the cross correlation showed an inverse or negative relationship between export flux from the euphotic zone and fish counts, in which the strongest correlation was present when fish counts were lagged 26 weeks after export flux (Refer to Fig. 2 in Appendix). A scatter plot was then created to incorporate the shifted weekly export flux and fish counts, in which there appeared to be a weak relationship between the two variables ($R^2 = 0.1377$; lag = 26 weeks; Refer to Fig. 3 in Appendix). While results show that there isn't a strong relationship between export flux and fish counts, it could be due to the small sample size and short time sequence.

CONCLUSION

The process of having to alter my thesis project throughout this internship has taught me a great deal about scientific research. Although I was unable to produce a large quantity of results, I feel that I have grown tremendously throughout this experience. I have learned that datasets are rare and hard to find, especially when dealing with a subject that so few people have examined. Existing data sets can also be difficult to process. While I spent much time altering the study design, this exercise has started me conducting my thesis research. I am optimistic looking forward to the outcome of my research now that I know exactly what I want to do and how I am going to go about it. While I am surprised that the data were so hard to collect, I realize that I am one of the few people to begin looking into Macrourid populations and how they are changing over time in relation to changes in climate and surface conditions. Given the length of time that I had to work on this project, it is too soon to distinguish possible relationships in the data. More data need to be collected and analyzed before any potential patterns can be observed.

FUTURE WORK

In order to determine whether grenadier life stages are impacted by climate, I will continue to work on my thesis after the internship has ended. I plan on expanding the study through the complete 28-year time series providing a more robust sample size. Once fish counts have been collected and physical variables are extracted for the entire time-series, cross correlations will be ran on the fish count data in relation to all previously mentioned physical variables to determine any potential correlations. Although 17 years of NOAA larval data cannot be used currently, the data collected from the years 2000-2015 are still useable. I plan on extracting all the life stages of the three grenadier species present at Sta. M from the 2000 – 2015NOAA datasets. These data will then be compared to climate indices and surface conditions over time. Lastly, the remaining 17 years' worth of data provided by NOAA that is currently unusable may be adjusted in the future to allow use in my thesis study. This would provide the means to compare all life stages data obtained through NOAA with data for the entire time-series providing a sufficiently large and robust data set to distinguish temporal trends in population structure. In terms of the bigger picture, findings from this research study can apply to similar ecosystems around the world. Studying how changing climate can impact life histories of important fish species will significantly contribute to the field of marine conservation, in that it will allow the science community to gain further knowledge and form a better understanding of how changes in climate variation will affect marine ecosystems and processes on a global scale. This in turn can contribute to the protection of fisheries in the future.

ACKNOWLEDGEMENTS

This work was supported by MBARI and the Packard Foundation. I'd like to give special thanks to my mentor, Ken Smith, and the internship coordinators, George Matsumoto and Linda Kuhnz, for making this research study and internship possible. I would also like to thank the Smith lab, Christine Huffard, Henry Ruhl, Larissa Lemon, Paul McGill, Waldo Wakefield, Ian Taylor, Ian Stewart, and MBARI staff for their help with sample collection and analysis.

REFERENCES

Allen, L. G., Pondella, D. J., & Horn, M. H. (Eds.). (2006). The ecology of marine fishes: California and adjacent waters. *Univ of California Press.*

Bailey, D.M., Ruhl, H.A., & Smith Jr., K.L. (2006). Long-term change in benthopelagic fish abundance in the abyssal N.E. Pacific Ocean. *Ecology, 87,* 549-555.

Brierley, A.S., & Kingsford, M.J. (2009). Impacts of climate change on marine organisms and ecosystems. *Current Biology, 19(14),* R602-R614.

Cohen, D.M., Inada, T., Iwamoto, T., & Scialabba, N. (1990). FAO species catalogue. Vol. 10. Gadiform fishes of the world (Order Gadiformes). An annotated and illustrated catalogue of cods, hakes, grenadiers, and other gadiform fishes known to date. *FAO Fish. Synop. 125*(10). *Rome: FAO.* 442. (Ref. 1371).

Drazen, J.C. (2002). Energy budgets and feeding rates of *Coryphaenoides acrolepis* and *C. armatus. Mar. Biol., 140,* 677-686.

