Title

Incorporating Climate Variability and Change into Marine Spatial Planning of Aquaculture in the Southern California Bight

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Publication Date

2021

UNIVERSITY OF CALIFORNIA

Santa Barbara

Incorporating Climate Variability and Change into Marine Spatial Planning of Aquaculture in the Southern California Bight

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in Environmental Science and Management

by

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Jade Fernanda Sainz Garduño

ACKNOWLEDGEMENTS

I want to thank my advisor Dr. Steve Gaines who always believed in me and guided my research. It has been great to have your support since I started my graduate studies as a Latin American Fisheries Fellow (LAFF). I will always remember the amazing science conversations during our meetings, the lab retreats in the Channel Islands, and the Thanksgiving dinners you hosted that made us feel at home. Dr. Hunter Lenihan, thank you for always encouraging me to be better in my research, and for your enthusiasm for aquaculture that made impact on many students at the Bren School. Dr. Robert 'Bob' Miller inspired me greatly to continue my graduate studies and become a PhD. I will be always thankful for your encouragement and support.

Dr. Emanuele di Lorenzo, thank you so much for having me as a visiting scholar in your lab, and for collaborating with me during my PhD project. Being at Georgia Tech surrounded by amazing scientists and projects, learning about climate and all the research being conducted at the Ocean Science and Engineering program has been an incredible experience. Thanks also for all your time, patience, and guidance, despite that I was new in the field of climate science. Thank you also for inviting us to the fun gatherings at your place.

To the LAFF and the Walton Family Fund, the Conacyt-UC Mexus program, and the Dr. Daniel Vapnek Scholarship: thank you for the funding and the opportunity to do my graduate studies in one of the most prestigious programs in environmental science and management.

Thank you to Drs. Sarah Lester, Tom Bell, and Becca Gentry for leading marine spatial planning projects that inspired me to develop my research questions. Dr. Tom Bell, thank you greatly for collaborating with me, and for guiding me in the application of aquaculture models and their interpretation based on your experience marine ecology.

I am very fortunate to say that along my PhD journey, I had the chance to made friends in different cities and institutions. In Santa Barbara, I got to be a member of the Gaines Lab which is a great honor. Lab mates are incredible and I always felt part of the Gaines Lab despite being far from campus. Thanks to my Brennie friends (Tracey, Lili, Jacy, Jenny and many others) for all the fun moments and learnings at class. Thanks to Dr. Satie Airame, Kristine Duarte, and the Bren Staff that were always supportive and helped me focus on my goals. Thank you also to the OISS staff that always supported me with my sometimes complicated paperwork.

The LAFF fellows were my first friends when I got to grad school and I will always be thankful for being part of this amazing network of fisheries champions. I also thank my

Mexican lunch club formed by Conacyt fellows (Yanitsa, Natalia, Sergio, Daniela Narezo, et al.) for your friendship and great lunches and many other memories. Thanks to Andrea, Sahar and all of the friends from other departments at UCSB that I got to have fun times with.

Thanks to former and current members of the Di Lorenzo Lab that I got to meet. Fabrizio, Mer, Youngji and Filippos, Tongtong, Elise, who are amazing climate scientists, and amazing friends as well. Thanks to Adriana, Ilias, Daniela Estrada and more friends that made me feel at home in Atlanta.

Thanks to Dr. Fernando Bello Fuentes who has been an amazing collaborator. The time I spent at UABC Ensenada was great, specially the company of amazing grad students at "La Caballeriza" office (Graciela, Roberto, Maricsa). While being in Ensenada, I got to talk to experienced people working in aquaculture, including Roberto Flores, Eric Pedersen, Erik Peterson, Jose Augusto Barcenas. Their feedback was of great value to me because it helped me to set up the modeling work and have a better understanding of the industry. Thanks to my former supervisors and colleagues at CONAPESCA who I always kept being in touch, and were always supportive with my new projects.

To me, the PhD has been a monumental journey. I was able to climb this mountain thanks to my parents Fernando and Paty and my sister Nio who have been walking with me even from the distance, and giving all the love and support that I have needed (which is a lot) and even more. Thanks to my cousins Laura and Ezequiel for letting me stay at their home during my time in Ensenada and also with their insights in the seafood industry. To my aunt Gaby and my cousin Alejandra for cheering me up all times. Thanks to all my life time friends from Mexico for keeping up with the group chats and their support, and for making me feel always welcomed back when I got to visit.

Lastly, I want to thank my husband Will Gutekunst who I was fortunate to meet during my PhD. He has filled my life with fun and inspiration, and even more love. I am so grateful for having all this support and experiences. Thank you all.

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Sainz, J.F., Di Lorenzo, E., Bell, T.W., Gaines, S., Lenihan H., and Miller, R.J. (2019). Spatial Planning of Marine Aquaculture Under Climate Decadal Variability: A Case Study for Mussel Farms in Southern California. *Frontiers in Marine Science* 6**,** 253

Ayres, A., Degolia A., Fienup, M., Kim, Y., **Sainz, J.,** Urbisci, L., Viana, D., Wesolowski, G., Plantinga, A. J., and Tague, C. (2016). Social Science/Natural Science Perspectives on Wildfire and Climate Change. Geography Compass, 10: 67–86. doi:10.1111/gec3.12259.

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Invited Talk: Climate and aquatic resources. Fisheries Management Class. Universidad Autónoma de Baja California (UABC). March 14, 2019, Ensenada, Mexico.

Poster Presentation: Spatial Planning of Marine Aquaculture Under Climate Decadal Variability: A Case Study for Mussel Farms in California. 4th International Symposium The Effects of Climate Change on the World's Oceans. June 4-8, 2018, Washington DC, USA.

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Poster Presentation: Tradeoff Analysis of Conservation Policies for Vaquita and Fisheries Management in the Upper Gulf of California. International Congress for Conservation Biology (ICCB)

ABSTRACT

Incorporating Climate Variability to Marine Spatial Planning of Aquaculture in the Southern California Bight

by

Jade Fernanda Sainz Garduño

Marine aquaculture is the most rapidly growing food sector and has great potential for expansion as part of a sustainable vision for seafood production in the future. Marine spatial planning for aquaculture is crucial to identify the best areas for productivity and profitability and to avoid conflict with other uses of the space. Given that climate change will likely change the answers to these spatial planning questions, effective marine spatial plans for aquaculture must assess expected changes and identify efficient adaptation strategies. To this end, we propose a novel approach to define climate change responsive marine spatial planning of aquaculture. We use the Southern California Bight (SCB) as a case study.

First, we focus on understanding the effects of interannual variability over site selection. In Chapters I and II, we use a historical reanalysis of environmental data to run aquaculture models of Mediterranean mussels, striped bass and giant kelp (mussels, fish, and kelp). We use empirical orthogonal functions and principal component analysis to identify spatial and temporal patterns of variability. We found that decadal variability has significant impacts on the productivity and profitability of farms. The different farmed species had quite different responses. Mussels had good productivity regions spread along the coast with the highest productivity in the northern region. By contrast, fish had highest productivity sites in the south given warmer temperatures, but differences among southern sites were small. Kelp production is limited to the northern-most region and productivity differences among sites were striking.

Finally in Chapter III, we look to the future and incorporate climate projections up to year 2100 to understand the effects of future climate change on site selection for mussels, kelp, and fish species. Given that mean conditions and interannual variance are both relevant components of climate, we analyzed both effects on future aquaculture productivity. Variability in production is projected to be most striking for kelp, followed by mussels. Fish production actually benefits from warming temperatures, and the increasing trend in the mean predominates over interannual variability. General lessons from historical records and future forecasts suggest that kelp and mussels are more prone to variability given their dependance on nutrients and plankton controlled by ocean conditions. By contrast, since fish are fed in aquaculture, the long term trend in temperature is the biggest driver of fish production. Ignoring variability, therefore, might have greater consequences for the profitable siting of kelp and mussel farms. Monitoring systems are valuable to both characterize productivity variation and to enhance the empirical foundation for better forecasts that can help create climate resilient marine spatial planning. Our results show that spatial patterns of productivity remain consistent despite growing climate variability and climate change until optimal thresholds for growth are reached. Selection of species and sites resilient to current and upcoming environmental conditions are important steps in the planning process. Although this work focuses on a single coastline region, it provides an analytical framework that can be

expanded to other regions of the globe to help design optimal adaptation strategies tailored to each region’s specific climate dynamics.

TABLE OF CONTENTS

I. Spatial Planning of Marine Aquaculture Under Climate Decadal Variability: A Case Study for Mussel Farms in Southern California 1

A. Introduction 2

Marine Aquaculture in Southern California 4

B. Methods 6

Description of the Area of study 6

Environmental forcing and spatial domain 7

The mussel aquaculture production model 8

Historical reconstruction of productivity 1981-2008 12

Variability Analysis 14

- a. Spatial statistics 14
- b. Empirical Orthogonal Functions and Principal Component Analysis... 15
- c. Links to North Pacific climate variability 17

Net Present Value and optimal site selection 18

- a. NPV: constant vs. variable 19
- b. The ranking procedure. 20

C. Results 21

D. Discussion. 26

The Importance of Natural Decadal Variability 30

E. Conclusions 32

Considerations about the impact of climate to be further explored. 33

F. Supplemental information 33

Appendix on Mortality 39

II. Marine spatial planning of fish and kelp aquaculture considering climate variability in the Southern California Bight. 40

A. Introduction 40

B. Methods 42
Spatial Domain and Historic Environmental Forcing Data 42
Aquaculture Simulation Models 44
  a. Fish Model (Striped bass) 44
  b. Kelp Model (Giant kelp, *Macrosystis pyrifera*) 46
Historical Reconstruction and Variability Analysis 47
SST Transfer Function Model 47
Correlation with Climate trends 48
Net Present Value 48
Ordinal Site Selection (Ranking) 49

C. Results 50
Spatial Statistics 50
Empirical Orthogonal Functions / Principal Components 50
Transfer function 52
Climate trends 53
Net Present Value (NPV) 55
Ranking 56

D. Discussion 57
Climate variability. 57
Implications for site selection 58

E. Conclusions. 59

F. Supplemental Information 61
Kelp Model Validation appendix 63

III. Marine Spatial Planning of Aquaculture in the Southern California Bight based on Future Climate Projections. 66

A. Introduction 66
Climate Change in the Southern California Bight 68

B. Methods 70
Aquaculture simulation models 70

Environmental forcing 70
Particulate Organic Matter (POC) reconstruction (LIM model for POC) 71
Projections of aquaculture productivity under Climate Change 74
    a. Time series of production and spatial statistics. 74
    b. Variability and Trend Analysis 74
    c. Ranking 75

C. RESULTS 75
Production time series 75
Relevance of variability vs trend 77
Ranking of sites based on future projections 79
    a. Fish production ranking 79
    b. Kelp production ranking 81
    c. Mussel production ranking 82

D. DISCUSSION 83

E. CONCLUSIONS 87

F. SUPPLEMENTAL INFORMATION 88
Primary productivity trend analysis 88

REFERENCES 92

LIST OF FIGURES

Figure 1. Region of study and schematic of time series of production. 13

Figure 2. Spatial statistics of mussel production 15

Figure 3. EOF and PC of mussel production. 17

Figure 4. PC and climate of the North Pacific. 18

Figure 5. Constant vs variable net present value example 20

Figure 6. Mean harvest time length. 22

Figure 7. First principal component and NPGO index with selected NPV periods. 24

Figure 8. Spatial ranking and best sites according to NPV. 26

Figure 9. Farm site locations with identifying number. 38

Figure 10. Mussel mortality analysis. 40

Figure 11. Southern California Bight (SCB) domain and aquaculture sites 43

Figure 12. Spatial statistics of fish and kelp production. 51

Figure 13. Empirical orthogonal functions and Principal Components. 52

Figure 14. Development of AR1 model. 53

Figure 15. Transfer function for fish and kelp production vs climate indexes relevant for the Pacific. 54

Figure 16. 10-year NPV horizons for fish and kelp. 55

Figure 17. Fish and kelp production rankings by region. 57

Figure 18. Time series of kelp observations vs kelp model outputs 64

Figure 19. Standardized means of kelp observations vs model outputs and pdf distributions 65

Figure 20. Correlation between SSTa with kelp biomass and model output indexes. 65

Figure 21. POC reconstruction vs POC observations 73

Figure 22. Example relevance of trend vs variability. 75

Figure 23. Mean time series of production 1980-2100. 77

Figure 24. Analysis of variability vs Trend calculated for 30-year periods. 79

Figure 25. Fish ranking time series and spatial maps. 81

Figure 26. Kelp ranking time series and spatial maps. 82

Figure 27. Mussel ranking time series and spatial maps. 83

Figure 28. Primary productivity projections for the California Current (time series). 89

Figure 29. Primary productivity projections for the California Current (maps). 90

Figure 30. Time series of environmental forcing 91

LIST OF TABLES

Table 1. Mussel model growth model parameters and environmental forcing variables. 10

Table 2. NPV periods matching with negative and positive phases of the NPGO. 25

Table 3. Costs of running a mussel farm 33

Table 4. Final rank by production (kg). 34

Table 5. Final rank by NPV. Only the sites that never have negative NPV values are shown (best 52 sites). 36

Table 6. Environmental variables for the two aquaculture models used (fish and kelp) 44

Table 7. Fish farm configuration, biological and economic parameters 61

Table 8. Kelp farm configuration, biological and economic parameters 62

Table 9. Environmental forcing for aquaculture models (model projections) 71

I. Spatial Planning of Marine Aquaculture Under Climate Decadal Variability: A Case Study for Mussel Farms in Southern California

*As originally published in Sainz, J.F., Di Lorenzo, E., Bell, T.W., Gaines, S.D., Lenihan, H.S., and Miller, R.J. (2019). Spatial Planning of Marine Aquaculture Under Climate Decadal Variability: A Case Study for Mussel Farms in Southern California. Front. Mar. Sci., 6***,** *253. doi.org/10.3389/fmars.2019.00253*

ABSTRACT

The growth of marine aquaculture over the 21st century is a promising venture for food security because of its potential to fulfill the seafood deficit in the future. However, to maximize the use of marine space and its resources, the spatial planning of marine aquaculture needs to consider the regimes of climate variability in the oceanic environment, which are characterized by large-amplitude interannual to decadal fluctuations. It is common to see aquaculture spatial planning schemes that do not take variability into consideration. This assumption may be critical for management and for the expansion of marine aquaculture, because projects require investments of capital and need to be profitable to establish and thrive. We analyze the effect of climate variability on the profitability of hypothetical mussel aquaculture systems in the Southern California Bight. Using historical environmental data from 1981 to 2008, we combine mussel production and economics models at different sites along the coast to estimate the Net Present Value as an economic indicator of profitability. We find that productivity of the farms exhibits a strong coherent behavior with marketed decadal fluctuations that are connected to climate of the North Pacific Basin, in particular linked to the phases of the North Pacific Gyre Oscillation (NPGO). This decadal variability has a strong impact on profitability both temporally and spatially, and emerges because of the mussels' dependence on multiple oceanic environmental variables. Depending on the trend of the decadal regimes in mussel productivity and the location of the farms, these climate fluctuations will affect cost recovery horizon and profitability for a given farm. These results suggest that climate variability should be taken into consideration by managers and investors on decision making to maximize profitability.

A. Introduction

Aquaculture is a promising alternative to fulfill seafood consumption by 2050 (Diana et al., 2013) and it is expected that about 60% of all seafood will come from aquaculture by 2030 (World-Bank, 2013). Marine aquaculture in particular is a promising sector because of the availability of space within countries' Exclusive Economic Zones (EEZ) in comparison with other aquaculture sectors (Kapetsky, 2013; Lovatelli, 2013; Gentry et al., 2017). This is especially true when moving further offshore because space is less limited than inshore environments (Gentry et al., 2017) and the environmental impacts over the sea floor and sensitive environments such as coral reefs are reduced (Bostock et al., 2010).

The National Oceanic and Atmospheric Administration of the United States (NOAA) indicates that imports comprised 90% of the seafood consumed in the US in 2015 (NOAA, 2016) and about half of those imports come from aquaculture (NOAA, 2017). Given the continuous rising demand of seafood and the opportunities that producing domestic seafood represent, there is increasing interest in expanding aquaculture in the United States (Lee et al., 2001). The United States is the 17th largest producer worldwide, and global production is dominated by Asian countries like China and India (FAO, 2016). Principal products from the United States are catfish, crawfish and trout for freshwater, and salmon and oysters for marine aquaculture. Freshwater production is by far more important in terms of volume: 234,615 metric tons for freshwater and 41,080 metric tons of marine production in 2014 (NOAA, 2015). A National Marine Aquaculture Policy has been developed to plan the activity to have minimum impact over the ecosystems while fulfills its role as source of jobs and local sustainable seafood (NOAA, 2011).

Given the interactions of marine aquaculture with natural habitats (e.g. benthic impacts, disease, invasive species introduction, entanglement) and human uses of the marine space (e.g. fishing, recreation, viewshed), farm siting must be developed under careful marine spatial planning frameworks that inform site selection (Sanchez-Jerez et al., 2016) and also estimate the site-specific costs associated with aquaculture (Lester et al., 2018). However, although spatial plans for marine aquaculture consider environmental variables to optimize growth rates and feasibility, the incorporation of natural variability is often ignored, despite the fact that climate variability and change are recognized as important drivers of productivity in marine aquaculture (Cochrane et al., 2009; Saitoh et al., 2011; Liu et al., 2013). This can lead to bias in the predicted productive capacity of aquaculture projects and sites, and if climate variability is not considered in spatial planning, the huge potential for marine aquaculture might be compromised by unnecessary costs (Callaway et al., 2012).

Understanding the impacts of environmental variability over aquaculture zones may lead to more reliable marine spatial planning schemes. This information should be of significant interest to managers and investors because it reduces uncertainty and increases our understanding of the long term profitability of aquaculture sites (Handisyde et al., 2006). The incorporation of climate is one of the key elements in the implementation of the Ecosystem Approach to Aquaculture (EEA) (Soto, 2008) particularly now that offshore aquaculture is taking its first steps towards expansion.

Marine Aquaculture in Southern California

California is one of the states with the highest seafood demand (Morris, 2015) opening a window of opportunity for marine aquaculture to grow sustainable seafood and provide economic benefits to the region. However, current and prospective farmers are facing challenges related to the permitting process which needs to be streamlined (CaliforniaSeaGrant, 2015) and coordinated between state and federal institutions, depending on the location of the project (Bryniarski, 2015). While permission frameworks for federal waters are being developed (> 3 miles from the coastline up to the EEZ), waters closer to the shore face conflicts with other uses of the space and also need approval from multiple agencies (Tiller et al., 2013). Concerns on the environmental impacts and spread of disease on wild populations potentially caused by marine aquaculture projects have been raised by environmental groups and local fishermen (Weisser, 2016) as in many regions in the world (Froehlich et al., 2017).

Despite such difficulties, marine aquaculture is finding its way in Southern California waters and thriving. Currently, there are few marine aquaculture sites operating in this region: Oyster aquaculture has been explored for this area but still remains concentrated in Northern California (Kettmann, 2015). However restoration efforts are being developed to enhance native Olympia oyster in wetlands of the region (Grant, 2017). Abalone are cultivated in seaside tanks, and there are two successful commercial marine aquaculture mussel farms in the

Santa Barbara Channel and the San Pedro Shelf. An upcoming project for mussel aquaculture in Ventura is just waiting for approval to start operating. The cultivation of kelp is also under development for future production of biofuels and agricultural products (Cohen, 2017).

Given its relevance for biodiversity and the placement of important marine protected areas, marine spatial planning is crucial to preserve and utilize the marine resources of the SCB with an ecosystem approach, particularly in a very crowded coastal region (Lester et al., 2018) with a population of greater than 22.6 million people (U.S.CensusBureau, 2010). In a planning exercise Lester et al., 2018 found that the SCB could potentially host many hundreds of farms without compromising other uses of the space or biodiversity. In addition, SCB is attractive to farmers and investors for its geographical features, the inshore regions are semi protected from the stronger currents of the Pacific (Kettmann, 2015), and there is a low incidence of storms and hurricanes (King et al., 2011; Shoffler, 2015). However internal variability mechanisms, such as the El Niño Southern Oscillation, the North Pacific Gyre Oscillation and the Pacific Decadal Oscillation (ENSO, NPGO and PDO) have a big influence over the productivity of the SCB, and climate change is also expected to modify the climatic norm in the region (Roemmich et al., 1995; Bograd et al., 2003; Snyder et al., 2003; Lluch-Belda et al., 2005).

In this study we focus on a single type of marine aquaculture that has been projected to be successful in the region given its social acceptance and minimum impact on the surrounding environment: Mediterranean mussels. Mussels are sensitive to environmental variables (Schneider et al., 2010; Kroeker et al., 2014; Gaylord, 2018) so it is expected that farmed mussels will need to consider how environmental variability of this region will affect productivity and profitability to develop spatial plans and adaptation strategies accordingly.

B. Methods

Description of the Area of study

The Southern California coastal region, also known as Southern California Bight (SCB), is the coastal area of the Eastern Pacific located between 31.6 and 35 degrees North latitude and 120 and 116 West longitude, from Point Conception in the north to Punta Banda, in Baja California Mexico in the South (SCCWRP, 1973; Schiff et al., 2016). The region of this work covers only the USA portion of the SCB, which is the delimited region of study: Point Conception down to the Mexico border in San Diego, Southern California (122°W - 117°W; 32°N - 35°N). The SCB is a platform with multiple submarine canyons and the presence of the California Channel Islands that shape a complex oceanography within the region (Jackson, 1986; DiGiacomo et al., 2001).

The SCB is within the southern limit of the California Current, one of the four Eastern Boundary Current Systems in the world where Ekman type upwelling promotes a high productivity that sustains fisheries and biodiversity (Carr, 2001). Point Conception, which marks the northern limit of the SCB is the transition between two major marine biogeographical regions: the Oregonian which is primarily influenced by the cooler temperatures of the southward California Current and the Californian characterized by warmer waters (Valentine, 1966; Airamé et al., 2003; Zacherl et al., 2003). These oceanographic features position the SCB as a climatic and biogeographic transition zone, and an important biodiversity hotspot, hosting diverse ecosystems such as estuaries and kelp forests (SCCWRP, 1973; Daley, 1993; Schiff et al., 2016).

Further classifications based on marine taxa find two bioregions within the SCB: the Southern Californian that goes from Point Conception to Santa Monica Bay; and the Ensenadian from Santa Monica Bay down to Punta Eugenia in Mexico (Blanchette et al., 2008; Briggs et al., 2011; Chivers et al., 2015). Increased primary productivity and lower temperatures are found towards the north in the SCB (Southern Californian bioregion) due to the influence of coastal upwelling processes from the north (Mantyla et al., 2008). In comparison, the south of the SCB (Ensenadian region) tends to be warmer and lower in nutrients due mainly to the northward superficial and sub superficial countercurrents that flow along the inshore (Bray et al., 1999; DiGiacomo et al., 2001). The SCB is characterized by seasonal upwelling of ocean nutrients (Di Lorenzo, 2003) and strong decadal climate variability associated with the basin-scale climate variability (Di Lorenzo et al., 2008; Di Lorenzo et al., 2009; Bell et al., 2015).

Environmental forcing and spatial domain

Historical environmental data was obtained from the Regional Ocean Model System (ROMS) (Shchepetkin et al., 2005) 4D Historical Reanalysis for the California Current System (Moore et al., 2011a, 2011b, 2011c). The domain of the reanalysis covers the SCB region down to the San Diego border (122°W - 117°W; 32°N - 35°N) (Figure 1a), where daily values of four environmental variables were extracted (salinity, temperature, current velocity, mixed layer depth) in daily values for the period 1981-2008. The model grid has 1/10 x 1/10 degrees (~121 km^2) of horizontal resolution and 42 vertical terrain-following depth layers; only <200 m of vertical depth were considered for this domain.

The reanalysis forcing data extracted from the UCSC Ocean Modelling and Data Assimilations website (http://oceanmodeling.pmc.ucsc.edu) was subdivided into 223 ‘sites’ along the coastal boundaries of the SCB. Each site represents a geographical location where a mussel farm is located (Figure 1a).

The mussel aquaculture production model

In order to incorporate the effects of climate variability into mussel production, we simulated the growth of Mediterranean mussels *Mytilus galloprovincialis* with a Dynamic Energy Budget (DEB) model approach, adapted to aquaculture conditions. First developed by (Kooijman, 1986, 2010), the DEB theory is useful to understand functional relationships of the organisms with the environment. The central paradigm of the DEB theory is the k-rule, which describes the fractions of energy that are allocated between somatic maintenance or reproduction (Sarà et al., 2012), incorporating the uptake and use of substrates (e.g. food, nutrients, light) by the organisms and the use of these resources for maintenance, growth, maturation and propagation by different life stages. The DEB model takes the individual as its central form of organization, but it has been applied to other organizational levels such as populations and ecological relationships (Kooijman, 2010). DEB models are also used for aquaculture and shellfish research to analyze growth and survival of bivalves in relation with environmental variables such as temperature, variable food and salinity (Pouvreau et al., 2006; Sarà et al., 2012; Maar et al., 2015). Particularly for mussels, empirical data has helped on calibrating DEB-type models, and to validate the application of this modelling approach to simulate mussel growth under variable conditions and across locations (Van Haren et al., 1993; Rosland et al., 2009; Thomas et al., 2011).

According to DEB theory, temperature ‘activates’ the basal activities of the organisms on a molecular level and directly regulates growth rates. The model is set to apply the principles of the k-rule when the mussel reaches a size of maturity and from then it starts to apportion energy towards gonads in addition to body biomass. If food supply and temperature levels are not adequate, mussels will starve.

The DEB model used in this project is based on the work of (Muller and Nisbet, 2000) which was adapted by (Lester et al., 2018) to simulate mussel growth in response to four relevant environmental drivers: temperature (°C), current velocity (cm s^{-1}), mixed layer depth (m) and particulate organic carbon (POC mg cm^{-3}). Biological parameters used in the model are shown in Table 1, and most of them gathered from the Add-my-Pet website (https://www.bio.vu.nl/thb/deb/deblab/add_my_pet/; Kooijman, 2014). In our analysis, the UCSC reanalysis that is used to reconstruct the historical evolution of the DEB model drivers did not contain POC. In order to estimate the time dependent changes in POC fluxes we used salinity anomalies at 50 meter depth. The use of this proxy is motivated by previous studies showing a tight correlation between variations in the halocline and nutricline along the CCS (Di Lorenzo et al., 2005; Di Lorenzo et al., 2008). The salinity proxy was calibrated using an existing set of POC data for the period 2000-2001 that was used originally to develop the mussel model (Lester et al., 2018). Given that we are interested in the relative change from one year to the other, the calibration procedure involves adjusting the 2000-2001 mean of the salinity proxy with that from the POC dataset and re-scaling the standard deviation to match that of the POC for the same period. The resulting scaling factors are then applied to all other years.

Table 1. Mussel model growth model parameters and environmental forcing variables.

Inputs	Parameter	Value	Source
Energy conductance	v_{ref}	0.01359 cm d-1	Kooijman et al. 2014
Maintenance rate coefficient	kM_{ref}	0.00447539 d-1	Kooijman et al. 2014
Maintenance ratio	$Maint_{ratio}$	0.446888	Kooijman et al. 2014
Yield of reserves from food	y_{EX}	0.696818 mol mol-1	Kooijman et al. 2014
Yield of structure from reserves	y_{VE}	0.878007 mol mol-1	Kooijman et al. 2014
Aspect ratio	d_m	0.1989	Kooijman et al. 2014
Fraction of reserves committed to growth + maintenance	K	0.9283	Kooijman et al. 2014
Conversion efficiency of reserves to gonad	k_r	0.95	Kooijman et al. 2014
Density of structure	$Mv_{density}$	0.0041841 mol cm-3	Kooijman et al. 2014
Maturity at puberty	Ehp	97.41 J	Kooijman et al. 2014
Chemical potential of reserves	m_e	550000 J mol-1	Kooijman et al. 2014
Structural length at puberty	L_p	0.753047 cm	Kooijman et al. 2014
Max specific feeding rate	Jx_{max}	0.0000783383 mol C d-1cm-2	Kooijman et al. 2014
Arrhenius temperature	T_a	3243 K	Kooijman et al. 2014
Reference body temperature	T_{ref}	293 K	Kooijman et al. 2014
Half saturation constant	Fh	0.0000000121 mol C m-3	Kooijman et al. 2014
Carbon content	$C_{content}$	0.034	Kooijman et al. 2014
Initial length	Lw_{init}	0.03 cm	Kooijman et al. 2014
Initial mussels	n_{init}	41,600,000	This study
Environmental Forcing			
Temperature	Temp	K	UCSC Reanalysis
Current speed	V	cm d-1	UCSC Reanalysis
Mixed layer depth	Mld	M	UCSC Reanalysis
Salinity (proxy for food)	X_c	mol C cm-3	UCSC Reanalysis

The biological model was evaluated in order to obtain its sensitivity to environmental variables. The analysis showed that temperature and POC were the most significative forcing, explaining 51% and 42% of the productivity annual variance, while current speed and mixed layer depth only accounted for 4% and 3% respectively. The analysis was done by running the model with small perturbations in each variable on a sequence to obtain variations of production, then fitting to least squares method to obtain the percentage of importance of each factor or variable.

In our adapted version of the DEB mussel model we simulated the change in biomass of an initial number of mussels (41,600,000) over a period of 365 days, which were seeded every year on October 1st. and harvested once they reach the commercial size of 23 g. The time of harvest is an important metric for productivity used in our analysis and is calculated every year along the 28-year period. It is expected that mussels in productive sites will reach the commercial size sooner in a cultivation year, resulting in a time factor of 1 plus the fraction of the remaining year. For example, if mussels were seeded in October of 2000 and grew up to 23 g in April 2001, the site will have a factor of 1.5 because it took only 6 months for this site to reach a commercial size. The final individual weight was then multiplied by the harvest factor and the total number of individuals to calculate the final mussel production weight of the farm. This resulted variable (mussel production) was used to develop the subsequent analysis.

The model not only took into account the growth of the mussels but mortality due to starvation as well. As part of the model, death due to starvation occurs when somatic maintenance requirements cannot be met. Detrimental temperatures for mussels of 24 °C (Anestis et al., 2007) are reached only in a minimum time and space for the period and region used in this study, so we expect that mortality due to temperature is not a major factor. Natural mortality is also not considered given the period of cultivation is just the grow out phase of the mussels. Mortality caused by predators was also set to zero.

Each of the 223 sites contained a hypothetical farm within the dimensions of 4 km^2. Infrastructure and production capacities can vary from farm to farm, for example, mussel farms at the Prince Edward Island Region produced ~414 tons per km^2 (Canada, 2006); farmers in the Santa Barbara coast produce around 445 tons per km^2 (Commission, 2018) and finally mussel farmers in Ensenada, Mexico produce 60 tons per km^2 (Diaz, 2018). In our case, the production capacity of each site is set for about ~251 tons per km$^{2.}$; this means that each site would produce 1,005 tons per farm, ranging in production from 274.67 tons up to 1354.67 tons from the less to the most productive farms, after considering the additional time factor described above. Our farm arrangement was based on Lester et al. 2018 but adapted to our farm dimensions and production capacity: 32 longlines, each longline with 3,962 m of fuzzy rope, and a density of 328 mussels per m of fuzzy rope.

Historical reconstruction of productivity 1981-2008

Mussels were seeded each year in October and harvested when reaching commercial size at 23 g every year, over a period of 28 years from 1981 to 2008. The choice of the 1981-2008 period is motivated by the availability of a high-resolution historical reanalysis of the California Current System conducted by UCSC. This reanalysis assimilates the long-term hydrography from the CalCOFI dataset and all available satellite information with a state-of-the-art regional ocean modeling systems to generate the best available estimate of ocean conditions over this period. This simulation was computed for the 223 locations distributed over the SCB. The historical environmental data was coupled with the mussel production model to perform a hindcast of mussel production. The mussel model was run every year using environmental data for the four forcing variables that the model feeds on. With this hindcast method, time series of mussel production were obtained for the 223 sites (Figure 1). The resulting time series were used to estimate the spatial statistics and covariance analysis in order to identify profitable regions based on mean productivity and variance.

It is important to mention that spatial constraints used for the zonification of aquaculture (marine protected areas, other uses of the space) were not considered. The purpose of this study is to understand how sites gain or lose aquaculture productivity in response to environmental variability. The resulting information can be further explored for identifying ideal regions for aquaculture productivity and farms profitability.

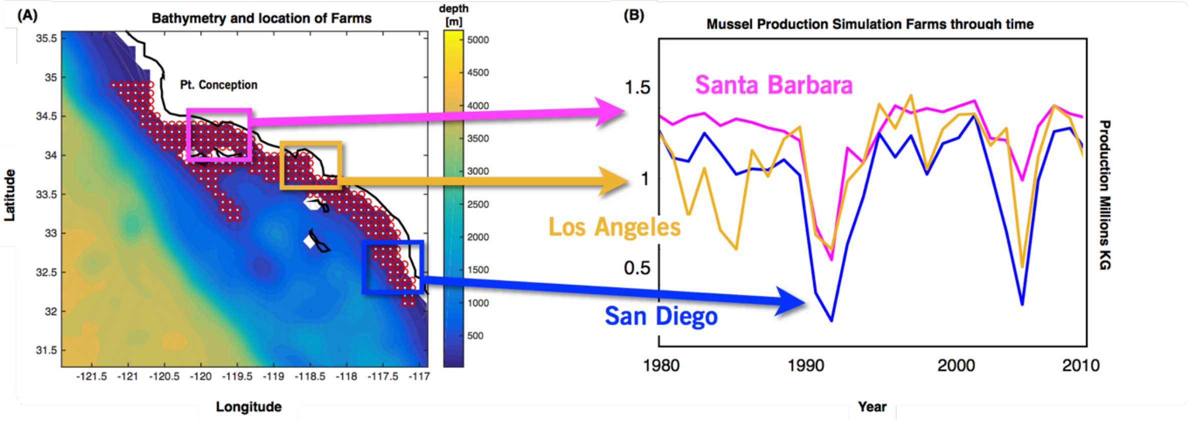

Figure 1. Region of study and schematic of time series of production. (a) The Southern California Bight (SCB) region was subdivided in 223 sites or locations (red circles). (b) Production time series of 3 representative sites of the three main regions in the SCB, for the 1981-2008 period, as an example of variability in production year by year. Each production is calculated on an annual time step and is considering the time of harvest

Variability Analysis

a. Spatial statistics

The spatial statistics over the 28 years of the mussel production hindcast were performed in order to visualize productivity and stability of production for the 223 sites (Figure 2). The mean productivity map (Figure 2a) shows high values along the coast with higher concentration south of Pt. Conception. On the other hand, the map of variance in productivity shows low values south of Pt. Conception and along the coast (Figure 2b). Taking the ratio of the mussel biomass production standard deviations over the mean (coefficient of variation) allows us to identify regions where production is stable (low values in Figure 2c) — that is the mean production is large compared to the year to year variation. This led to the recognition of three regions with clusters of sites in the North, Central and South where mussel farms are likely to be the most stable in terms of production and profit (Figure 2c). Aquaculture clusters reflect the geographical regions previously defined for the SCB as Southern Californian, and Ensenadian, having the central region of Santa Monica bay as a transition area (Blanchette et al., 2008).

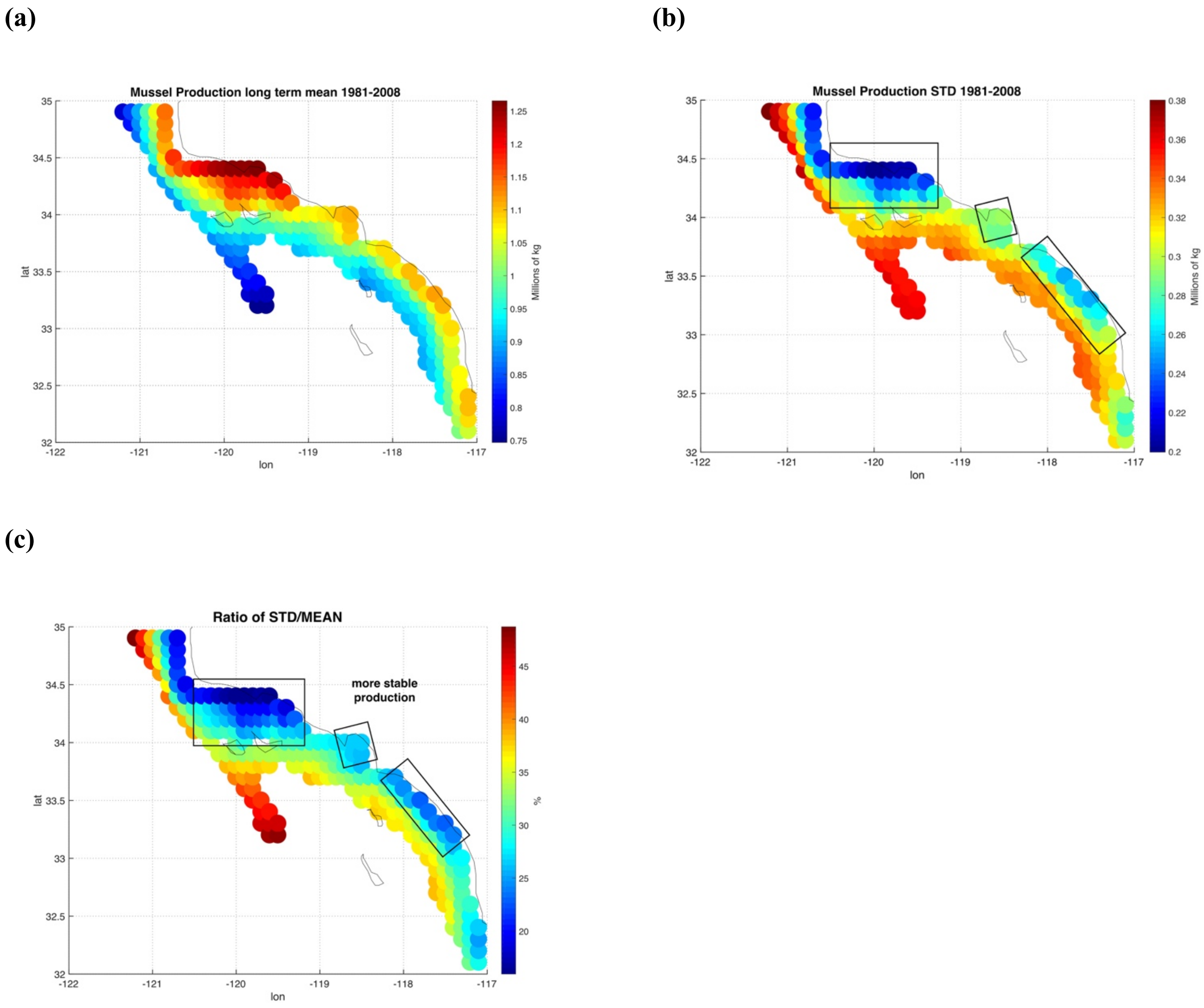

Figure 2. Spatial statistics of mussel production (a) Long-term mean of production from the mussel model along in the Southern California Bight (SCB) at the 223 sites. (b) Standard deviation of mussel production. (c) Ratio between standard deviation and long-term mean of production expressed in percentage.

b. Empirical Orthogonal Functions and Principal Component Analysis

To characterize the variability and the level of coherence across the 223 sites, we performed Empirical Orthogonal Functions (EOF) and Principal Component Analysis (PCA) to decompose the variance map of mussel production (e.g. Figure 2b). The PCA allows to extract and quantify the coherent dominant variability across the sites (e.g. mussel farms) and understand the extent to which this variability is linked to dominant climate modes in this region. After assembling a matrix of the yearly production anomaly estimate at the end of the growing season (e.g. one year after the seeding of the farm in October) at each site, we computed the covariance matrix of the anomalies and decomposed it in eigenvalues and eigenvectors. The eigenvectors associated with the largest eigenvalues are referred to as Empirical Orthogonal Functions (EOF) and correspond to the dominant spatial patterns of variability (Lorenz, 1956; Di Lorenzo et al., 2008). In the case of the mussel production, the first EOF (Figure 3a) explains 83% of the total variance and exhibits the same spatial structure as the total variance map (Figure 2b), implying that this pattern of variability is coherent across all sites. The temporal variability of the first EOF was extracted by projecting the EOF1 onto the matrix of yearly production anomaly estimates and is referred to as the first Principal Component (PC1) (Figure 3b). The time series of PC1 exhibits strong low-frequency fluctuations that are not connected to interannual events such as El Niño (e.g. there is no evidence for strong fluctuations associated with the 1982 and 1997 events). This suggest that other climate dynamics of the Pacific exert a more dominant control on mussel productions.

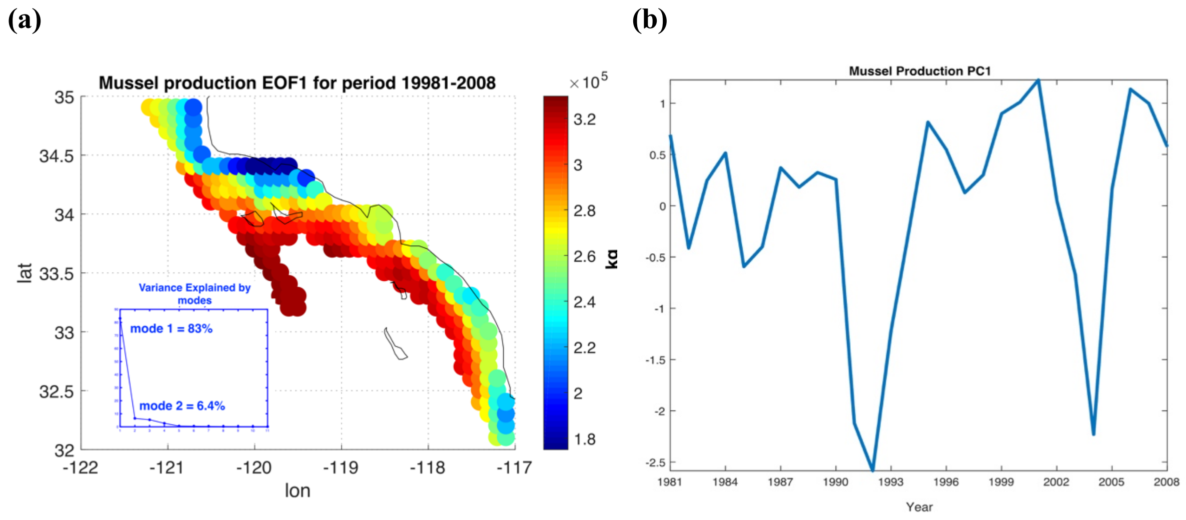

Figure 3. EOF and PC of mussel production. (a) Dominant Empirical Orthogonal Function (EOF) of the annual anomalies in mussel production. The EOF1 explains 83.08% of the interannual variability. (b) The time series associated with interannual fluctuations in EOF1, also referred to as the first Principal Component (PC1). PC1 is evaluated 20 months after the date of farm initiation due to the lag of harvest with respect on the environmental data.

c. Links to North Pacific climate variability

The first mode of spatial variation (EOF1) and its temporal variation (PC1) was further explored to analyze what features of the climate are relevant for aquaculture production. The first principal component (PC1) shows synchrony (Figure 4a) and high correlation (r ≈ 0.67, *p*-value < 0.001) with the North Pacific Gyre Oscillation Index (Di Lorenzo et al., 2008). The relationship between modeled production and the NPGO Index is also demonstrated by the correlation of the PC1 with global sea surface temperature anomalies (SSTa from the NOAA ERSSTa v3) (Figure 4b), which exhibits the typical NPGO SSTa pattern. Mussel production variability in the SCB correlates not only locally with SSTa but with the rest of the Pacific Basic domain, demonstrating that such variability does not respond to regional scale variability but to global decadal trends associated with Pacific climate modes such as the NPGO.

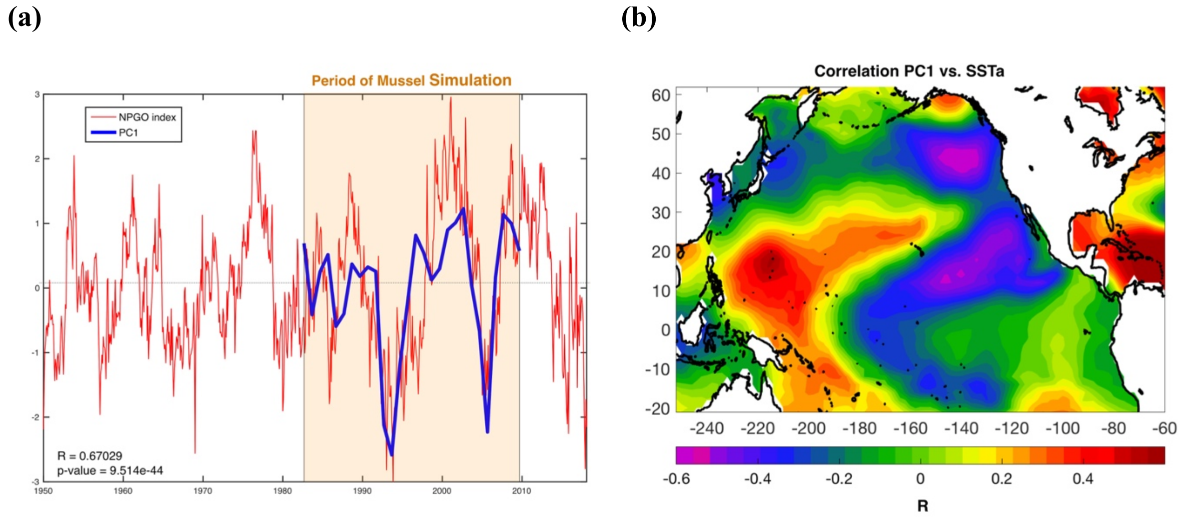

Figure 4. PC and climate of the North Pacific. (a) NPGO index (red) for the entire available record and PC1 of mussel production (blue). (b) Correlation between PC1 and Pacific sea surface temperature anomalies (SSTa) reveals a large-scale climate pattern resembling the North Pacific Gyre Oscillation (NPGO).