ERDDAP: https://coastwatch.pfeg.noaa.gov/erddap/index.html

FRAM: https://www.nwfsc.noaa.gov/data/map

Hastie, J., & Ralston, S. (2007). Pre-Recruit Survey Workshop September 13-15, 2006 Southwest Fisheries Science Center Santa Cruz, California. Report to Pacific Fishery Management Council. Agenda Item E, 1.

Iwamoto, T. (2015). *Coryphaenoides leptolepis*. The IUCN Red List of Threatened Species 2015: e.T15522140A15603525. Retrieved August 11, 2017, from http://dx.doi.org/10.2305/IUCN.UK.2015-4.RLTS.T15522140A15603525.en.

Jamieson, A. J., Priede, I.G., & Craig, J. (2012). Distinguishing between the abyssal macrourids *Coryphaenoides yaquinae* and *C. armatus* from in situ photography. *Deep Sea Research Part I: Oceanographic Research Papers*, *64*, 78-85.

Large, P.A., Hammer, C., Bergstad, O.A., Gordon, J.D.M., & Lorance, P. (2003). Deep-water fisheries of the northeast Atlantic: II. Assessment and management approaches. *Journal of Northwest Atlantic Fishery Science, 31,* 151.

Lindegren, M., Checkley, D.M., Ohman, M.D., Koslow, J.A., & Goericke, R. (2016). Resilience and stability of a pelagic marine ecosystem. *Proceedings of the Royal Society B-Biological Sciences, 283,* 10.1098/rspb.2015.1931.

Recent Global Warming. (2002). Retrieved August 05, 2017, from http://earthguide.ucsd.edu/virtualmuseum/climatechange2/08_1.shtml.

Wilson, R. R., & Waples, R. S. (1983). Distribution, morphology, and biochemical genetics of *Coryphaenoides armatus* and *C. yaquinae* (Pisces: Macrouridae) in the central and eastern North Pacific. *Deep Sea Research Part A. Oceanographic Research Papers*, *30*(11), 1127-1145.