Net Present Value and optimal site selection

To analyze the effects of environmental variability over the economic value of the aquaculture sites, an economic model component is added based on the final mussel production at the end the year. The economic indicator used in this work is the Net Present Value (NPV), commonly used in economics and finance to analyze the feasibility of productive projects, including aquaculture (Whitmarsh et al., 2006; Liu et al., 2007). NPV also provides important information on the time of investment recovery and the value of the investment in present time. The calculation of NPV (Equation 1) utilizes information on investments and costs of running a farm minus the cash flow derived from profits of the farm. Profits are based on the revenues of selling mussels at gate price to distributers year by year. Real farms often increase their production gradually up to their maximum capacity. However we assumed that farms would work at full capacity from the beginning (Lester et al., 2018). The discount rate selected was 8.07% which is the average for the aquaculture industry in developed countries for 1991-2015 (Ruiz Campo et al., 2018).

$$Net\ Present\ Value = \sum_{t=0}^{t=10} \frac{C_A}{(1-\delta)^t} - C_{Init} \qquad \text{Eq. (1)}$$

C_{Init} = Initial investment
C_A= Annual profits
t = Time period
δ =Discount rate

All information on costs of running a farm were taken from (Lester et al., 2018) and adapted to the characteristics of our farm model (Table 3).

a. NPV: constant vs. variable

To show the importance of climate variability over profitability we compare a constant NPV against a variable NPV approach. Constant NPV was calculated with a constant production, using the mean production of the 28 years for each farm site simulating lack of variability in order to simulate zonification exercises where environmental conditions are assumed constant. Variable NPV was computed using the yearly production across 10 year horizons (see example in Figure 5). To do this, we selected periods of 10 years starting from 1981 until 2008; the next period would start in year 1982 and end in 1992 and so on, giving in total 18 NPV periods for each of the 223 sites. In Figure 5, we show two examples of starting the farm in different years (e.g. 1991 vs 1993/1994) for two sites located in the Northern region and SCB. Clearly, depending on the decadal trend in a specific site, certain farms do not recover costs over the 10-year horizon (e.g. Figure 5a, red timeseries).

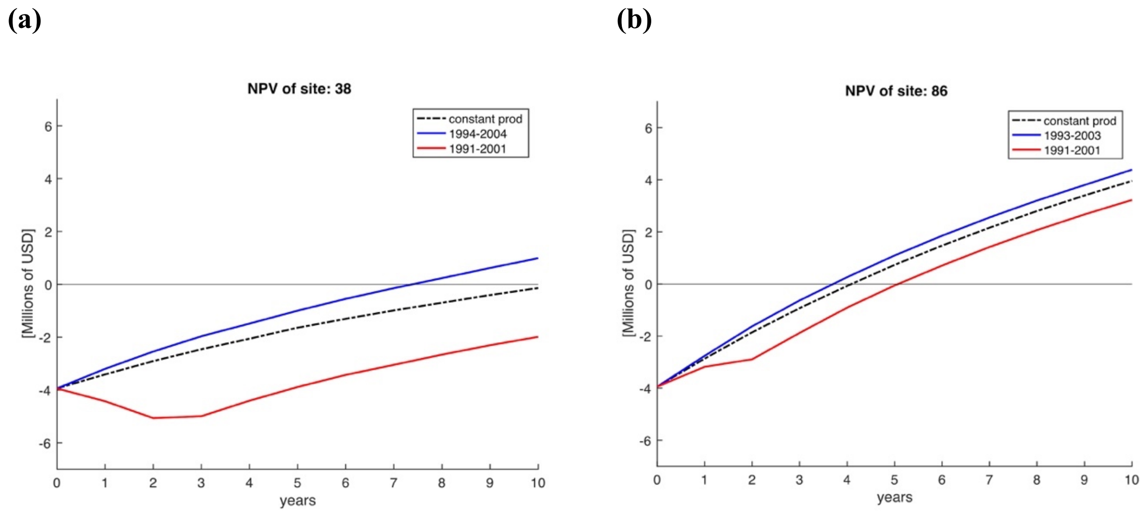

Figure 5. Constant vs variable net present value example. Net present value (NPV) calculations on a 10-year horizon, indicating net present value for sites 38 (a) and 86 (b), both located in the Northern region of the SCB. NPV profile if calculated constant (averaged) across the 28 years of simulation is represented by the dashed black line. The red line indicates the NPV profile obtained for period 1991-2001 indicating less profits than a posterior NPV profile (blue line) calculated for periods after. Horizontal line indicates the time when the investments are recovered at the time at intersection with NPV lines. **The ranking procedure.**

A practical approach to better understand the effects of variability over site selection is a ranking system to organize all sites from best to worst based on the performance of the sites year by year. We developed two separate rankings, one for mussel productivity only and the other for NPV. Ranking both separately allows us to identify productive sites vs sites with economic constraints, which are reflected on their NPV such as distance from port and effects of variability. The ranking procedure complements calculations of the mean and standard deviations. While spatial statistics provide useful information on productivity and stability, the ranking incorporates the variability behavior into NPV calculations and informs investors and managers with a list of best sites for mussel aquaculture, making the selection more straightforward (see Supplementary Table 4 and Table 5**,** and Figure 9 for geographical reference).

The first rank (productivity ranking) was developed by positioning the sites from best to worst based on final weight of mussels every year. For example, the site with best tonnage and time of harvest performance will be number one at that specific year and the process continues for all the years of the environmental data available (28 years/ranking total). It is expected that sites with less variability will stay on similar positions in the ranking year by year, while sites with more variability will flip positions more drastically. A final rank is calculated to obtain the best site, based on the prior 28 years' performance.

The second rank is calculated with the NPVs calculated for the 10 year periods. Therefore, 18 annual ranks are calculated for this particular ranking. Similar to the productivity rank, a final rank that summarizes the results of all 18 NPV periods is calculated. The top values in these rankings indicate the best sites to place farms from an economic perspective.

C. Results

Production of mussels varies year by year across the 28-year modeled period Figure 1b. Using spatial statistics of production (Figure 2) we find that the region around Pt. Conception shows the highest yield and less overall year to year variations implying stable production rates though time. Productivity in the southern region tends to be less compared to the north and similar to the center region. Lower productivity in the southern SCB is likely linked to the seasonal presence of the warm countercurrents coming from the South (DiGiacomo et al., 2001) and a stronger effect of variability over temperatures in these areas (Kim et al., 2015). However, the southern region tends to be more stable than the center. Some sites in the southern portions of the SCB show high mean production and low standard deviations exhibiting more spatial heterogeneity compared to the north. Sites where the mean production is highest are also the sites where the time of harvest is shorter – that is mussels reach the harvest size sooner (Figure 6).

Along the coast, overall production values are higher compared to offshore locations. Sites closer to the coast show a low std/mean ratio compared offshore sites, which are characterized by high values of the std/mean ratio (>30%) implying less sustained production and more interannual uncertainties. Offshore waters tend to be more oligotrophic than coastal waters in the SCB (Eppley, 1992; Kim et al., 2009) which explains this productivity gradient from the shore.

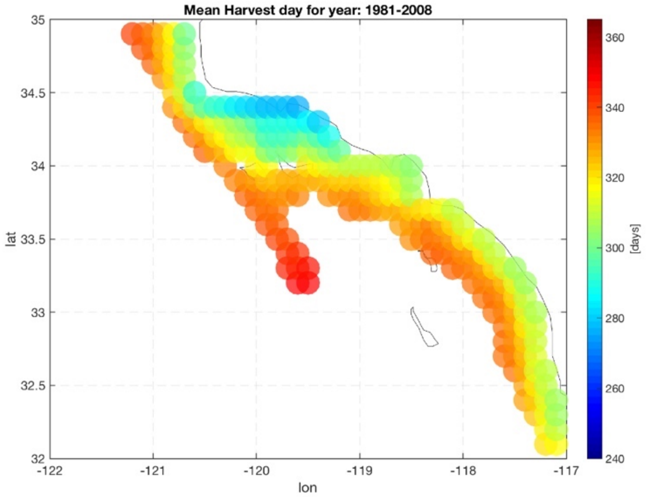

Figure 6. Mean harvest time length. Color indicate the number of days required to grow mussels up to the commercial size (23 g).

Despite the yearly variability in production (Figure 1b**)** there is evidence of significant low-frequency variability that gives rise to decadal trends in the time series of production. This behavior was analyzed and linked to climate regimes of the SCB. The EOF decomposition of the variance of mussel production shows that the first mode (EOF1) recovers the main features of the standard deviation pattern (Figure 3a), which account for the largest fraction of variance (~83%). The temporal variability of this pattern shown by PC1 (Figure 3b) confirms a very strong low-frequency variability shared across all sites. Given that the farms have no memory from one year to the next (i.e. farms are re-seeded every year), the low-frequency changes must be associated with cumulative integration effects associated with the environmental drivers (e.g. SSTa, mixed layer depth, current speed and food supply) (Di Lorenzo et al., 2013). Interestingly, there was no clear signature of interannual variations associated with the El Niño Southern Oscillation (ENSO) and most of the variance was on decadal timescales. Further analyses of the PC1 revealed that the low-frequency variance is linked with the regional expressions of large-scale climate variability in the Pacific Basin (Figure 4b), specifically the NPGO mode.

In terms of profitability of the sites, the North region shows high NPV and stability. Recovery times are shorter than the other two regions (around 4 years). These two aspects give the northern region an advantage over the other two regions. As mentioned before, productivity in the south is less than the center but stability is better. Not surprisingly, the NPV in the center region is less stable than the North and the South and recovery times can also take longer (from 4 up to 8.5 years). The lack of profitability in some sites can be attributed to economic factors (long distance from ports) or being located in an unsuitable environmental conditions for mussel growth.

The calculation of all eighteen NPV periods also displayed spatial and temporal heterogeneity. All regions' NPV curves vary depending on the time periods where projects initiate. This means that there are good productions during specific time periods, so a temporal component related to productivity and profits is also identified. Given the principal component analysis pointed at the NPGO as the main driver for mussel productivity, we matched the NPV profiles with the numerical index to illustrate possible effects of decadal variability over profitability of the farms. As representative examples, during 1988-1998 the NPGO index is moving towards a negative phase and during the period 1990-2000 the index stays on negative (Figure 7a). In contrast, period 1994-2004 shows upward direction indicating transition towards a positive phase, and finally period 1997-2007 is mostly positive. These four periods were linked with NPVs of representative farm sites of the identified northern, center and southern regions (Figure 7 b, c, d**).**

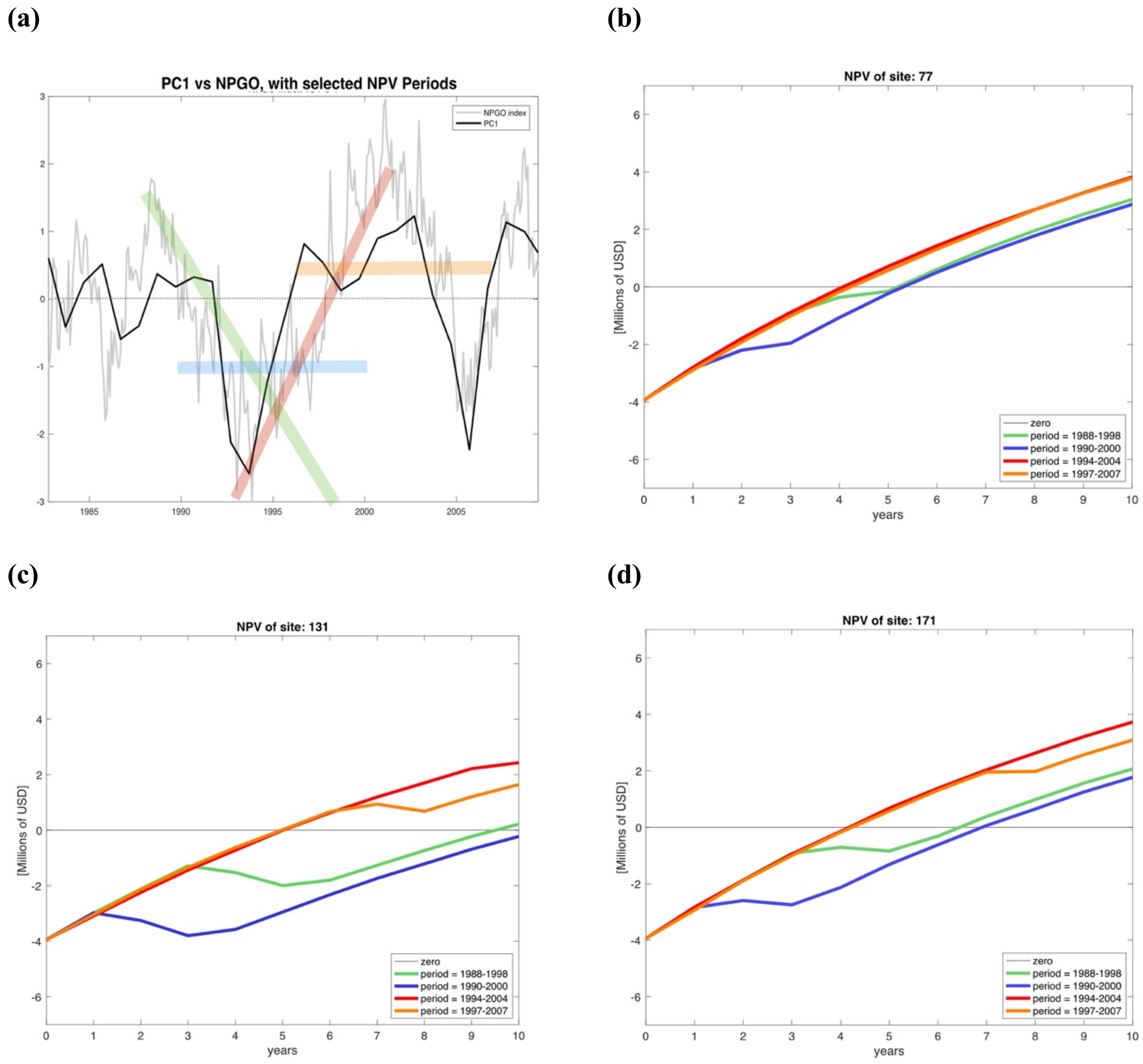

Figure 7. First principal component and NPGO index with selected NPV periods. (a) NPGO index (grey) for the period of available environmental data (1981-2008) and PC1 of modeled mussel production (black). The time periods highlighted in green (1988-1998), blue (1990-

2000), red (1994-2004) and orange (1997-2007) indicate different phases of the NPGO. (b, c, d) NPV profiles of the corresponding stages of NPGO for representative sites of the north, center and south of the SCB.

The profitability at all sites depends on the phase of the NPGO. For example, on Table 2 the periods 1988-1998 and 1990-2000, both considered to be negative, result in a drop in NPVs, while in the following two periods the profitability is considerably higher, and all sites follow this behavior. The critical period in terms of profitability is 1990-2000, where most sites dropped profitability compared to other periods. Choosing to start a project in this period results in economic loss for sites with less productivity and highly sensitive to variability. Period 1994-2004 displays the best NPVs for all the sites, which indicates good timing to initiate an aquaculture project of this nature.

Table 2. NPV periods matching with negative and positive phases of the NPGO.

	10 year NPV by NPGO periods (Millions of USD)			
Phase	Negative		Positive	
Years	1988-1998	1990-2000	1994-2004	1997-2007
North	3.043	2.870	3.820	3.776
Center	0.220	-0.224	2.431	1.643
South	2.066	1.769	3.726	3.088

Best ranked sites are highly productive (> 1000 tons annually, based on its global long term mean) and the variation low compared to their mean production values (<0.26 std/mean ratio). If ranked by production, the northern region concentrates most of the top sites (Figure 8a). Not surprisingly, site 97 located in the northern region was found to be rated the top site of the productivity ranking (Figure 8a). However, the NPV ranking (Figure 8b) was more heterogeneous.

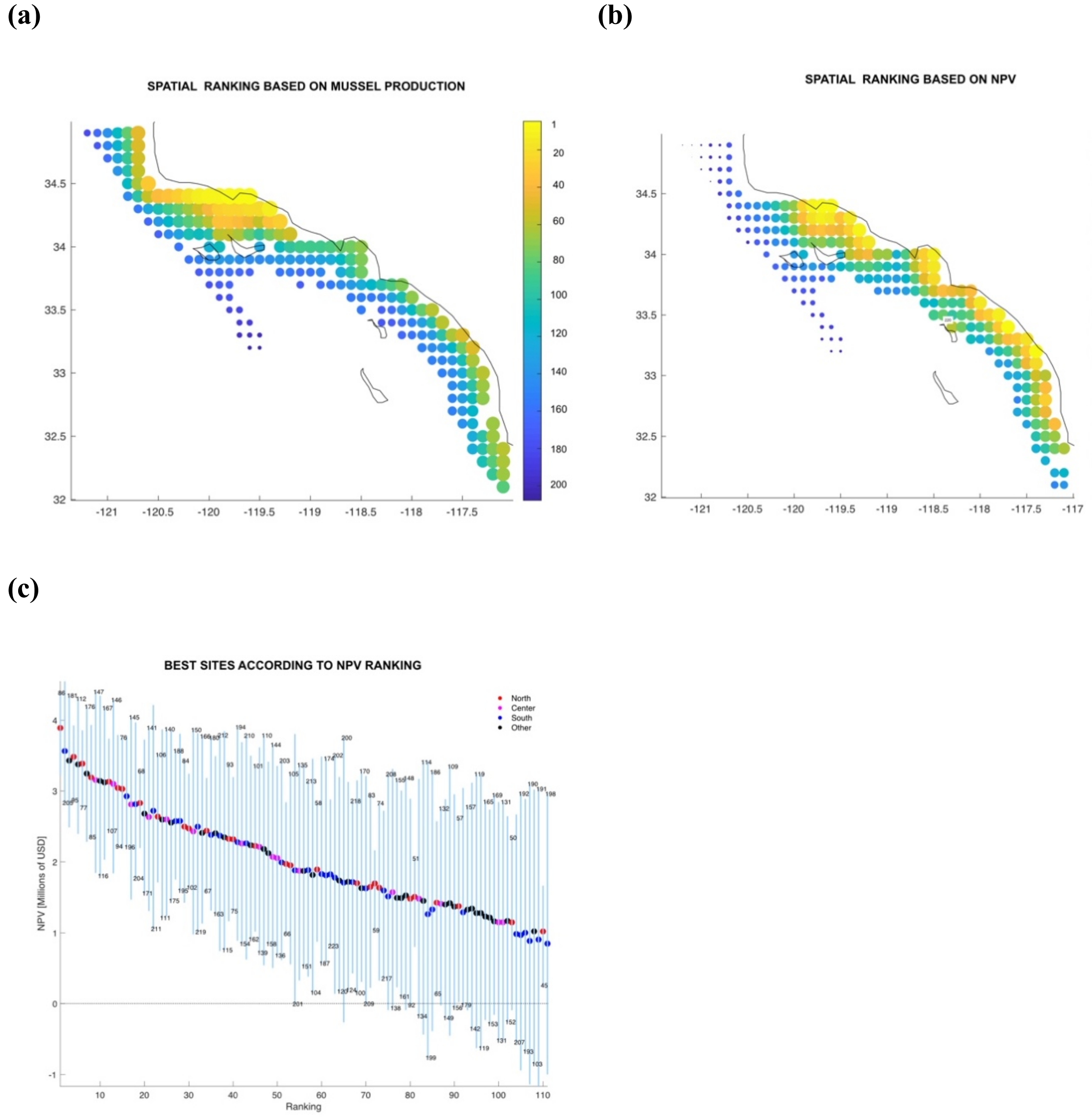

Figure 8. Spatial ranking and best sites according to NPV.(a)(b) Individual ranking displayed spatially showing top sites in yellow down to bad sites in dark blue. Color bar and the size of the marker indicates the site rank.(c) Farm sites above the mean organized from best to worst displaying the minimum and maximum (blue vertical lines) and average (colored dots) values in million USD (Y axis). The X axis shows the ranking order, where sites organized from best to worst. Sites are represented by each of the blue vertical lines and the color on the average dot represent the region where the site is located. The numbers above and below the vertical lines are the site identification numbers. Legend shows the number of sites in each region and the proportion of total sites.

Discussion.

Variability is a big challenge for aquaculture developed in the marine environment. Efforts to understand the effects of variability include seasonal forecasts, which provide farmers with reliable climate information to plan along with the environmental forcing from week to months ahead (Spillman et al., 2014; Hobday et al., 2016). Climate change is considered a problem of longer time scale, expected to alter variables important for bivalve productivity. GIS suitability methods (Handisyde et al., 2006; Saitoh et al., 2011; Liu et al., 2013); (Aura et al., 2017) and end-to-end models address productivity under ocean acidification and carrying capacity (Bell et al., 2013; Guyondet et al., 2015) to identify winner and loser species (Filgueira et al., 2016; Froehlich et al., 2018), and provide a very complete understanding on how the environment influences mussel performance in a farm (Matzelle et al., 2015). In general, this particular body of work is based on a sensitivity-type approach, where key variables for bivalve production are changed based on the most feasible scenarios projected for climate change in the future.

Our work presents two methods that help incorporate climate variability into zoning plans for aquaculture and site selection. First, we propose EOFs and PC analysis to identify what decadal trends are the most important depending on the region and species that are planned to be cultivated, and the ranking method can inform decisions for selection and valuation of sites which is important for managers, investors and farmers. A key difference with previous work is that we approached aquaculture production as time dependent based on the historical evolution of environmental forcing. In this context, modeled mussel production time series in the SCB showed dependence on decadal fluctuation, which is consistent with positive and negative phases of the NPGO. The calculation of the NPV is inherently a time dependence problem because is calculated according to continuous years of costs and profits.

Time dependence is also reflected on the ranking system developed in this work. The results from a single year of mussel aquaculture production in the SCB could lead stakeholders to assume that all sites found in the north are the most profitable. However, adding variability led to interesting results. An analysis of the production ranking shows that certainly, the majority of the good sites are found in the north, but it also shows some good sites in the south (Figure 8a). Local oceanographic conditions might play an important role on this. For example, site 205 which is located in the region south (North San Diego) has the 27th place on the production rank (Table 4). North San Diego has been found to have an important nutrient flux from upwelling (Howard, 2014). A sudden change on the spatial trend occurs in the NPV rank (Figure 8b and c). Productive and profitable farm sites can be found across all the SCB. Sites found in the central and southern regions, as well as outside of the identified clusters in the statistical analysis were above the ranking's mean. The reason for this behavior is that NPV rank summarizes the interplay between productivity, variability and the economics of the sites (distance from ports, wave height, etc.). The proposed ranking system thus provides additional criteria for spatial planning and allocation of aquaculture areas and increases the resolution for site selection.

It is clear that there are sites that are less productive which results in lower income (NPV), but since the production of those sites are more stable, their incomes are quite constant over all periods. Such sites have stability that allows decisions on expansion with low risk (e.g. site 180, located at region south). On the other hand, there are sites that are highly productive but their fluctuations rate them as optimal in some periods and causing losses in other periods (e.g. site 124, at the Central region of the SCB). This behavior may encourage adaptive spatial management for marine aquaculture: sites could produce other species during decades when mussels are not profitable.