APPENDIX

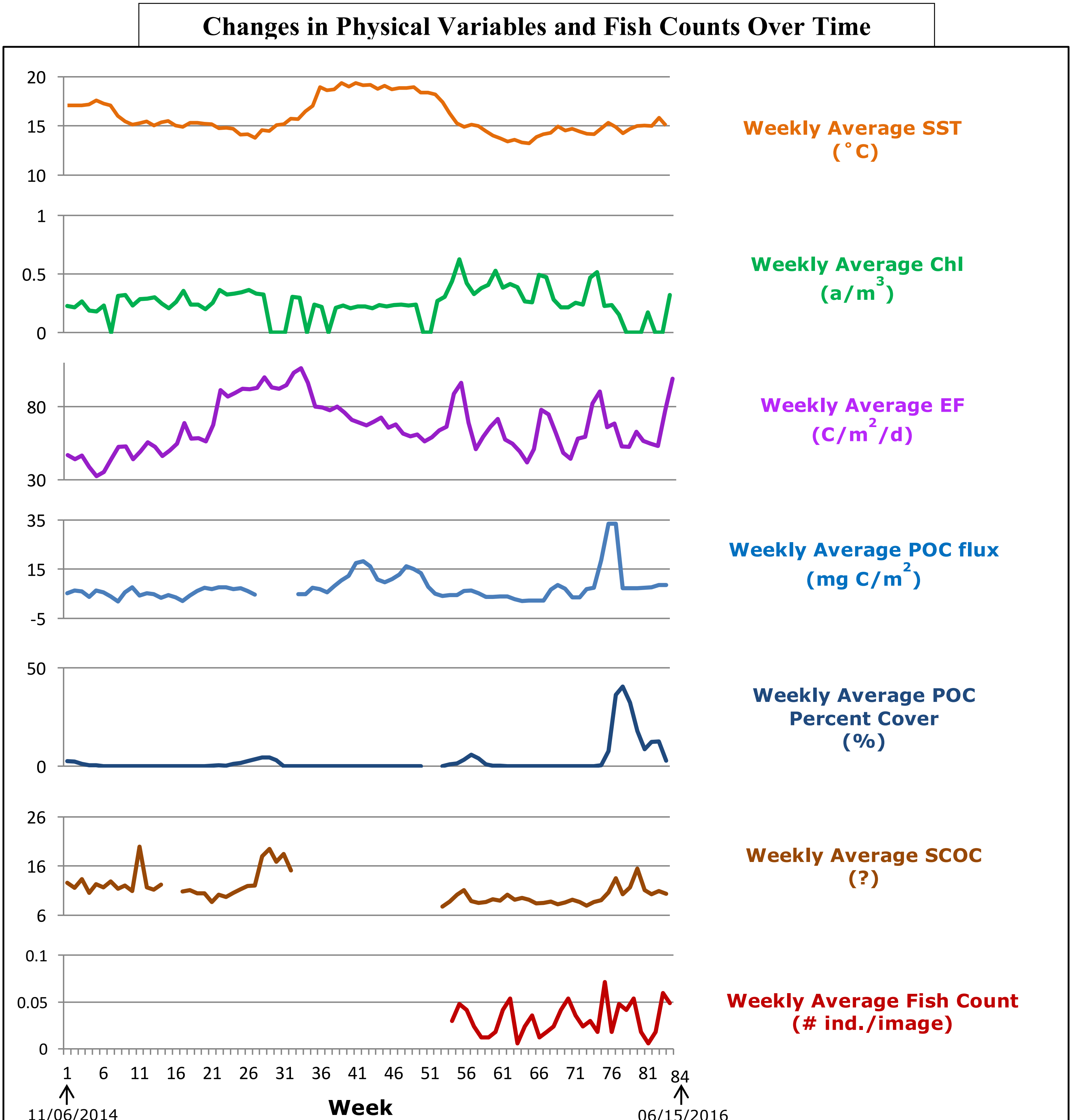

Figure 1(A): Weekly averaged physical variables and fish counts plotted over time. The data spans over an 84 week period; with week #1 beginning on 11/06/2014, and week #84 ending on 06/15/2016.