There is little empirical work that directly links productivity of farms with climate trends has been developed in comparison to other food production sectors such as fisheries. ENSO has been found to have effects over productivity of cultured green mussels in New Zealand due to indirect inputs on nutrients (Zeldis et al., 2008) and over calcification and growth in scallops cultivated in an upwelling region in Chile (Lagos et al., 2016). Despite the big influence of ENSO over regional productivity, we did not find significant correlation with ENSO. The productivity signal of ENSO appears to be more relevant during certain years depending on its strength (Kahru et al., 2000; Bograd et al., 2001; Kim et al., 2009). ENSO influences precipitation in the SCB (Schonher et al., 1989; Cayan et al., 1999) and such indirect effects over mussel productivity could be explored using this historical approach in combination with end-to-end models mentioned above adapted to this goal. Adequate environmental data resolution and quality are relevant to approach the effects of climate and aquaculture performance through modelling (Montalto et al., 2014).

Availability of mussel larvae is very important for farmers who in most cases capture mussel spat from the wild. Reduced mussel larvae abundance followed a seawater chlorophyll-a concentration weakening in 2009–2010 that coincides with positive phases of MEI and PDO in Northern Patagonia, Chile (Lara et al., 2016). For study sites in Oregon, the role of the NPGO is relevant on recruitment and food availability (Menge et al., 2009) and filtration rates of later stages of mussels (Menge et al., 2011) which potentially reinforces the relationship between the NPGO and aquaculture success. The SCB region seems to have more heterogeneous patterns in recruitment and growth in comparison with Northern California

(Smith et al., 2009), so further empirical work is required to confirm the influence of the NPGO over these variables for recruitment and growth of mussels in the SCB. This opens a window to link ecological research and aquaculture productivity, in collaboration with the aquaculture industry in the SCB. Analysis of mussel larvae along with grow out experiments are two possible paths to corroborate the findings of our modeling work.

The Importance of Natural Decadal Variability

The initial focus of this study was to evaluate the role of interannual variability (e.g. ENSO) because the initial annual runs revealed a year by year variation on the productivity of mussel farms in the SCB. However, our results revealed that the decadal-scale variability associated with large-scale Pacific climate may be more important in planning frameworks for mussel aquaculture. The EOFs analysis demonstrated that mussel productivity in the SCB is highly coherent in space and correlated to the decadal variability of the NPGO compared to little influence of interannual-like phenomena like ENSO.

The emergence of decadal-scale fluctuations in the mussel production as opposed to interannual events is ascribed to the fact that farms are sensitive to multiple drivers. The integration of these multiple forcing tends to extract and amplify the lowest frequency variability that is common to the different drivers (Di Lorenzo, 2018). It is likely that productivity of aquaculture farms of other species that rely on multiple environmental drivers like food and temperature (e.g. bivalves and algae) will also have similar decadal fluctuations. For example, decadal oscillations of natural giant kelp forests have been linked to the NPGO in California (Bell et al., 2015). Future kelp aquaculture in the SCB will likely be affected in a similar fashion. In contrast, assuming that oxygen is not limiting, farmed fish which are highly sensitive to temperature may exhibit stronger interannual variability associated with the ENSO extremes.

Decadal forcing is known to impact ecosystems in the Pacific Basin (King et al., 2011) and the California Current upwelling system (Chhak et al., 2007; Di Lorenzo et al., 2008). The NPGO index is earning increasing relevance in explaining productivity switching regimes with important consequences on marine ecosystems along the California Current (Di Lorenzo et al., 2008), including the Southern California Bight (Nezlin et al., 2017).

Decadal-scale variability has also been observed in natural populations of the Greenland smooth cockle *Serripes groenlandicus* in the Barents Sea, where growth mechanisms were correlated to increased riverine discharge influenced by a negative phase of the North Atlantic Oscillation Index (NAO) (Carroll et al., 2009).

There is a strong relationship between the NPV and decadal trends. NPV periods that coincide with negative phases of the NPGO display a generalized reduction in profitability. However, there is spatial heterogeneity on how the farm sites respond to negative phases of the NPGO. On the other hand, the positive periods also move profitability up at most of the sites. This can be critical especially when starting a new aquaculture venture when big investments are at risk.

The results of our bioeconomic analysis highlights the possibility of predicting production based on the decadal climate state. From a management perspective, dependence of mussel aquaculture on decadal fluctuations is a remarkable statement: there are decades of ‘good years’ and decades of ‘bad years’ for mussel aquaculture. Although is still unclear the extent to which these climate decades can be predicted (Meehl et al., 2010; Meehl et al., 2016;

Liu, 2018; Liu et al., 2018), this information would allow managers and investors to plan accordingly the best times to invest in such venture.

E. Conclusions

The effect of the variable behavior of production of mussels over site selection of aquaculture was an initial motivation of this work. Our climate sensitive analysis of productivity showed that the spatial heterogeneity of the SCB as well as its climate regimes resulted in a variable panorama in production and profitability that raises questions on the use of constant environmental conditions (e.g. temperature and nutrient fluxes) in the spatial planning of aquaculture farms such as mussels.

Our results indicate that climate variability is a key component of the site selection process for marine aquaculture. Finding a good site location is important, however selecting the right time to start a mussel farm is also key to success. We highlight the importance of taking into account decadal trends in addition to the short term climate.

The strong relationship between decadal variability and mussel productivity in the SCB resulted in different investment recovery scenarios. This decadal trend causes alternation in the profitability between "good" and "bad: decades of some farm sites. Understanding aquaculture planning in the context of marine climate variability is critical for the planning and zonification of marine aquaculture. In addition, this knowledge can benefit managers and investors because they will be able to know when to expand, move, hold, or change the species to be farmed in order to keep the food and investment security.

We propose that the industry and all stakeholders involved in spatial planning of marine aquaculture consider environmental variability and climate trends that might be crucial for the success of their operations.

Considerations about the impact of climate to be further explored.

Although this study only considered four environmental variables in mussel farms simulations, the framework presented here can be improved with the addition of variables important for aquaculture production. Such variables include the effects of harmful algal blooms (HABs), hypoxia and ocean acidification, particularly because of recent climate extremes that led to prolonged warm events and HABs along the California Current (Moore et al., 2008; Hallegraeff, 2010; Gruber, 2011). Although upwelling is the main source of nutrients in the SCB (Howard, 2014), additional sources of nutrient inputs should also be considered. For example runoff in the SCB is strongly influenced by interannual variability in precipitation (i.e. El Niño) (Nezlin et al., 2005).

Stronger North Pacific decadal variability in the Northeast Pacific is also predicted in future climate (Joh et al., 2017; Liguori et al., 2018), so the effects of changes in such mechanisms must be also be explored because they may lead to decades of enhanced profit but also decades of extreme loss.

F. Supplemental information

Table 3. Costs of running a mussel farmAll information on costs of running a farm were taken from (Lester et al., 2018) and adapted to the characteristics of our farm model. Such arrangement does not affect the total productivity of the sites since NPV computations are done separately from the growth numeric model. Costs of running a farm are divided on fixed costs and variable costs, assuming variable are costs related to location, and such calculations also based on the supplemental information from (Lester et al., 2018) with the difference that labor is considered a fixed cost. Variable costs include the effect of the time of harvest (Harvest

Factor) where, despite sooner harvest is a plus for a site, costs are increased due to the extra labor needed for multiple harvests. Chosen gate price of kg of mussels is based on a value between (Lester et al., 2018) and (Buck et al., 2010).

Inputs	**Description**	**Value**
Starting costs	Initial investment needed to start a mussel farm	$3,941,300
Fixed annual operating costs	Costs that do not vary with location	$ 777,040
Variable annual operating costs	Cost vary depending on a) Distance from port to farm b) Maintenance for depth and wave height c) Harvest factor Annual averaged variable costs across sites	$ 570,610
	Total annual costs (Fixed + Annual average variable costs)	$ 1,347,650
Mussel market price		$ 2.3 per kg

Table 4. Final rank by production (kg). Minimum and maximum values obtained along the 28 year period are shown, as well as long term means. Only the first 54 sites are shown based on best profitability in NPV.

Rank	Site By Production	Avg TM rank	Min Prod. (kg)	Mean Prod. (kg)	Max Prod. (kg)
1	95	6.64	521486.2	1265504.2	1455452.98
2	77	8.71	541199.76	1256338.13	1439643.34
3	86	9.32	517880.94	1255076.36	1445163.36
4	68	10	557355.97	1252621.82	1443448.13
5	59	12.64	557328.75	1242980.79	1436745.87
6	107	13.86	463151.6	1237791.63	1422003.68
7	51	15.07	541074.36	1233334.4	1428585.3
8	45	20.36	515149.04	1216656.36	1416513.76
9	102	22.75	396515.71	1200247.84	1406085.85
10	94	23.32	407540.07	1197590.55	1420224.67
11	85	27.25	411312.85	1190559.73	1415287.47
12	76	27.5	417380.36	1189530.23	1417480.39

13	40	28.96	474112.85	1192586.78	1413818.66
14	112	29.14	343746.39	1186483.08	1410170.93
15	67	31.25	428394.14	1182817.74	1415407.5
16	27	34.89	477209.91	1175678.51	1390630.6
17	106	36	368487.43	1169443	1403750.81
18	35	36.64	446851.18	1170026.91	1391595.26
19	66	37.75	373369.07	1164953.1	1401978.08
20	75	38.36	365841.96	1161770.37	1398428.36
21	84	40.68	357469.89	1155624.18	1392985.45
22	31	40.89	429562.23	1159732.29	1385053.57
23	58	43	379331.88	1151831.6	1403204.51
24	93	46.86	329917.81	1142690.6	1380497.49
25	23	48.82	554868.8	1143670.66	1358149.51
26	196	51.57	370956.48	1114818.74	1399573.27
27	205	52.07	349207.53	1108808.25	1398355.84
28	22	54.14	522963.38	1128872.4	1366826.09
29	116	54.39	268213.53	1129727.12	1402564.87
30	21	55.39	487730.29	1121912.09	1370560.73
31	50	55.61	352250.98	1121500.63	1385586.46
32	20	57.75	454451.82	1110560.72	1372348.53
33	74	58.04	279862.87	1118787.2	1378267.81
34	101	58.5	306203.09	1122557.69	1374613.07
35	26	58.64	375811.74	1111900.33	1371382.77
36	181	61.36	349577.52	1098355.27	1406648.57
37	213	61.68	395981.95	1079825.3	1403070.57
38	57	61.79	300664.9	1109840.34	1373133.22
39	65	62.25	289841.44	1115171.72	1368718.32
40	176	62.54	376507.87	1100418	1396017.79

41	223	62.82	476135.08	1097065.53	1485372.44
42	222	63.82	501196.86	1099691.59	1470876.52
43	111	64.54	257382.9	1111917.65	1382665.32
44	204	65.07	360520.3	1076692.51	1389282.04
45	19	65.46	401401.52	1084259.9	1369371.13
46	188	65.96	363024.27	1085936.28	1364689.39
47	83	66.82	269158.89	1104276.72	1371490.21
48	218	67.54	492579.3	1070963.43	1414849.68
49	44	67.86	329453.76	1096425.48	1376861.55
50	219	68.93	384386.58	1064455.35	1441072.99
51	212	69.29	392763.08	1058387.2	1404142.38
52	221	69.68	460554.34	1084370.14	1466660.24

Table 5. Final rank by NPV. Only the sites that never have negative NPV values are shown (best 52 sites).

Rank	Site By NPV	Avg NPV rank	Min NPV (USD)	Max NPV (USD)	Mean NPV (USD)
1	86	1.22	3225493.84	4385598.6	3891059.74
2	205	4.11	2831538.83	4547189.67	3565647.11
3	181	4.28	2485424.55	4348106.49	3428847.55
4	95	4.56	2869445.19	3927007.06	3481734.03
5	112	5.89	2393839.92	4302308.37	3375865.93
6	77	6.78	2760838.23	3857035.29	3385621.01
7	176	8.67	2282438.46	4190533.7	3246045.18
8	85	9.5	2349854.29	3933275.23	3190216.99
9	147	10.94	1844304.04	4399731.83	3153420.12
10	116	11.67	1802670.52	4347351.4	3141489.45
11	167	12.39	2030687.66	4171418.92	3119676.11
12	107	12.72	2435832.81	3739799.06	3129760.37

13	146	13.28	1838219.14	4286081.04	3097427.89
14	94	14.94	2217755.81	3792540.75	3041015.59
15	76	16.06	2188063.81	3755982.56	3027623.61
16	196	17.56	2208907.08	3776065.4	2924478.04
17	145	20.72	1469961.31	4041380.53	2809785.03
18	204	21.56	1768694.9	3969722.26	2813146.93
19	68	23.61	2195002.32	3281628.04	2828710.43
20	171	26	1557476.43	3726307.22	2678298.56
21	141	26.22	1309542.46	3893306.48	2631784.97
22	211	27.44	1057252.42	4214122.44	2718952.65
23	106	27.83	1710246.56	3512451.79	2636905.68
24	111	28.5	1210845.6	3871524.8	2595406.56
25	140	28.78	1234041.01	3874466.15	2597440.92
26	175	29.78	1452854	3850611.34	2552575.87
27	188	30.39	1751530.82	3568243.1	2573170.64
28	195	30.61	1594924.25	3808138.66	2575858.55
29	84	33.56	1425379.79	3425507.59	2496507.44
30	102	35.33	1639263.98	3244185.42	2469924.47
31	150	36.11	978996.5	3863398.96	2428582.93
32	219	36.72	1012704.69	3817337.29	2495717.13
33	166	37	1131744.97	3772522.13	2407565.7
34	67	37.17	1589581.42	3183959.78	2437612.29
35	180	38.11	1313399.32	3753865.48	2379960.38
36	163	38.22	1265836.76	3489919.85	2403270.63
37	212	38.56	745260.83	3787562.1	2368090.87
38	115	39.56	757680.98	3845271.77	2345654.81
39	93	41.11	1164292.98	3373147.85	2323839.3
40	75	42.28	1305684.78	3196388.12	2317942.39

41	194	42.61	890139.11	3902269.9	2277103.92
42	154	43.78	846210.6	3689052.79	2258859.2
43	210	44.28	621927.57	3782608.8	2261913.33
44	162	44.89	910314.77	3496546.14	2233948.44
45	101	45.89	1017105.5	3353425.29	2224673.49
46	139	46.17	719928.23	3617550.17	2211014.93
47	110	47.83	541238.88	3784360.87	2180544.9
48	158	51.17	844819.83	3412383.2	2122790.72
49	144	53.5	503021.57	3652888.42	2070014.69
50	136	54.83	680873.62	3353148.13	2053338.4
51	203	56.33	614932.41	3427504.62	1991947.37
52	66	58.28	986933.88	2840388.9	1972297.56

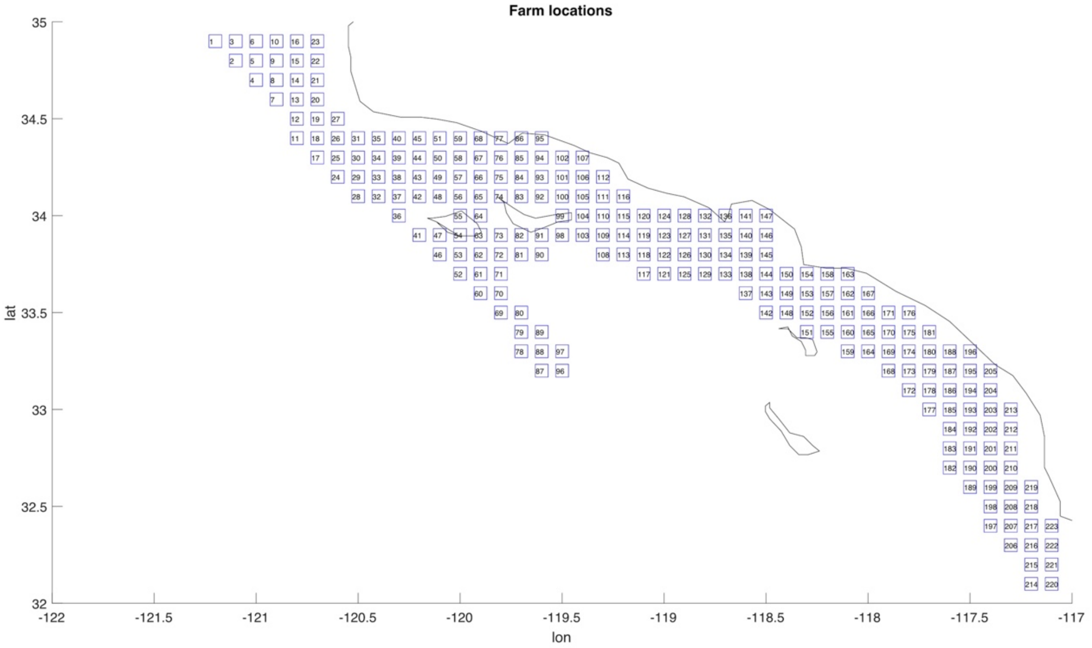

Figure 9. Farm site locations with identifying number.

Appendix on Mortality

The model not only took into account the growth of the mussels but also mortality due to starvation. In the model, death due to starvation occurs when somatic maintenance requirements cannot be met. However, in the formation of the model (originally based on *Mytilus edulis*), Muller & Nisbet (2010) state that this model "highlights the need for better mechanistic models of mortality." We concede that additional information on mortality would strengthen this manuscript. We took the reviewer's advice and investigated mortality due to thermal stress. We used data from Anestis et al. (2007) to model % mortality of *Mytilus galloprovincialis* due to temperature effects. Data from a laboratory experiment showing the effect of high ambient temperature on mussels (Figure 1A in Anestis et al. 2007), were collected using ImageJ software and a mortality rate look up table was generated by interpolating between the four temperature treatments using the interp1 function with a piecewise cubic spline in Matlab (figure shown below). Anestis et al. (2007) found that there was < 1% mortality at temperatures less than 24 ºC. We estimated the % mortality of all farms based on high seawater temperature events using this look up table. We were conservative and estimated mortality based on the number of consecutive days ≧ 24 ºC and used the highest ambient temperature recorded during this run as the temperature input for the look up table. We only found that only 3 of the 223 sites maintained consecutive days of ≧ 24 ºC temperatures during our period of study. These sites all had between 5 and 6 consecutive days with maximum temperatures = 24.03 ºC. We estimate this would lead to a mortality of 1.86% at these three sites. Therefore, we expect that mortality due to temperature is not a major factor in the geographic range of our study.

There are multiple sources of mortality, food driven mortality, which is accounted for in the model, environmental causes of mortality such as temperature (shown here) and predation, which was outside the scope of this study. Predation can be a major source of large-scale mortality of these farms (e.g. by diving ducks, Bernard Friedman, personal communication), but the spatial and temporal patterns of this effect are difficult to predict.

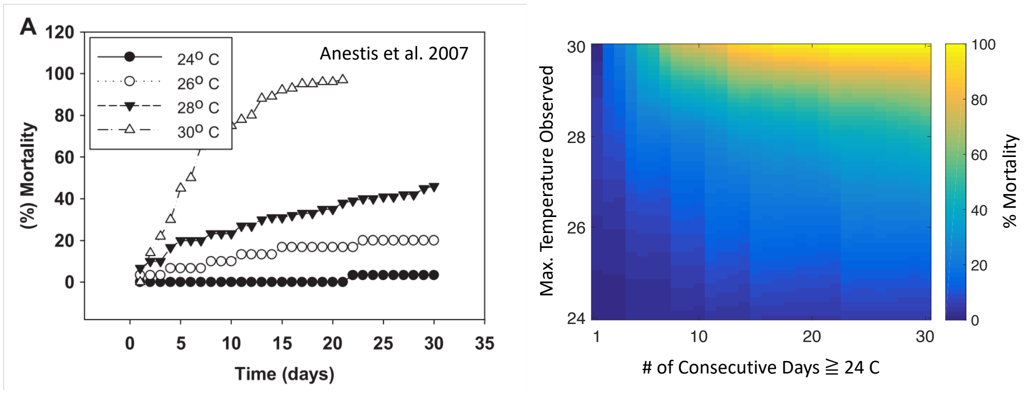

Figure 10. Mussel mortality analysis. The plot of the left was taken from Anestis et al. 2007 and shows the % mortality of *Mytilus galloprovincialis* (the same species in our manuscript) during consecutive days for four temperatures ≧ 24 °C. The plot on the right is the % mortality look up table derived from the data shown in the left.

II. Marine spatial planning of fish and kelp aquaculture considering climate variability in the Southern California Bight.

A. Introduction

In Chapter I, we compared fixed vs variable climate scenarios of mussel aquaculture farms along the Southern California Bight. As outcomes of that work, Sainz et al. (2019) pointed out that aquaculture of mussels in this region probably respond strongly to decadal modes of variability, particularly to the North Pacific Gyre Oscillation (NPGO), which is characterized by its influence on the nutrient dynamics of the California Current along with the Pacific

Decadal Oscillation (PDO) (Nezlin et al., 2017). Another key lesson of that work was that the best areas for the cultivation of mussels chosen at one point in time remain consistently highly ranked despite the large impacts of climate variability on yearly productivity. Both findings reinforce the relevance of performing marine spatial planning for aquaculture and considering decadal trends of variability in the planning process.

Yet, different aquaculture systems growing different types of species potentially pose their own unique management challenges in terms of climate variability in environmental forcing. Sensitivity to climate forcing can be different between aquaculture species due to differences in their physiological traits (Froehlich et al., 2016). This suggests that while mussels might be sensitive to decadal variability, other species might respond more strongly to interannual variability or other features of the climate of the region. Filter-feeding organisms rely on the nutrient variability of the surrounding environment (Fry et al., 2018), while fish in aquaculture are not food limited since food is provided by farmers. However, temperature modifies the efficiency of feed conversion in cultivated fish, which impacts costs (Besson et al., 2016).

The aquaculture spatial planning framework developed by Lester et al. (2018) identified the most productive areas in the Southern California Bight for three types of aquaculture: Mediterranean mussels, striped bass, and sugar kelp. However, this analysis ignored climate variability by forecasting production based upon patterns for a single year. In Chapter 1, we extended this approach by using 28 years of environmental data to identify the most important climate modes for productivity of mussels. Here in Chapter II, we expand this exercise to test our framework on a broader range of aquaculture species. We used the same species of fish as Lester et al. (2018): striped bass (*Morone saxatilis,* henceforth referred to as fish*)* that is commercially successful in the area[1]. Instead of sugar kelp, we chose giant kelp (*Macrosystis pyrifera,* henceforth referred as kelp), given its importance as a local species of the region.

In this chapter, we explore the effects of climate variability over site selection for striped bass and giant kelp farms (fish and kelp). We use available environmental forcing (updated timeline: 1980-2017) and empirical based aquaculture simulation models to generate time series of harvested biomass. We develop a forcing transfer function of production to understand how both species integrate the physical forcing into growth. Such transfer functions are then analyzed in the context of the regional climate. The objective of this chapter is to identify differences or similarities between the two types of aquaculture in the context of a variable environment, and apply this knowledge to marine spatial planning and optimal site selection.