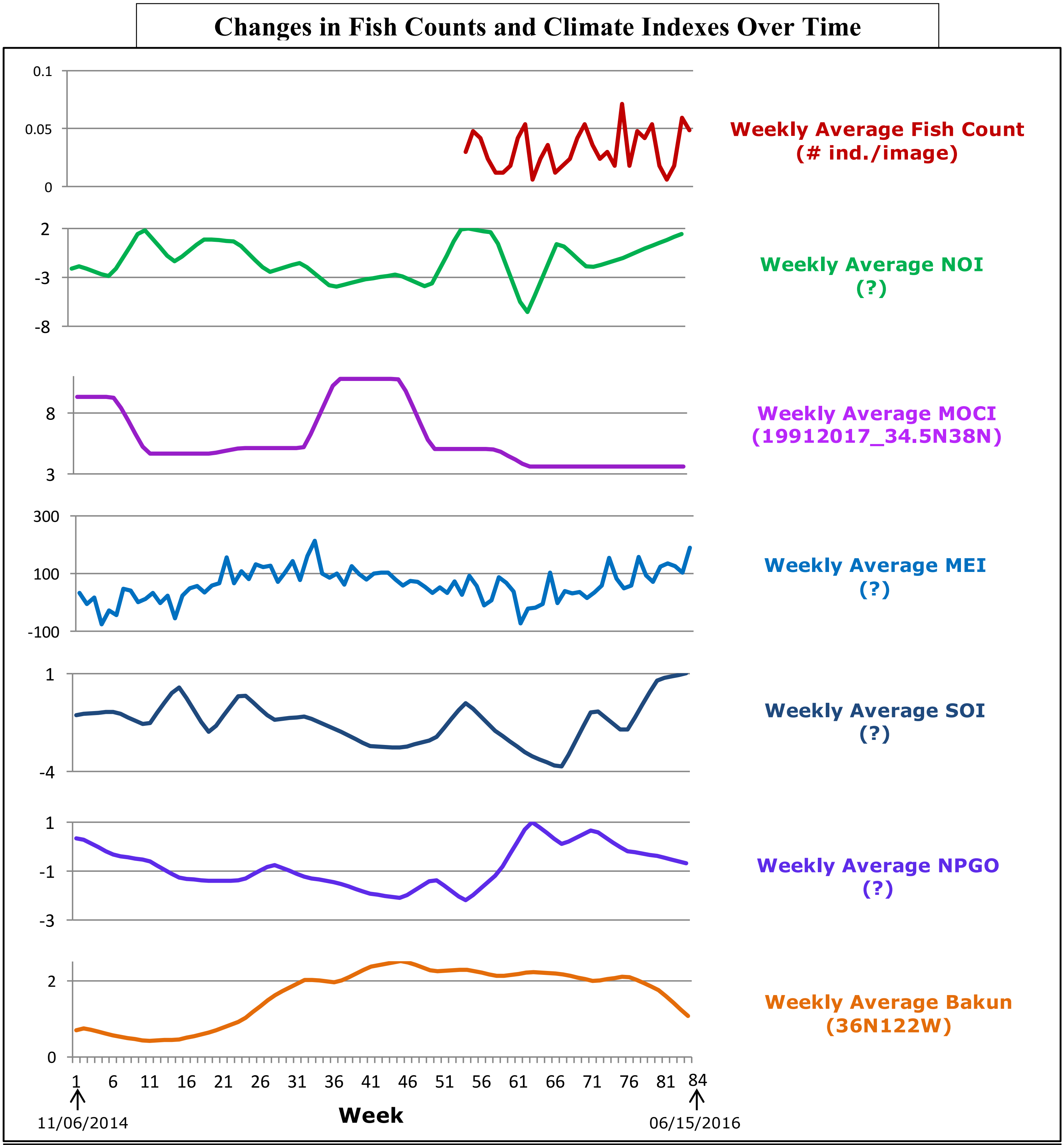

Figure 1(B): Weekly averaged fish counts and climate indexes plotted over time. The data spans over an 84 week period; with week #1 beginning on 11/06/2014, and week #84 ending on 06/15/2016.