B. Methods

Spatial Domain and Historic Environmental Forcing Data

A dataset of forcing variables for the years 1980-2017 was obtained from the 4D Historical Reanalysis Product for the California Current System (Moore et al., 2011a, 2011b; Moore et al., 2011c) for the domain of the SCB coastal region (122°W – 117°W; 32°N – 35°N) with a maximum water depth of 500 m. This product was developed using Regional Ocean Model System (ROMS) (Shchepetkin et al., 2005) and incorporated observation data from CalCOFI, which makes this product very appropriate for the needs of the aquaculture models and the

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[1] A commercial farm exists in Ensenada, on the Mexican side of the San Diego border, which is considered within the Southern California Bight, but this particular spot was not selected for our study.

resolution of the area of study. This product is available from the UCSC Ocean Modeling and Data Assimilations website (http://oceanmodeling.pmc.ucsc.edu/). The forcing data were subdivided in a grid with 223 aquaculture sites along the SCB (Figure 11) with a resolution of 1/10 x 1/10 degrees (~121 km^2). All environmental data curation was done in Matlab_R2018b.

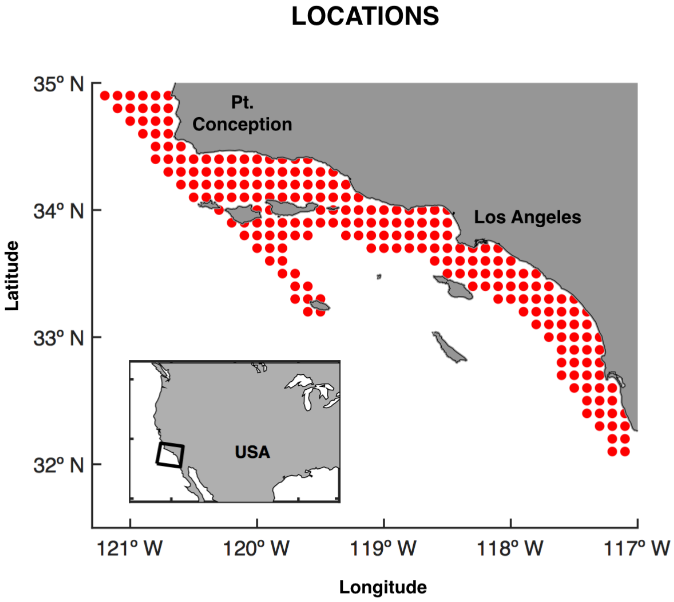

Figure 11. Southern California Bight (SCB) domain and aquaculture sites in red.

We used temperature as the single relevant forcing variable for fish aquaculture. Temperature drives growth rates, respiration rates, and food consumption rates on fish farms (Besson et al., 2017). In addition to direct temperature effects on growth, kelp requires nutrients provided by the surrounding environment. Therefore, the kelp aquaculture growth model considers the impacts of variation in nitrogen, a key limiting nutrient for kelp, as well as temperature. In Southern California, nitrate concentration has a consistent relationship with water temperature (Zimmerman et al., 1984). We used a temperature to nitrate (T2N) relationship developed by Snyder et al. (2020) for the region of study to compute a timeline of nitrate concentration. In this T2N relationship, nitrate concentrations are driven to near zero around 17 ºC. Forcing variables are described on Table 6.

Table 6. Environmental variables for the two aquaculture models used (fish and kelp)

Species	Variable	Units	Source
Striped Bass, Giant Kelp	Temperature	Deg C	UCSC Reanalysis
Giant Kelp	Temperature to Nitrate proxy	µmol L-1	Snyder et al. 2020

Aquaculture Simulation Models

Aquaculture models were designed to simulate organisms' growth under farming conditions. In these models, growth is the integration of biomass forced by the selected environmental variables. Every cell of the domain grid (~121 km^2) contains a hypothetical farm, adding up to 223 geographical locations or 'sites' distributed across the SCB (Figure 11) where kelp or fish would grow based on the environmental forcing gathered for that specific location. The farm characteristics and parameters of the fish and kelp models are described in supplemental Table 7 and Table 8. Although real farms have the capacity to have multiple cohorts of organisms and harvest continuously, our models are set to simulate growth of a single cohort per year. The resulting time series of biomass is used for the climate variability analyses. The aquaculture models were done in Matlab R2018b.

a. Fish Model (Striped bass)

The fish model describes the daily weight gain of fish based on the Thermal Growth Coefficient (TGC) theory (Iwama et al., 1981). This model proposes that fish growth rate is a function of weight and daily temperature. A thermal coefficient is obtained from empirical growth rates and temperature data and then used to model fish growth at different locations and times. This model has been used to analyze the effect of environmental variability on growth rates, particularly during the juvenile phase, which is the grow out stage in fish aquaculture (Iwama et al., 1981; Cho, 1992; Young Cho et al., 1998; Alamar et al., 2016; Besson et al., 2017) and also has been used for bioeconomic applications (Besson et al., 2017). A TGC coefficient for striped bass (*Morone saxatilis*) was computed based on initial and final weights of the fish in farms (personal communication with farmers) and temperatures of the region. By solving final weight (W_f) in Equation 2, the growth prediction is obtained from the daily effective temperatures over the period (Equation 4).

Thermal Growth Coefficient (TGC)

Eq. (2)

$$\mathrm{TGC} = \frac{\mathrm{W_f^{1-b}} - \mathrm{W_i^{1-b}}}{\sum \mathrm{T}_{corr}}$$

Corrected temperature index (Besson et al., 2016)

Eq. (3)

$$T_{corr} = \frac{T_{opt} * (T_{data} - T_{min}) * (T_{data} - T_{max})}{(T_{data} - T_{min}) * (T_{data} - T_{max}) - \left(T_{data} - T_{opt}\right)^2}$$

Final Weight

Eq. (4)

$$\mathrm{W_f} = \left(W_i^{1/3} + TGC\ x \sum T_{corr}\right)^3$$

where:

W_f = Final weight = 1500 g,
W_i = Initial weight = 20 g,
1-b = 1/3 (Mayer et al., 2008),
TGC = 0.00140

The fish model simulates the outgrowth phase of juveniles of 20 g starting on October first of each year. The cultivation cycle is 18 months and a typical harvest weight is ~ 1.5 kg. The total yield of a farm (in tons) is computed as the modeled fish weight multiplied by the number of fish in each farm. Expressing the yield over 18 months can be confusing when comparing it with the other species or when used to compute the yearly profits of a farm. As a result, we linearly distributed yields into each 12 month period to simplify analyses. This yearly linear distribution does not modify the impact of climate variability.

b. Kelp Model (Giant kelp, *Macrosystis pyrifera*)

A simple kelp aquaculture model was designed to simulate giant kelp yield based on a seawater nitrate-based kelp growth curve (Bell et al., 2015) and a temperature-based decline curve that forecasts kelp decline when temperature exceeds 21ºC (Cavanaugh et al., 2019). Both curves are derived from Landsat-derived kelp canopy biomass data from the region.

Temperature and nitrate, the two forcing variables used in this kelp model, are known to be key drivers for kelp growth (Fram et al., 2008) and physiological performance (Fernández et al., 2020). However, there are other relevant physical and ecological drivers of biomass in natural kelp stands such as wave disturbance and urchin herbivory (Lafferty, 2004; Reed et al., 2011; Bell et al., 2015) that were not considered, because they likely play far less important roles in aquaculture with appropriate management and site selection. To validate this model, both observations and model outputs (yield in tons) were analyzed in terms of their consistency with the climate of the region (see Kelp Model Validation appendix)).

In this model, outplant occurs on January 1st starting from an initial outplant of 126,000 sporophytes with 100 g of individual weight approximately (see Table 8). Biomass is computed in a quarterly time step according to surface seawater nitrate concentration and temperature during each quarter. Harvest occurs on December 31 each year so the complete cultivation cycle lasts 12 months.

Historical Reconstruction and Variability Analysis

The fish and kelp models were run yearly from 1981 to 2017 with the observed environmental forcing across the region. This historical reconstruction of production generates a 3D matrix of 223 sites and 36 years. Basic spatial statistics including spatial mean, standard deviation and std/mean ratio were performed to get an initial diagnosis of the domain variability in production. We then used empirical orthogonal functions (EOF) and principal components (PC) analysis, a technique commonly used in climate science (Lorenz, 1956; Radiarta et al., 2008; Deser et al., 2009) to extract the main spatial and temporal components of variability in aquaculture production.

SST Transfer Function Model

To understand how low frequency and high frequency climate processes are being incorporated by the farmed species, we developed a simple auto regressive model type 1 (AR1) or transfer function. This method provides more accurate correlations with SSTa and climate trends of the Pacific than only using principal components, because it considers all variability that is being transferred into growth during the cultivation period.

A first step was to find the physical forcing pattern that best matches with the PCs of production. There will be an inherent time lag between forcing and aquaculture production because species' growth is integrating climate variability over time. This pattern of variability or lag is used to set the temporal memory of the AR1 model. We use the forcing pattern with the highest match to correlate with the production PC1 and projected to obtain its temporal index. The index is then incorporated in the AR1 model or transfer function by the equations:

$$\mathrm{dFISH(t)/dt = SST\_forcing(t)\ - Fish/18\ m} \qquad \text{Eq. (5)}$$

$$\mathrm{dKELP(t)/dt = SST\_forcing(t)\ - Kelp/12\ m} \qquad \text{Eq. (6)}$$

where: SST_Forcing (t) is the correlation pattern of best SST Forcing pattern(t) and the PC1 of production compacted in a single vector (index) of production, divided by the length of the farming cycle ‘damping’ function (18 months for fish or 12 months for kelp).

Correlation with Climate trends

Resulting AR1 model outputs are correlated with the most important modes of climate variability of the North Pacific: ENSO, PDO, and NPGO (http://www.o3d.org/npgo/) (Jacox et al., 2019). Because the progression of the climate trends is sequenced (Xu et al., 2021), we also explored the correlation with the AR1 model outputs with a 1 year lead to account for this evolution.

Net Present Value

Net present value (NPV) calculations were added as a bioeconomic component to understand the profitability of the farms using the historic time series of production. We used the same NPV equation used in Chapter I (Equation 1) to indicate if the farm recovered the initial investment and was profitable over a 10-year horizon. The NPV calculation is done every year. NPV for 1982 uses the estimated production of the years 1982 to 1992, and the next NPV uses 1983 to 1993 estimated productions, and so on. Although the biological model runs for 12 months, the economic model for kelp adjusts costs to the time of maximum yield in the year. For example, if the maximum yield occurs in the second quarter of the year, the farm only runs until the second quarter because the kelp model does not increase yield beyond that date. The most productive sites keep production growing until the end of the year, so the cost model keeps the costs running all year round. Final NPVs at the end of the 10 years were used to rank sites based on economic value. Details on investments amounts and other economic parameters are listed in Table 7 and Table 8.

Ordinal Site Selection (Ranking)

An overview of production time series shows that, in both species, all sites respond to climate variability similarly, and they have parallel patterns of variation (Figure 17b). This result suggests that the most productive regions are the most resilient, and that moving to another region in ‘bad’ years is not a good strategy to counter variability.

We designed a ranking system to increase resolution within regions as a means to visualize site to site differences in variability. Aquaculture sites were ordered from best to worst in an ordinal ranking system. Every year, an ordinal number was assigned to each site based on its performance with respect to the other sites. For example, the site with most production will have the 1st place in this ranking for that particular year, but it could be that the same site ranks far lower in the next year. At the end of the studied period (1980 -2017) we obtain 36 ordinal numbers for each site, which is the length of the studied period. We then averaged across the full time series to obtain a final ranking. This final ranking is a practical indicator of site performance along the period of study and gives relevant information for investments and site selection from the standpoint of picking a site.

We developed two rankings to identify best sites for kelp and fish: one based on production (tons of aquaculture biomass) and a second one for NPV (Millions of US dollars). Having two separate rankings helps to identify differences between production and economic feasibility. Such differences could be due to distance from port or growth rates.

C. Results

Spatial Statistics

Optimal areas for kelp farming are found in the northern region of the SCB, whereas fish grows better in the south. These general spatial patterns are consistent with the results of Lester et al. (2018), although our results show a broader array of good sites for fish in the center region as well. Mean fish production of the area between 1981-2016 is 971 tons and southern farms produce around 800 tons more than the northern farms. Standard deviation is between 100-200 tons. Production means of fish are large compared to their standard deviations, so ratios indicate production along the studied timeline is quite stable (15-20% ratio). Mean kelp production of the period 1982-2017 is ~800 tons, but only the northern region is productive. Kelp production in the northern region fluctuates about 200 tons across years. Kelp production ratios are unstable in transitional areas (Figure 12).

Empirical Orthogonal Functions / Principal Components

Spatial EOF maps show areas with most significant variation towards the south for fish and in the north for kelp (Figure 13). A notable feature in the fish PC1 is that production in years 2000 to 2010 is lower than the previous decades. Kelp PC1 does not show a particular decadal behavior, but production increases considerably in years 2000 to 2010, by contrast to the behavior of the fish production in the same decade. These production differences might be associated with cold or warmer phases of decadal variability in the region. First principal components of both species captured anomalous conditions around years 2014-2015 possibly as a result of the marine heat wave nicknamed ‘The Blob’. During these years, reported sea surface temperatures in the NE Pacific (Alaska to California) were about 2.5 – 4 °C above mean (Bond et al., 2015; Zhu et al., 2017) and its impacts remained until 2016 (CalCOFI, 2016). These anomalous conditions explain the considerable peak in fish production while kelp shows a drastic drop, as shown in their PC1.

Detrimental temperature in the kelp model was set to 21 ºC and nitrate was near zero at ~ 17ºC. For the fish model, detrimental temperature was set at 26 ºC according to reported range temperatures for this species (Davis, 2004). Temperatures of > 26 ºC were reached in the environmental data used, but just in a single month and in a single location (July, 2016, site 147 located at the southern portion of the SCB). However, this was a single mortality event which did not have impact in the climate analysis.

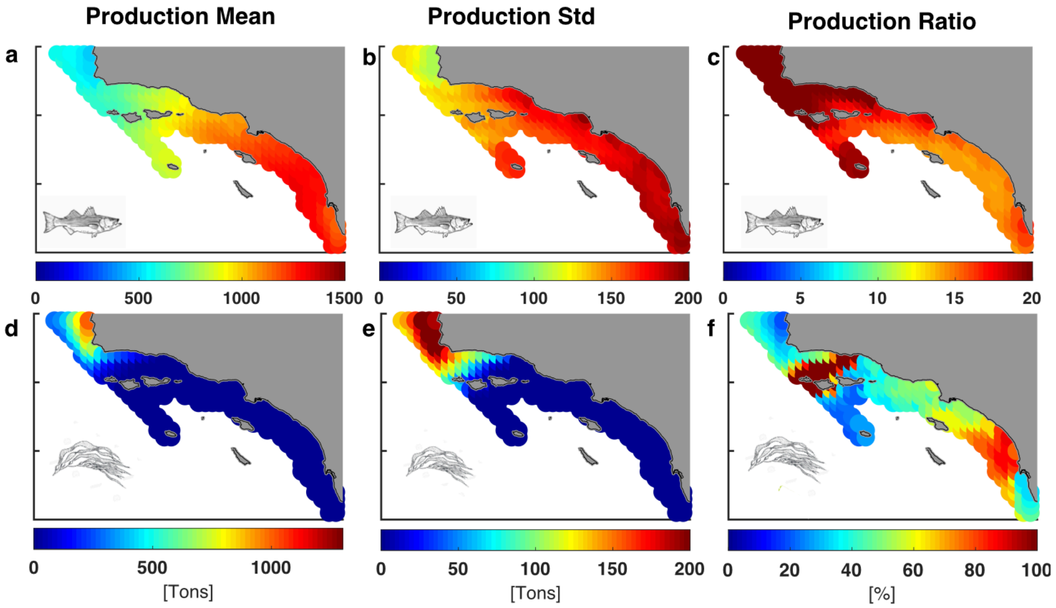

Figure 12. Spatial statistics of fish and kelp production. Mean production, standard deviation, Ratio of fish production (tons) for fish (a, b, c, respectively, time period: 1981-2016) and kelp farms (d, e, f, time period: 1982-2017).

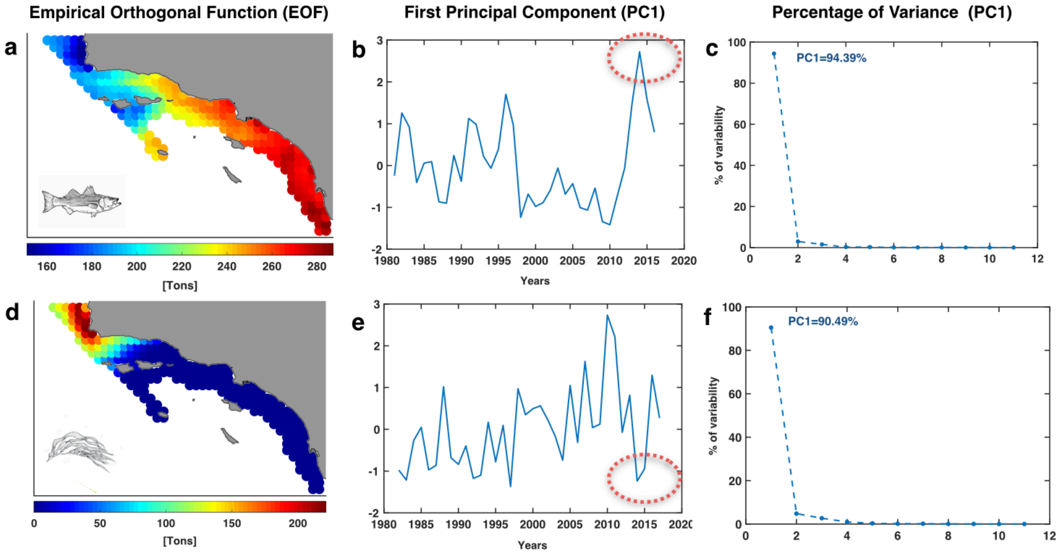

Figure 13. Empirical orthogonal functions and Principal Components. First empirical orthogonal functions (EOF1) spatial map (a, d) first principal component (PC1) (b, e), red dashed circle indicates approximate dates of The Blob marine heatwave. Percentage of variance explained by PC1 of fish and kelp production (c, f, 94.39% and 90.49% respectively).

Transfer function

Correlation between fish and kelp principal components and Pacific SST shows a very similar pattern (Figure 14 a, d) and time series (Figure 14 b, e) in both species, only being different by the sign given kelp shows sensitivity to colder temperatures. These patterns show that both fish and kelp are sensitive to the same type of low frequency variability of the Pacific Basin. However, this low frequency is integrated into biomass in slightly different ways. During the development of the transfer function, the temporal pattern with most correlation was the one with 1 month lag for kelp and a 9 months lag for fish. This indicates that kelp is more sensitive to interannual variation and has less memory from 1 year to the next, while the fish has more memory so it shows a lagged response. When these patterns are incorporated to the AR1 model, they produce different time series because of these disparate time integrations.

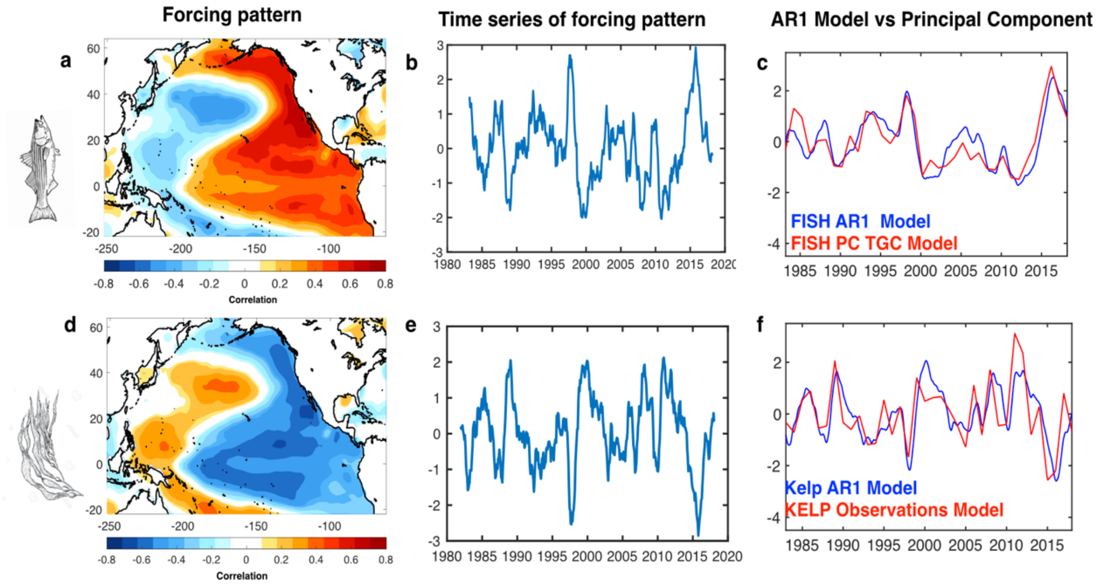

Figure 14. Development of AR1 model. Maps of forcing patterns of correlation first principal components of production (PC1) vs SST of the Pacific Basin (a, d). Time series index of forcing pattern (b, e) and temperature transfer function (AR1) model vs first principal components of production (c, f).

Climate trends

Correlation of AR1 vs the climate indices is high and significant for both PDO and NPGO in fish. PDO is also relevant for kelp, but given that kelp responds to higher frequency variation, the interannual component of ENSO becomes more important (Figure 15b). Although at different proportions, fish and kelp AR1 time series have strong correlation with low frequency variability of the North Pacific. Low frequency variability in this region has contributions from the different climate modes used in this analysis: PDO, NPGO, ENSO (Di Lorenzo et al., 2015).

AR1 of both species are capturing the contribution of all these different modes at different phases and times also because they are not independent. NPGO and the PDO are connected with a 1 year lead, with NGPO typically leading the cycle (Joh et al., 2017). When adding a 1 year lead (-365 days) to the AR1 models the NPGO becomes the most important climate trend for both species (Figure 13b). While all the climate trends incorporated in this analysis: PDO, NPGO, ENSO are relevant in the climate of the North Pacific (Chenillat et al., 2012) the NPGO strongly impacts the nutrient dynamics at latitudes of the region of study (Di Lorenzo et al., 2008; Di Lorenzo et al., 2009; King et al., 2011).

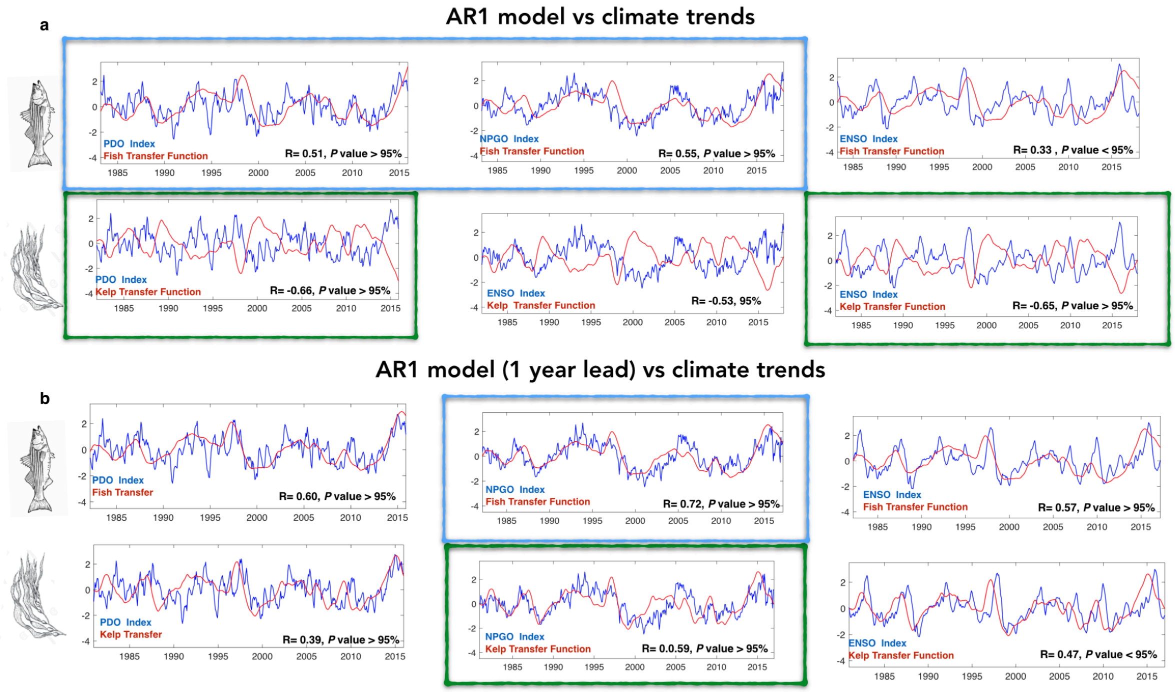

Figure 15. Transfer function for fish and kelp production vs climate indexes relevant for the Pacific. Pacific Decadal Oscillation (PDO), North Pacific Gyre Oscillation (NPGO) and El Nino Southern Oscillation (ENSO) (a) and with 1 year lead (b)

Net Present Value (NPV)

As in Chapter I, 10 years NPV horizons that overlapped negative and positive phases of the NPGO were analyzed to see economic impact. NPV calculations tend to smooth out variability, because it incorporates 10 years of production in a final NPV value. The 10-year horizons show that periods of negative and positive phases of the NPGO can have considerable impact over profits. Figure 16 shows how negative (1990-2000) NPGO results in higher profits for fish given increased temperatures, while decreased upwelling and therefore nitrate availability decreases profitability for kelp farms. During the positive phase (1997-2007) the inverse happens.

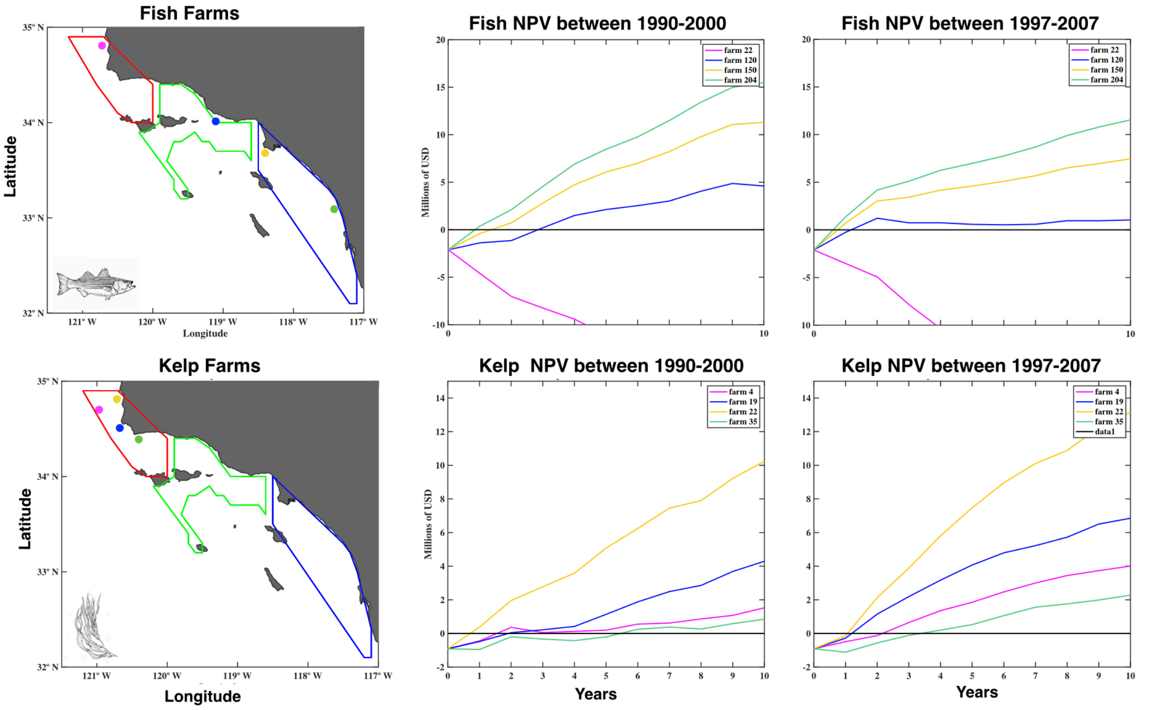

Figure 16. 10-year NPV horizons for fish and kelp.NPV 10- year horizons for fish and kelp calculated for production during periods of negative (1990-2000) and positive (1997-2007) phases of the NPGO. Each horizontal line represents a site, strategically chosen to show spatial differences. Color of horizontal lines correspond to colored points (sites) in the map.

Ranking

Similar to the previous analysis, the spatial maps of the ranking show very well defined areas of differential production: North, Central and South. Best sites for kelp are restricted to the North portion of the SCB, while for fish the highest production happens in the South because of warmer temperatures which is congruent with the MSP work done by Lester et al 2018. By looking at the best to worst ordinal plots we see that both species medians happened toward the minimum values (Figure 17 c, d). One of the differences in rankings between both species is that kelp's best sites are more extreme outliers relative to the patterns for fish. The slope of the rankings is far steeper for kelp sites compared to more gradual declines for site rankings of fish. This indicates that a focus on site selection is likely more important for kelp aquaculture than for fish aquaculture. Interannual variability in rankings of sites by NPV is smaller than for production, because 10 years of production are integrated into annual site rankings. Since NPV rankings also includes issues other than site to site variation in production (e.g., costs due to distance from ports) the order of site rankings differ somewhat.

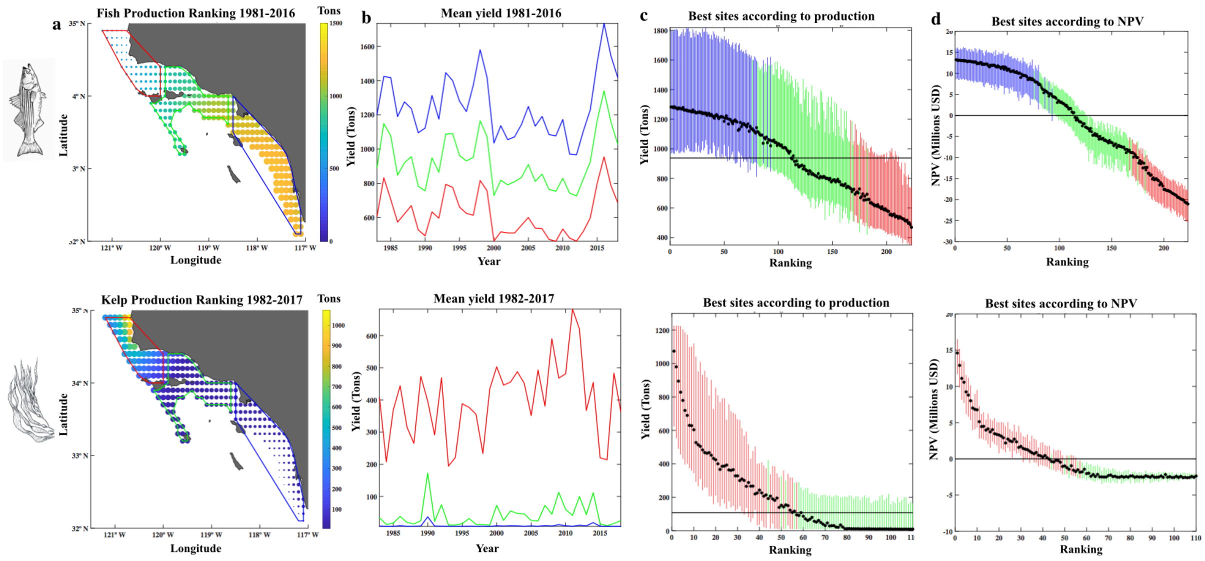

Figure 17. Fish and kelp production rankings by region. (a)Spatial maps of mean production ranking. Color bar show production and size of marker indicates position in ranking. Color polygons show regions: red = Northern Region, green Central Region, blue = Southern Region. (b) Mean production time series by region. Color corresponds with each region. (c) Ordinal ranking plot for sites: x axis indicates ranking going from best to worst (1 to 223). Black dot is the median in production along the period of study. Color vertical lines indicate maximum and minimums in production and color corresponds with each region. Horizontal line is the mean ranking. All sites above the line are considered best. (d) Ordinal ranking using 10 year NPV along the analyzed timeline

D. Discussion

Climate variability.

The application of the AR-1 model to our historical hindcast of aquaculture production illustrates that variability in the physics is expressed differently in fish and kelp because of the differing ways such taxa are affected by climate forcing. Fish show a 9 month lag, which creates a longer memory that integrates all forcing during that time. By contrast, kelp only had a 1 month lag, because its growth is more sensitive to higher frequency variability. Functional physiologies (Froehlich et al., 2016) and life spans of these species contribute to these differences as well.

According to our results, decadal variability seems to be the most relevant driver of modeled aquaculture production both fish and kelp in the SCB. PDO and NPGO promote deepening of the mixed layer depth and delivery of nutrients to the euphotic zone (Nezlin et al., 2017) . Positive (cold) phases of the NPGO favor upwelling and availability of nutrients for kelp in both wild populations (Cavanaugh et al., 2011) and aquaculture (Snyder et al., 2020). Conversely, negative NPGO phases correspond to warmer waters, which stimulate fish growth rates in farms. This association of higher fish productivity in warmer phases of the NPGO for aquaculture contrasts with patterns in wild fish populations, because colder phases of the NPGO promote upwelling that enhances the availability of pray for fish (Sydeman et al., 2013).

ENSO teleconnections also influence SST and nutrient availability in the SCB (Fagan et al., 2019) and precipitation (Cayan et al., 1999; Du et al., 2020). Runoff is a source of nitrogen in the area (McPhee-Shaw et al., 2007), although less relevant than upwelling (Howard, 2014). In addition, decadal variability (NPGO, PDO) was more dominant than interannual variability (ENSO) according to our results.

Implications for site selection

Our results are consistent with Lester et al. (2018) finding most productive areas for kelp in the north, and fish production higher in the south. In addition, we found that the most productive zones remain being more productive despite environmental variability (Sainz et al., 2019). These results highlight the value of spatial planning to increase resilience of aquaculture farms in a variable environment.

According to the rankings, kelp is more sensitive to environmental forcing and this is reflected through higher variability among sites. Local dynamics of the sites such as internal waves could mark a big difference in kelp forest particularly during seasons of nitrate scarcity (Fram et al., 2008; Brzezinski, 2013). Fish farms seem to have a more homogeneous distribution of ranks than kelp, perhaps due to their dependance on temperature only. It is possible that increasing the number of forcing variables will change the distribution in the ranking. For example, current velocities are relevant for fish swimming performance and health (Hvas et al., 2018; Yuen et al., 2019; Allen et al., 2021).

Despite the high productivities of fish towards the south region, increased temperatures can influence recurrence of harmful algal blooms (HABs) (Moore et al., 2008; Gobler et al., 2017; Trainer et al., 2020) and hypoxia (Levin et al., 2015; Howard et al., 2020) events which were not including in this analysis. Given the our framework is a historical reconstruction, incorporating past hypoxia and HAB events could be interesting when contextualized with the climate variability of the region. For example, positive phases of the NPGO can be beneficial for mussels and kelp productivity, but upwelling has been linked to the shoaling of hypoxic waters in the SCB and northern regions (Low et al., 2021) and past domoic acid events in the Santa Barbara Channel (Sekula-Wood et al., 2011). HAB monitoring systems and forecast models are key tools to incorporate possible impacts in the aquaculture and fishing industries particularly in a future warmer marine environment (Anderson et al., 2021).

E. Conclusions.

The NPGO is known to have important implications for the climate and biology of the California Current System, in particular near SCB (Di Lorenzo et al., 2008). Positive (high upwelling) phases of the NPGO can have a big impact on the productivity of aquaculture farms, particularly for filter feeders.

Key differences between fish and kelp imply that fish are more resilient to climate variability, but our analysis assumes no limitations in food, conflicts with other uses of the space, and impacts related to hypoxia, HABs or parasitism. In addition, striped bass, our model species, has a very wide thermal range (Cook et al., 2006) with juveniles preferring warm thermal niches of 24 to 28 º C (Coutant, 1990), and thrives in temperatures reported for this region in sea cage aquaculture farms (Del Rio-Zaragoza et al., 2021). Given that giant kelp seems to be more sensitive to environmental variability, environmental monitoring systems can increase kelp aquaculture's resilience and even help to optimize productivity (Snyder et al., 2020).

Marine aquaculture in other regions might be impacted by climate variability differently than this case study. For example, ENSO might have more relevance to regions closer to tropical latitudes. In addition, climate change is known to modify the norm of the regional climate including the California Current system (Di Lorenzo et al., 2010; King et al., 2011; Sydeman et al., 2013; Bakun et al., 2015). Future applications of this framework should also consider the impacts of future climate change on these sources of variability.

Our framework confirms the value of marine spatial planning for aquaculture given that, for this particular region and the species used, most productive sites are also the most resilient to climate variability. Although the generality of this finding needs exploration in other settings, in the SCB good sites remain good and bad sites continue to be bad across decades of variation. Whether this relative consistency of rankings persists in the face of future climate change remains to be evaluated.

F. Supplemental Information

Table 7. Fish farm configuration, biological and economic parameters

Fish Farm Characteristics			
Description	Value	Unit	Source
Number of Cages	16	units	Thomas et al. (2019)
Cage radius	15	m	acuasesor.conapesca.gob.mx
Cage depth	14	m	acuasesor.conapesca.gob.mx
Volume per cage	9896.02	m3	acuasesor.conapesca.gob.mx
Stocking density	98960	Fish/cage	Besson et al. 2016
Total Stocking Fish per farm	1583360	individuals	Calculated in this study
Harvest Density	20	Kg/m3	acuasesor.conapesca.gob.mx
Estimated Total Yield	variable	tons	Calculated in this study
Fish Biological model input			
Description	Value	Unit	Value
Initial fish Weight	20	[g]	Lester et al. 2018
Final fish Weight	2000	[g]	Calculated in this study
Max biological weight	57	[kg]	fishbase.org
Thermal Growth Coefficient	0.0010053	[g/ºC]	Calculated in this study
1-b	1/3	[dimensionless]	Mayer et al., 2008
Growth period length	540	[days]	pacificoaquaculture.com
Mortality	10	%	Besson et al. (2016)
Fish optimal temperature	24	[ºC]	Davis (2004)
Min. temperature[2]	8	[ºC]	Davis, 2005
Max. temperature[3]	26	[ºC]	Davis, 2004
Mean daily temperature	variable	[ºC]	UCSC Reanalysis data
Fish Economic model input			
Description	Value	Unit	Source
Growth period / work days	540	[days]	pacificoaquaculture.com
Discount rate	0.0876	[dimensionless]	Ruiz-Campo & Zuñiga-Lara, 2017
Cage cost (cage and machinery)	68750	[usd]	Pers. Comm. Industry
Boat cost (2 boats)	1,000,000	[usd]	grandseaboat.en.made-in-china.com
Permits	10000	[usd]	greenwave.org
Wage payroll	12	[usd]	Min. wage California, as of 2019
Daily work hours	12	[hours]	Calculated in this study

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[2] Minimal temperature when fish stops eating. Fish dies after 14 days of not eating.

[3] Max. temperature when fish stops eating and is stressed. Fish will die after 5 days of not eating.

Number of employees	40	[units]	Thomas et al. (2019)
Gas cost	1	[usd/L]	psmfc.org
Mean boat speed	12.8	[km/h]	Lester et al. 2018
Boat efficiency	60	[L/h]	Lester et al. 2018
Cage maintenance	6,899	[usd]/m3	Rubino, 2018
Boat maintenance	30,000	[usd]	Rubino, 2018
Juvenile cost	1.5	[usd/plants]	Thomas et al. 2019
Food cost	2	[usd/kg]	skrettingusa.com
Food convertion rate	500	[dimensionless]	calculated in this study
Management cost per kg	1	[usd/kg]	calculated in this study
Gate price	5	[usd/kg]	capecodtimes.com

Table 8. Kelp farm configuration, biological and economic parameters
NOTE: Despite the biological model runs for 12 months, the economic model for kelp adjusts costs to the time of maximum yield in the year. For example, if the maximum yield happens in the second quarter of the year, the farm only runs until the second quarter because the kelp model does not increase yield beyond that date. The most productive sites keep production growing until the end of the year, so the cost model keeps the costs running all year round.

Kelp Farm Characteristics			
Description	Value	Unit	Source
Number of longlines	600	Longlines	Based on Lester et al., 2018
Longline length	210	m	Lester et al., 2018
Separation between Longlines	2	m	Lester et al., 2018
Initial weight per plant	100	g	Based on Celis Plá et al. (2012)
Total individuals	126,000	plants	Calculated in this study
Final individual weight	10	kg	Correa et al. (2016)
Final density	~10	Kg/m	Camus et al. (2019)
Final total weight	1260	Tons/year	Variable (calculated)
Kelp Biological model inputs			
Description	Value	Unit	Source
Sea Surface Temperature	variable	C	UCSC Reanalysis
Nitrate proxy	variable	µmol L-1	Snyder et al., 2020
Detrimental Temperature	21	C	Cavanaugh et al. 2019
Starting biomass percentage	0.2	%	Calculated in this study
Cultivation period length	12	months	Calculated in this study
Kelp Economic model inputs			
Description	Value	Unit	Source
Wet weight	Variable	kg	Calculated in this study
Discount rate	0.0807	dimensionless	Ruiz Campo et al. (2018)
Initial investment	910,000	USD	Based on Lester et al 2018, and Froehlich et al. 2019

Fixed costs	126,000	USD	Based on Lester et al 2018, hatchery
Variable costs:			
Growth Period/work days	Variable	Months	Calculated in this study
Wage payroll	12	USD/hr	Minimum wage California as of 2019
Daily work hours	12	hours	Calculated in this study
Number of employees	10		Calculated in this study
Gas cost	1.1	USD/L	psmfc.org
Mean boat speed	12.8	Km/h	Lester et al., 2018
Boat efficiency	60	L/h	Lester et al., 2018
Gate price	3	USD/kg	Lester et al., 2018

Kelp Model Validation appendix

To validate the kelp model, we compared Landsat pixel biomass with biomass outputs of the model (Figure 18). The model does not take wave disturbance or other processes, such as herbivory, into account as these would likely differ in the farm environment compared to a natural kelp forest. This explains the differences between both time series. However, standardized means of kelp observations vs kelp model outputs, and their probability distributions (PDFs) show consistency (Figure 19).

Finally, we used standardized means as indexes of production and correlated each of them with SST data of the Pacific (NOAA, cite). Figure 20 shows that both modeled and observed biomass have a similar correlation pattern, which suggest observed data behave similarly to modeled outputs.

Kelp forests in Sothern California, are influenced by large scale patterns (NPGO, PDO) but they are also very susceptible to coastal local dynamics such as wave height, local upwelling and ecological dynamics (urchin barrens) (Harrold et al., 1985; Lafferty, 2004; Bell et al., 2015) . Given that farms do not have the same ecological limitations of a natural forest, physical forcing should be the primary driver of production.

Temperature is a good indicator of nitrate in the SCB (Zimmerman et al., 1984) and we used the most up to date temperature to nitrate data (Snyder et al., 2020). However, advection is known to have big influence in transport of superficial waters potentially affecting temperature to nitrate measurements, particularly towards southern region of the SCB (Di Lorenzo et al., 2005). Similarly, other sources such as internal waves and runoff should be explored as these are known to provide nutrients to kelp forest in this area (Brzezinski, 2013).

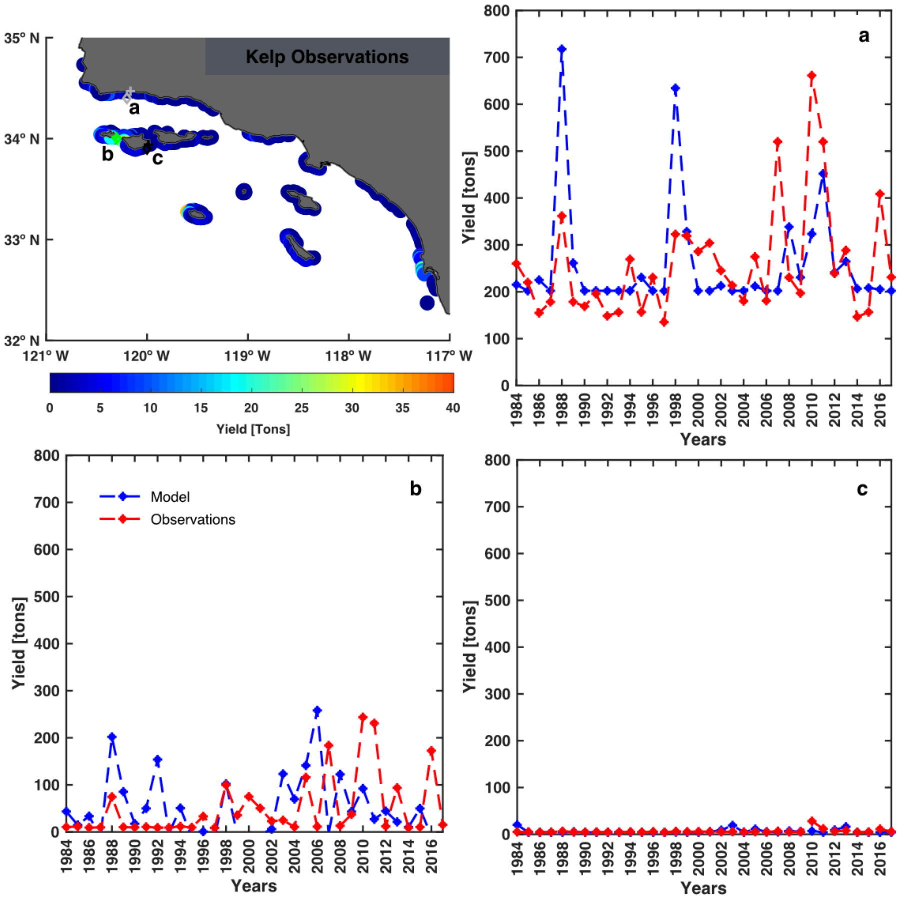


Figure 18. Time series of kelp observations vs kelp model outputs. Map of kelp observations along the SCB and comparison between model (blue dashed line) and observations (red dashed line) at different locations (a)(b)(c).