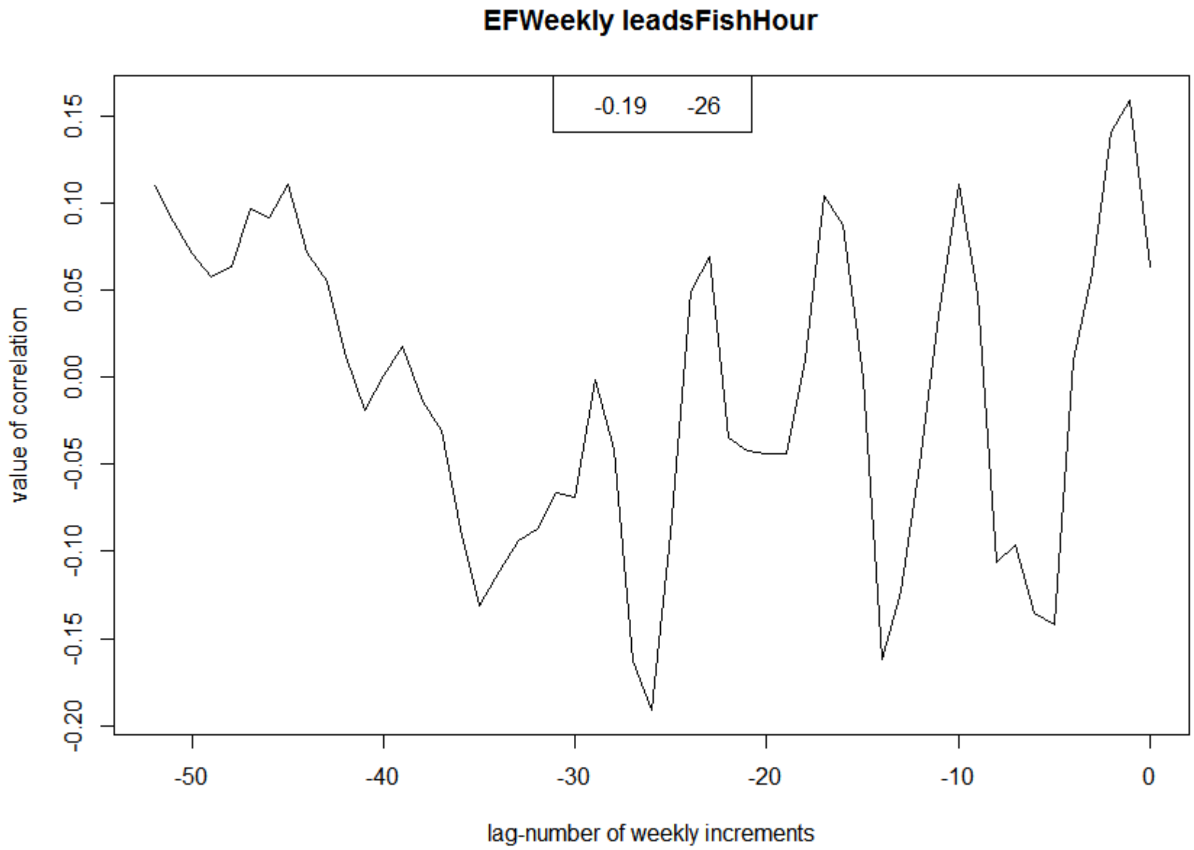

Figure 2.) Time lag cross correlation between weekly averaged export flux (EF Weekly) and weekly averaged fish count (leadsFishHour). The strongest correlation is present at a 26 week lag, suggesting an inverse relationship between export flux and fish count.

Shifted Weekly Export Flux and Fish Count

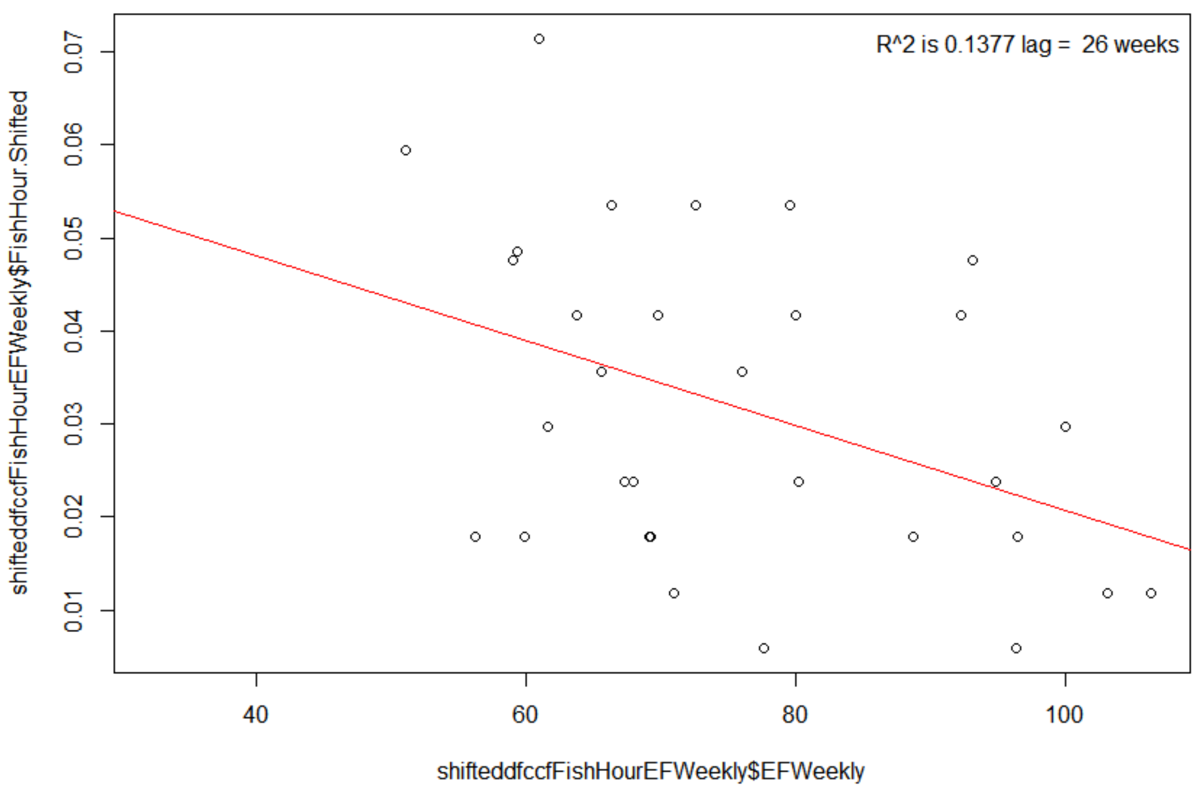

Figure 3.) Scatter plot of shifted weekly export flux(shifteddfcdFishHourEFWeekly$EFWeekly) and fish count (shifteddfcdFishHourEFWeekly$FishHour.Shifted). The data is shifted to account for a 26 week lag period (R^2 = 0.1377).