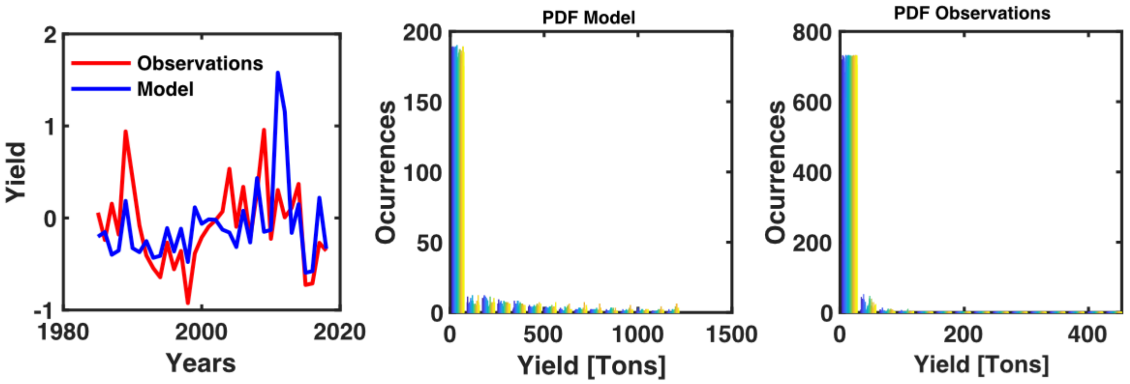


Figure 19. Standardized means of kelp observations vs model outputs and pdf distributions

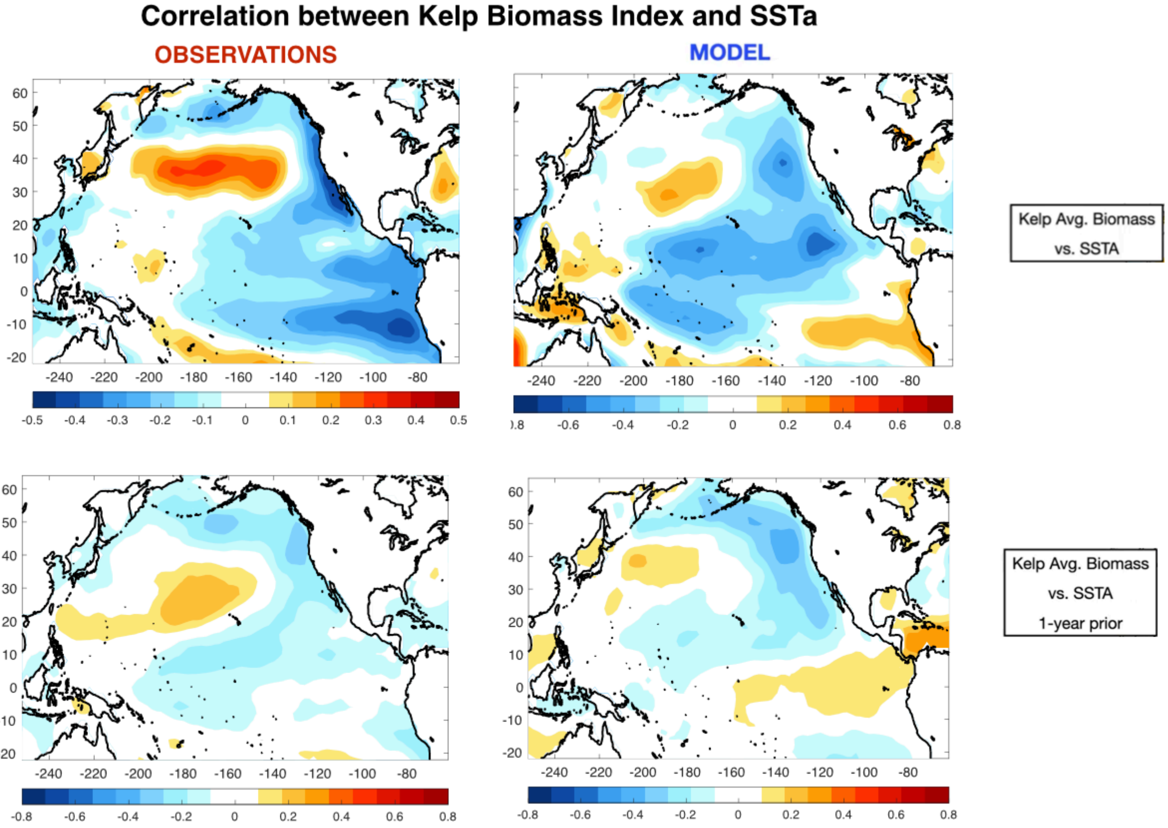


Figure 20. Correlation between SSTa with kelp biomass and model output indexes. Large scale climate patterns in both kelp biomass and model predictions are consistent and respond to similar large scale climate drivers and show typical patterns of Pacific decadal variability.

III. Marine Spatial Planning of Aquaculture in the Southern California Bight based on Future Climate Projections.

A. Introduction

Marine aquaculture is projected to be one of the most efficient food systems in terms of carbon emissions (Ray et al., 2019; MacLeod et al., 2020) and ecosystem interactions if planned properly (Alleway et al., 2019; Clavelle et al., 2019). The sustainable expansion of marine aquaculture will depend on adequate planning and regulatory frameworks (Couture et al., 2021). Incorporating climate change into marine spatial planning of aquaculture increases resilience and adaptation capacity of this industry (Gentry et al., 2017; Grebe et al., 2019) and aligns marine aquaculture with the Sustainable Development Goals, including food security (FAO, 2017).

Climate change due to anthropogenic emissions is already impacting the oceans and it will continue being a big challenge for marine ecosystems management, including food production (IPCC, 2019). As in many other sectors of ocean food production, including fisheries (Cheung et al., 2010; Lam et al., 2016) and biodiversity (Doney et al., 2012; Pecl et al., 2017), global studies on marine aquaculture under climate change indicate that, as a general guide, tropical regions will mostly decrease their production potential given lower latitudes will be more vulnerable by intolerable temperatures and decreased primary productivity, while temperate regions will have a considerable increase in production potential (Handisyde et al., 2006; Klinger et al., 2017) although the impacts of disruptions in upwelling systems located in these latitudes (e.g. the California Current) over ecosystem dynamics and primary production are still difficult to understand (Xiu et al., 2018) and impacts over coastal dynamics are uncertain (García-Reyes et al., 2015). In terms of species, potential for finfish aquaculture expands compared to filter feeders towards the end of the century at a global scale (Froehlich et al., 2018). Marine aquaculture of finfish might be limited by its reliance on fishmeal (Naylor et al., 2005) although development of alternative feeds and improved fisheries management could offset this limitation (Merino et al., 2012).

In a parallel yet slightly different situation than fisheries in the move, “climate change will affect where mariculture development can take place” (Kapetsky, 2013). Modeling work suggests that optimal areas for aquaculture will move geographically (Sarà et al., 2018) which highlights the need to move from static towards adaptive marine spatial frameworks, capable of incorporate the non-linear nature of a changing climate (Craig, 2019).

Each region has a different set of challenges in the face of climate change, depending on exposure and adaptation capacities (Brugere, 2015). Extreme events already happening around the world give a glimpse of what is expected to happen under future climate change (Brander et al., 2017). In the California Current System (CCS) acidification events caused massive oyster larvae die offs in Washington State (Clements et al., 2017), and marine heatwaves that persisted between 2013 to 2015 generated a hotspot area for Pseudo-*nitzschia* harmful algal blooms (HABs) in Northern California (Trainer et al., 2020).

Studies at regional scale help to develop possible scenarios and adaptation/mitigation strategies for aquaculture on a case by case basis. The coarse resolution of climate change projections (1 °C) makes it difficult to evaluate the impacts of climate change at a higher scale. If available, downscaled climate products coupled with aquaculture end-to-end models allow scenario building and provide relevant information for spatial and risk management (Filgueira et al., 2014; Guyondet et al., 2015; Matzelle et al., 2015; Hobday et al., 2016).

Available literature focuses on future trends in aquaculture production under climate change. For example, Froehlich et al. (2018) maps aquaculture production of finfish and bivalves identifying areas with increased and declining potential. Klinger et al. (2017) analyses changes in potential for finfish with different thermal ranges. Climate change is modifying the variance in internal variability patterns (Sydeman et al., 2013; Bonino et al., 2019) and the incidence of extreme events (IPCC, 2019). Despite studies have highlighted the relevance of climate variability for aquaculture spatial management and site selection (Liu et al., 2013; Sainz et al., 2019) the relationship between future productivity of aquaculture and changes in variance of regional variability is not clear.

The aim of this study is to understand how climate change will influence spatial planning and site selection at a regional scale, in the Southern California Bight (SCB). We test three aquaculture species of interest: giant kelp (*Macrosystis pyrifera*) striped bass (*Morone saxatilis*) and Mediterranean mussels (*Mytilus galloprovincialis*) (henceforth kelp, fish and mussels, respectively) using three separate models for each species, coupled with downscaled climate change projections. We compare projected changes in aquaculture productivity, spatial patterns, and account for variability fluctuations and their effects on spatial management and site selection.

Climate Change in the Southern California Bight

The Southern California Bight (SCB) has gained a lot of interest for aquaculture development and has been selected as one of the first Aquaculture Opportunity Areas to develop sustainable aquaculture in the United States of America (NOAA, 2020). However, ongoing and future farm projects could be susceptible to the risks imposed by climate variability and change projected for this region.

The SCB is biogeographic region located towards the south of the California Current System, one of the most productive regions due to Ekman coastal upwelling characteristic of the Eastern Boundary Upwelling Systems (EBUS) (Iles et al., 2012; Stone et al., 2020). In the SCB, delimited by Point Conception in the north and Punta Colonet in the south (Fumo et al., 2020), cooler equatorward waters of the California Current start mixing with warmer waters of the California Undercurrent (Lynn et al., 1990; Snyder et al., 2003) generating an area of sharp biophysical transition (Harms et al., 1998).

The SCB has shown signs of biological declines due to changes in oceanographic conditions, including phytoplankton concentration and different species composition (Bograd et al., 2015) and zooplankton declines due to warming surface waters by 1.5 ºC (Roemmich et al., 1995). However, these changes have been largely attributed to regime shift and decadal variability instead of anthropogenic climate change (Holbrook et al., 1997; Di Lorenzo et al., 2005; Kim et al., 2007).

It is expected that in the California Current System the increased temperature gradient between the land and ocean due to anthropogenic warming will influence upwelling (Bakun et al., 2015). In the SCB, future upwelling could be more intense during upwelling seasons, but upwelling may be decreased in other seasons (Snyder et al., 2003) and during short upwelling events (Iles et al., 2012). Increased stratification might also be a risk factor for oxygen depletion, which is an effect already happening in the SCB (Bograd et al., 2008). Although major hotspots for ocean acidification are located in more northern regions of the California

Current, including the Oregon and Washington (Peterson et al., 2017), it expected that the SCB will also experience decreased pH in surface waters (Hauri, 2012). Incidence of marine heatwaves is also expected to increase as a consequence of climate change in the California Current and the SCB (Fumo et al., 2020).

B. Methods

Aquaculture simulation models

Aquaculture models were used to simulate annual production using environmental forcing as model inputs in each of the 223 locations described in previous chapters (Figure 1 and Figure 9). A Dynamic Energetic Budget (DEB) type model is used for Mediterranean mussels (from now on referred as mussels) growth simulation (see Chapter I, Methods), a thermal growth coefficient (TGC) model for striped bass (fish), and a nitrate-temperature curves growth model for giant kelp (kelp) (see Chapter II, Methods).

Environmental forcing

We obtained climate projections of relevant variables from 3 Earth System Models (ESMs) from the CMPI5 project (Taylor, 2012): GFDL-ESM2M, - IPSL-CM5-MR, HADGEM2-ES for the period 1980 – 2100 under the RCP 8.5 pathway (IPCC, 2013). The downscaled ROMS projections forced by these 3 ESMs were developed by Pozo Buil et al. (2021). These projections were used to run our farms on a monthly time step. The resolution of the ROMS data was of 1° x 1°and then interpolated to the 4 x 4 km scale of our farm grid, for the domain of the SCB (32-35 N and -122 -117 W).

Table 9. Environmental forcing for aquaculture models (model projections)

Variable	Unit	Source	Species
Sea surface temperature (SST)	°C	Pacific, ROMS: GFDL, HAD, IPSL	Fish, Kelp, Mussel
Nitrates	10 m from surface, μmol m^{-3}	Pacific, ROMS: GFDL, HAD, IPSL	Kelp
Current speed	cm s^{-1}	ROMS: GFDL, HAD, IPSL	Mussel
Mixed layer depth	m	ROMS: GFDL, HAD, IPSL	Mussel
Particulate Organic Carbon (POC)	mg m^{-3}	LIM model, ROMS: GFDL, HAD, IPSL	Mussel

Particulate Organic Matter (POC) reconstruction (LIM model for POC)

Particulate Organic Matter (POC) is positively correlated to phytoplankton concentrations in the SCB (Miller et al., 2013), and it was used as food for mussels by Lester et al. (2018) so we used POC to force our mussel aquaculture model as well. However, the complete timeline of available POC data was from 1997 to 2020. We developed a linear inverse model (LIM) to reconstruct POC for the complete timeline of our climate projections (1980 – 2100) using the methods published in Xu et al. (2021). The kernel for the LIM model was developed using available POC data gathered from the NASA Ocean Data website at a 4 km resolution (available in: oceandata.sci.gsfc.nasa.gov) and SST data from the NOAA 'Extended Reconstructed Sea Surface Temperature (ERSST)' dataset with a resolution of 2° from 1857 up to June 2018 (Smith et al., 2004).

The LIM model is defined as

$$\frac{d\mathbf{x}}{dt} = \mathbf{Lx} + \boldsymbol{\epsilon} \tag{7}$$

where $\mathbf{L}$ is the dynamical operator, $\boldsymbol{\epsilon}$ is the temporally varying white noise forcing. $\mathbf{x}$ represents the state vector, which in our study is

$$\begin{bmatrix}\mathbf{x}_1(t)\\ \mathbf{x}_2(t)\end{bmatrix},$$

with $\mathbf{x}_1(t)$ the leading principal components of POC anomaly and $\mathbf{x}_2(t)$ the leading principal components of the SST anomaly. Anomalies of POC and SST data were computed as the difference between the seasonal cycle mean and the observed data of the corresponding month (i.e. January – all Januarys mean). To define x we used used 2 PCs of POC, and 15 PCs of SST of the Pacific (140°E to 100° W, 20° to 70° N), which explain 76.43 % and 84.97% of the variance of POC and SST, respectively. The most probable state from (1) is

$$\mathbf{x}(t+\tau) = \mathbf{G}(\tau)\mathbf{x}(t) = \exp\,(\mathbf{L}\tau)\mathbf{x}(t) \tag{8}$$

which therefore represents the ensemble-mean forecast at lead τ. For reconstruction, $\tau = 1$ month. After solving $\mathbf{G}(\tau = 1)$ based on the data from 1997 to 2020, the reconstruction process using the state vector of the century length SSTa is as followed:

$$\begin{bmatrix}\hat{\mathbf{x}}_1(1)\\ \hat{\mathbf{x}}_2(1)\end{bmatrix} = \mathbf{G}(\tau)\begin{bmatrix}\mathbf{0}\\ \mathbf{x}_2(0)\end{bmatrix}, \qquad t = 0 \tag{9}$$

$$\begin{bmatrix}\hat{\mathbf{x}}_1(2)\\ \hat{\mathbf{x}}_2(2)\end{bmatrix} = \mathbf{G}(\tau)\begin{bmatrix}\hat{\mathbf{x}}_1(1)\\ \mathbf{x}_2(1)\end{bmatrix}, \qquad t = 1 \tag{10}$$

$$\dots \tag{11}$$

$$\begin{bmatrix}\hat{\mathbf{x}}_1(T)\\ \hat{\mathbf{x}}_2(T)\end{bmatrix} = \mathbf{G}(\tau)\begin{bmatrix}\hat{\mathbf{x}}_1(T-1)\\ \mathbf{x}_2(T-1)\end{bmatrix}, \qquad t = T-1 \tag{12}$$

Thus, we obtain the reconstructed POC of the century by concatenating $[\hat{\mathbf{x}}_1(1), \hat{\mathbf{x}}_1(2), \dots, \hat{\mathbf{x}}_1(T)]$ and project them back to the EOF space.

To confirm POC is being calculated properly we compared anomalies of POC observations with reconstructed POC:

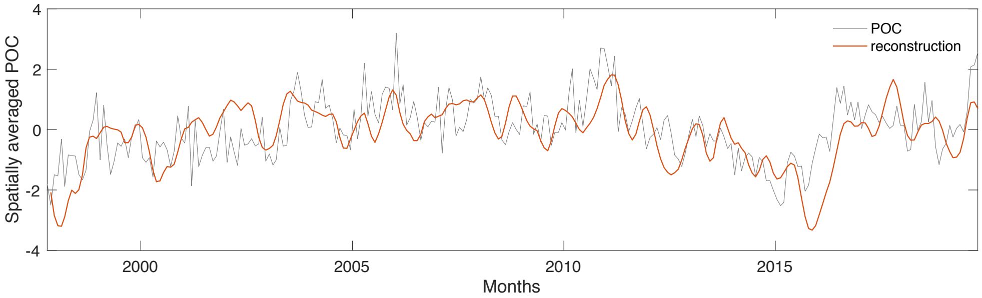


Figure 21. POC reconstruction vs POC observations

We then use the temperature anomalies of high resolution climate change projections (GFDL, HAD, IPSL) to reconstruct POC for the complete time line used in this study (1980 – 2100).

There is no clear trend in available primary productivity for the SCB (Supplemental , and our model proxy for POC does not show a trend (see supplemental Primary productivity trend analysis). However, climate projections indicate a decline in nitrate in the region, which seems to be a logical pathway given POC and nitrate concentrations are often correlated (Martiny et al., 2013). In order to add the trend of nitrates to POC, the trend and amplitude of nitrates of the models (GFDL, HAD, IPSL) was computed for each location of our grid individually to generate a scaling factor that produces an equivalent trend in POC data.

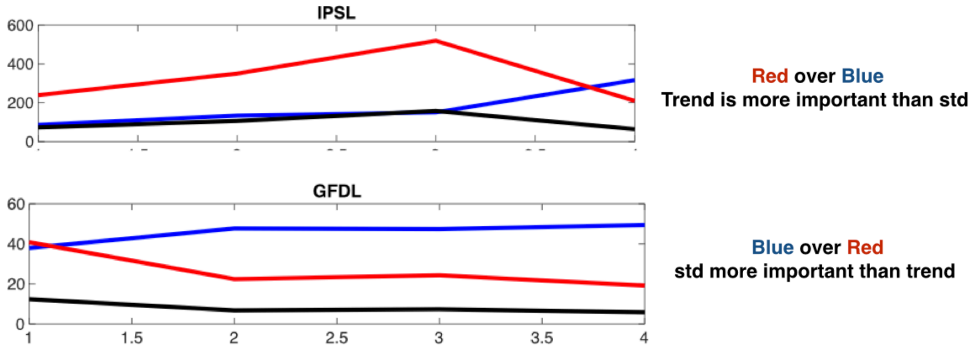
Projections of aquaculture productivity under Climate Change

a. Time series of production and spatial statistics.

The aquaculture models are run with the 3 climate forcing projections separately in each of the 223 locations and for the entire time line of environmental data (1980-2100). The resulting time series are averaged to generate a unique production time series per forcing model (GFDL, HAD or IPSL) to understand differences between them Figure 23. To describe general behavior, we computed an ensemble of the three averaged production time series which is used in the subsequent variability and ranking analysis.

b. Variability and Trend Analysis

Internal variability and trends are components of the climate projections that impact aquaculture productivity. The variability and trend analysis was made to explore the implications of using each factor in spatial planning. The trend is calculated for each 30-year period (e.g. 1980-2010, 2011-2040, 2041-2070, 2071-2100). The standard deviation of the mean production (detrended) of each period was computed and contrasted vs the net change difference between the end point and initial point of the trend (blue and red lines respectively in example in Figure 22). When the red curve is above the blue curve, it means that trend is more important than the variability. Such simple analyses can help farmers to understand what they should worry about, either the trends in production or the expected interannual variability during a selected time period.



Red over Blue
Trend is more important than std

Blue over Red
std more important than trend

Figure 22. Example relevance of trend vs variability.

As described in Chapters I and II, Empirical orthogonal functions (EOF) and principal components (PC) for the production of the 3 species were calculated by each model separately (GFDL, IPSL, HAD) therefore obtaining 3 EOFs and 3 PCs of production for each species.

c. Ranking

The ranking was calculated for production using a mean ensemble of the three production time series (using GFDL, IPSL, and HAD data) and a second ranking using an ensemble of net present values projected for 10 years for the time period (1980 – 2100). See Methods, Chapter II, for description of the ranking system.

C. RESULTS

Production time series

Figure 23 shows the mean time series of aquaculture production of all of the farms, using each model forcing separately (GFDL, IPSL, HAD) and an ensemble of them. Fish production has an upward trend for all of the individual forcing models. Since the fish aquaculture model only uses temperature, the model accurately follows the increasing trend in temperature. GFDL data have a less pronounced trend compared to IPSL and HAD, but all of the three projections show an increase in variability towards the second half of the century.

Kelp production shows significant differences between climate forcing models. In two of the models (HAD and IPSL) the two forcing variables that feed the kelp model (temperature and nitrates) have a decreasing trend (Figure 23), although the declines are less pronounced in nitrates. Historical patterns suggest resilience of kelp forests to heatwaves, as long as nitrate is not scarce (Fernández et al., 2020; Schmid et al., 2020). In a sensitivity analysis performed for the kelp model nitrate showed the most impact in kelp growth. Nitrate dynamics are different in each of the climate models, and slight differences in nitrate concentrations explain the significant differences in kelp production when using one forcing or the other.

Mussel mean time series show a decreasing trend in production similar to the pattern of POC forcing. However, production time series using GFDL, IPSL or HAD forcing are not substantially different in magnitude and show similar behavior in both trend and variability.

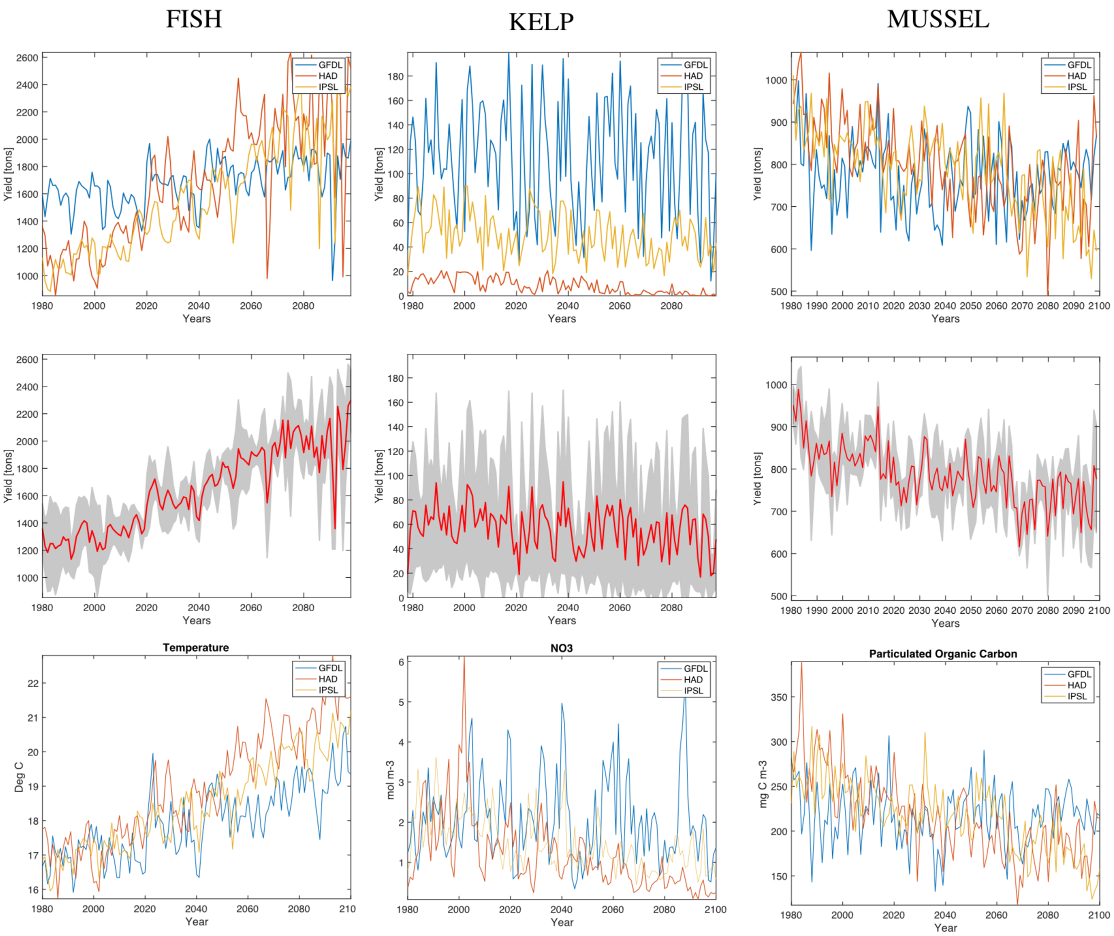


Figure 23. Mean time series of production 1980-2100. Top three figures show each individual model and middle three figures show ensemble mean. Gray shadow is std of all three curves. Bottom three figures show time series of most relevant forcing by individual model.

Relevance of variability vs trend

As observed in the time series analysis (Figure 23), trends in the forcing help to explain the trends in aquaculture production. However, these time series show a variability component that can also be relevant. Figure 24 (panels a, b, c) show a principal component ensemble (averaged principal components of the 3 models, amplitude shown in the dashed lines) in blue, and the trend calculated for periods of 30 years. Each 30-year period shows that the trends are mostly decreasing for kelp and mussel, or increasing in case of the fish.

According to the relevance of trend vs. variability plots (Figure 24 d, e, f), the increasing trend is most relevant for fish production, since the red trend line exceeds detrended variability (blue line) along most of the timeline. This pattern changes in the last 30 year period, which coincides with increased variability shown in the principal component (Figure 24a) over the same period. For kelp, variability is very important along the entire time period, despite a general decreasing trend in production. For mussels, there are periods of dominance by both trend and variability.

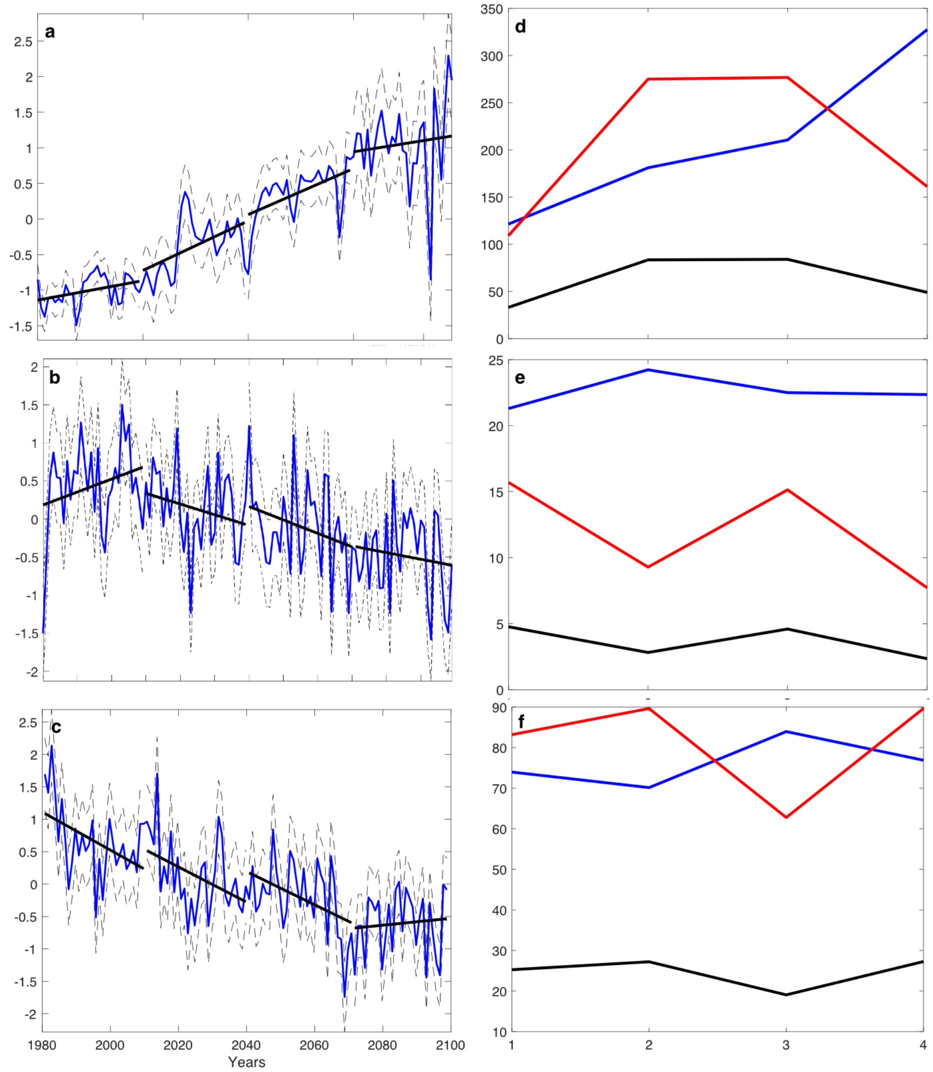


Figure 24. Analysis of variability vs Trend calculated for 30-year periods. Principal component of production with trend for each period (a, b, c). Relevance of trend over variability (d, e, f) show net change in trend, (red line), std of detrended mean production (blue line), and variance of the trend (black line). Curves in these panels are absolute values, so upward or downward lines do not represent behavior.

Ranking of sites based on future projections

a. Fish production ranking

The best region of the SCB for fish production is the south (blue) followed by the center (green). This pattern remains during most the period. However, variance increases gradually and uniformly amongst regions. In the last 30 year period, (2070-2098) production in the southern and center regions becomes highly unstable. Particularly in the south, temperatures start to be detrimental for this species of fish towards the end of the studied period, and mortalities happen often in this region. This last period ranking shows the transition between the south and center regions, that become similar in production. Over the projected time period, the northern region improves in performance as productivity increases substantially and mortality crashes do not happen.

The fish NPV ranking plots show less variance because every calculated NPV incorporates the production of 10 years in the future. In the NPV ranking the declining transition of the south to less profitability happens earlier in the 2040-2069 period. Although variance impacts both the south and the center regions, the center region becomes more stable and profitable than the south. The south eventually becomes unprofitable in the spatial ranking, a product of the frequent crashes in production.

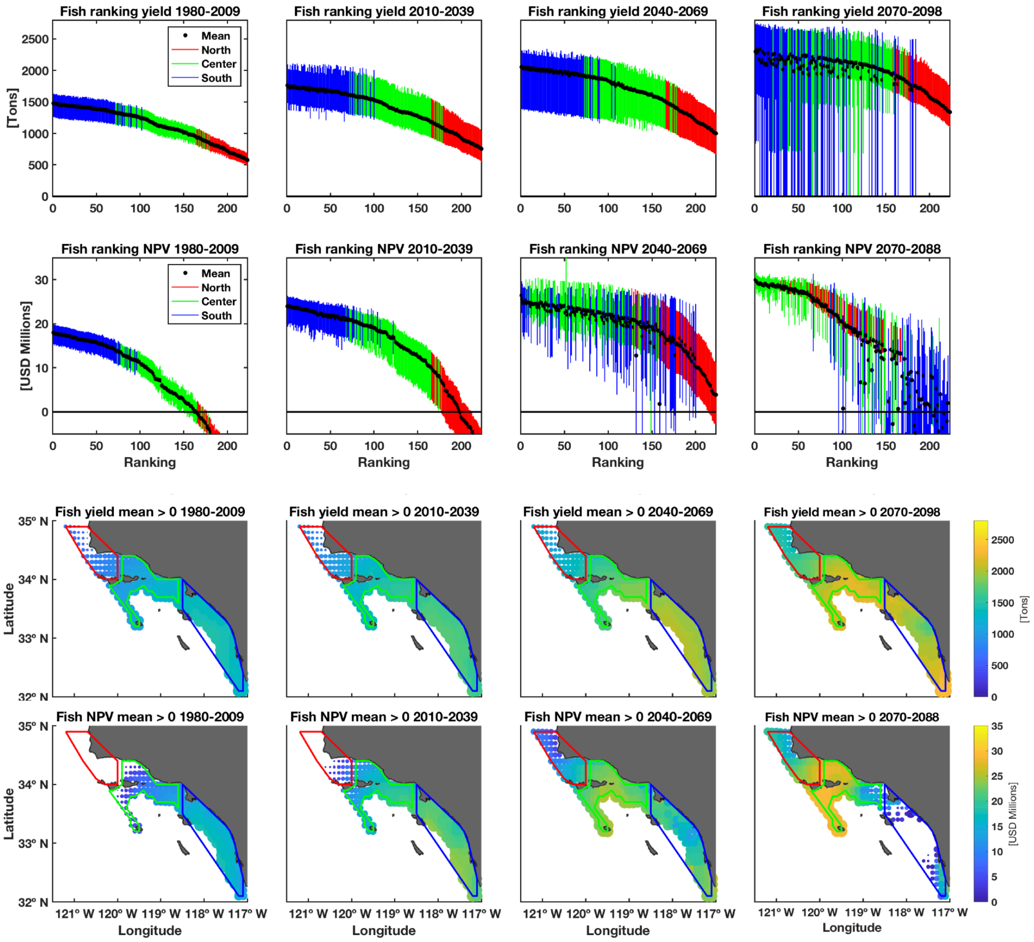


Figure 25. Fish ranking time series and spatial maps.

b. Kelp production ranking

The best region for kelp production is in the north (red) followed by the center (green). Production in the south is largely non-existent. Unlike the temporal changes in fish rankings, kelp production patterns remain relatively consistent across all periods. Production decreases slightly across all regions, and interannual variance remains relatively consistent. However sites in the center show a slight increase in production towards the end of the period. The NPV rankings for kelp show that fewer sites in the north are actually profitable than the number that have significant production.

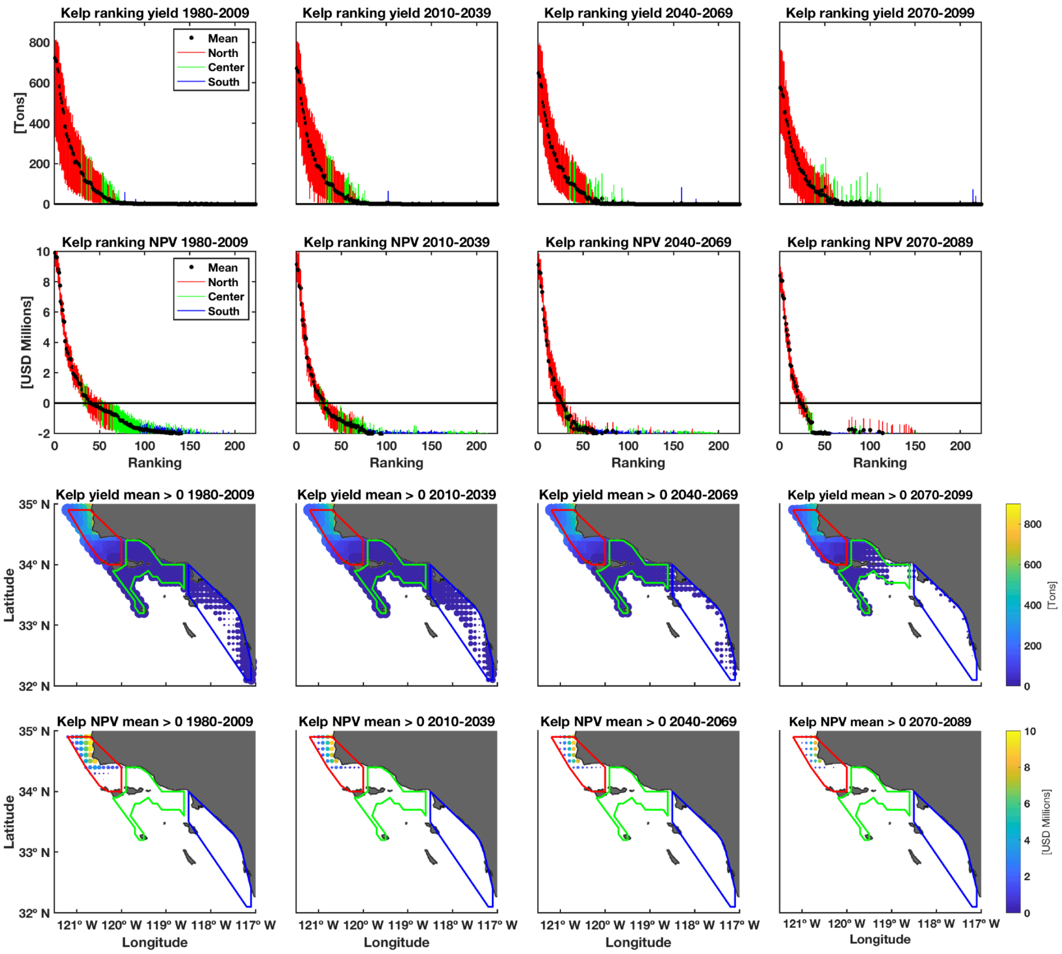


Figure 26. Kelp ranking time series and spatial maps.

c. Mussel production ranking

The best region for mussel production is in the north (red), and the worst is in the south (blue). Sites in the center (green) span almost the entire range of production rankings, which is far more spatially heterogeneous than the fish and the kelp. Similar to kelp, this pattern remains consistent during all time periods. Production decreases over time in general across all of the regions, but mostly at the south. Variance also remains similar across the periods of study. The NPV rankings for mussels show that a sizeable fraction of sites in the south and center are unprofitable, and the fraction grows over time.

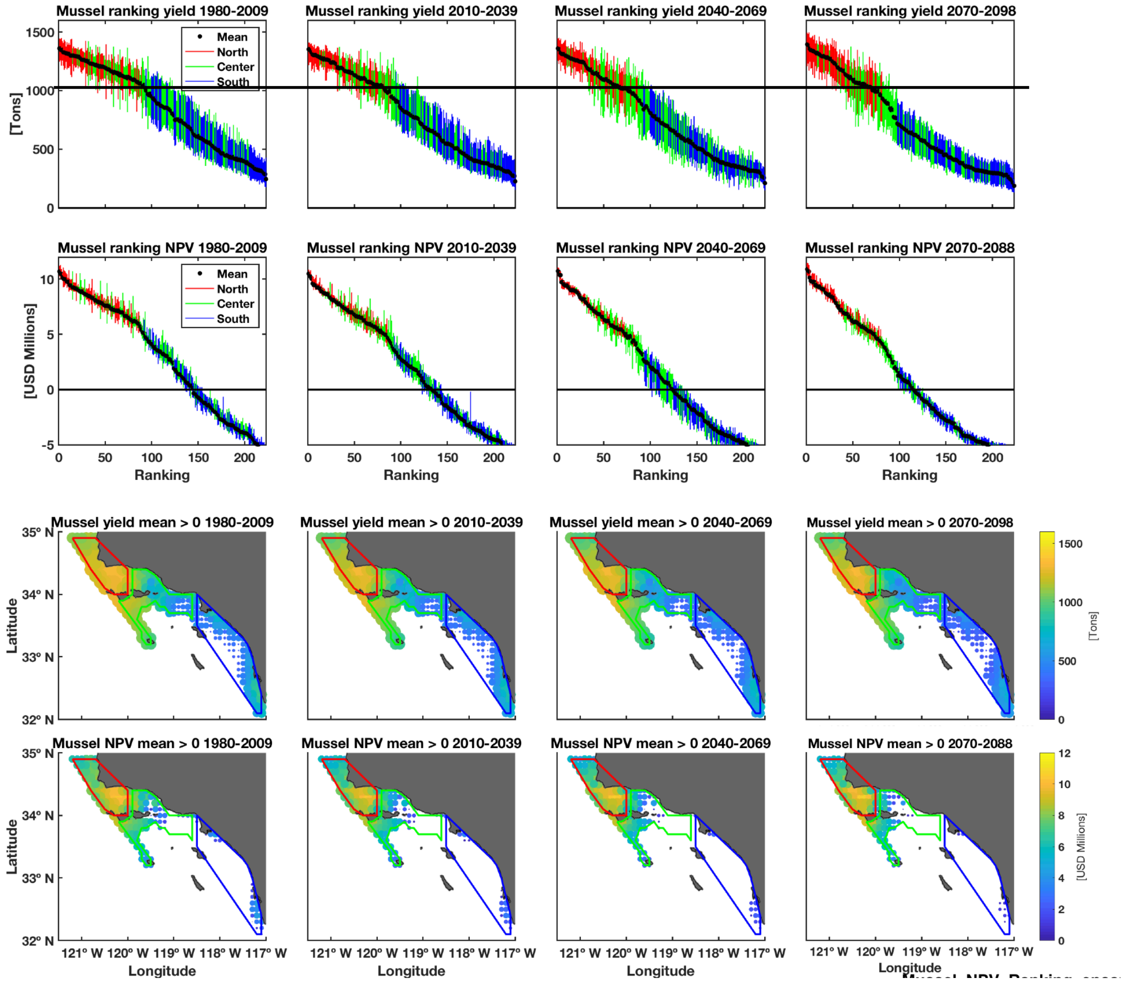


Figure 27. Mussel ranking time series and spatial maps.

D. DISCUSSION

Our results confirm the importance of developing marine spatial plans for aquaculture. Selecting the best sites now fortunately brings some confidence that such sites will remain productive and profitable in the future for all three species in our case study. As shown in the ranking patterns (Figures 25, 26 and 27) individual sites stay relatively consistent along the periods of time. This brings confidence that marine spatial plans developed to optimize productivity may have value in the SCB for several decades until thermal tolerances are reached.

Selecting adequate species is an important step for planning profitable farms. In addition strategies such as selecting breeding can add further resilience to climate change (Klinger et al., 2017; Reid et al., 2019). For this case study, we selected a fish species that has a wide thermal range and benefited from increasing temperatures. Productivity of fish increases considerably overtime, but eventually decline when temperatures go higher than 26 deg C in the southern region. In the case of the mussel and kelp, these species are toward the southern limits of their distribution ranges in the California Current. Therefore, it is expected that the poleward shift of temperatures will affect them more profoundly than the fish species that was modeled. Indeed, our models show a decrease in production in both kelp and mussel. Farming species that are already near their thermal limits will undoubtedly lead to greater expected declines in productivity. In the latitudes of the SCB, picking species that are closer to the equatorward edge to their range, as opposed to the poleward edge of the range is more likely to generate benefits over time. A strategy could be to focus on switching species (if this is ecologically and economically possible) instead of switching locations, as suggested previously (Kapetsky, 2013; Sarà et al., 2018).

Although we confirmed that the ranking of sites remain similar across time for these three species, we do not suggest that the impact of climate change and variability is negligible. Productivity in all species respond to the climate change signal and variability in the forcing. The temperature forcing in the models (GFDL, IPSL, and HAD) show an increasing trend with a parallel decrease in POC and NO_3. The aquaculture models consequently show an increasing trend in fish (which depends only on temperature), while kelp and mussels have a decrease in production. The domain of this study is quite small (only the SCB), but the gradient in conditions is quite steep. Therefore, the modest poleward shift of optimal sites observed here may not be representative of patterns in other regions.

The analyses of the production time series show fluctuations that correspond with internal variability of the region projected by the climate models (Figure 23). The effects of such variability over aquaculture production is different for the three species used. For fish, the general climate trend is stronger than the impact of interannual variability in most of the time series. What this means is that fish farmers will benefit most from picking sites that increase production in the long term. This assumes that feeds, oxygen, or other unstudied issues are not limiting factors.

For kelp, farmers will benefit from paying more attention to interannual variability and its impacts on kelp farms, both now and in the future. Literature highlights the role of decadal variability in particular for natural kelp forests (Parnell et al., 2010) and the viability of kelp farms in this region (Snyder et al., 2020). By not considering variability of the region, kelp production and profitability could be over or underestimated.

Finally, mussel farmers will be faced with likely impacts from both the climate change trend and variability. Decreasing production along with strong effects of variability should be expected. Historical distribution of biological communities of Mediterranean mussels in the California Current have contracted southwards contrary to poleward expansion expected from climate change. This is mostly attributed to a switch to a cold phase of the PDO (Hilbish et al., 2010) supporting the influence of decadal variability over this species. Despite this species prefer warmer waters (Lockwood et al., 2011), the projected decreasing trend in productivity shows future temperatures might reach their detrimental thermal limit around 24ºC (Anestis et al., 2007). The impact of variability remains relatively consistent over time, so it is another factor to consider, as suggested in Chapter I.

We concur with Hobday et al. (2016) that climate change projections are relevant for the spatial planning of aquaculture at a long term. However, when available, knowledge on internal variability can be valuable for farmers to know what to expect during the term of their leases. For example, leases for cultivation of bivalves and fish in California state waters are for 25 years and 5 years respectively (California Department of Fish and Wildlife (2016). Within such time frames, particularly the extent of the bivalve leases, decadal shifts could occur in internal variability and its impacts over productivity can be most concerning for farmers. There are scientific limits to our ability to prescribe climate change impacts and decadal variability predictions changes (Meehl et al., 2010; Liu et al., 2018) but our work aims to help with scenario building and planning (Couture et al., 2021) .

We limited the environmental forcing to key variables, and did not consider other elements such as aragonite saturation, oxygen, incidence of harmful algal blooms, increasing storms, which are important variables of concern for marine aquaculture planning in the face of climate change (Cochrane et al., 2009; Barsley, 2013; Brander et al., 2017; Reid et al., 2019). However, this framework helps to start thinking about how to include climate variability and change into management plans for marine aquaculture. NPV calculations need to be computed including the uncertainty increases by climate change estimated in economic theory (Sumaila et al., 2011).

We analyzed species individually instead of in functional groups, but we share the lessons of previous work that certain latitudes (temperate) and species might be benefited in the future (Froehlich et al., 2016, 2018), so it is worth investing in species that are not already near their thermal maximum and match them with the region of interest accordingly.

Finally, the lessons found in this work might not hold for other regions. In our area of study, the gradient in temperature and productivity is quite steep across a modest stretch of coastline. In addition, the oceanographic features of the SCB include a semi-permanent gyre in the Santa Barbara Chanel (Harms et al., 1998; Oey et al., 2001). The gyre provides a source of upwelling that boosts kelp and mussel productivity, and therefore contributes to maintaining the general spatial pattern of productivity in the future.

Every region has different temperature, nutrient and ecological dynamics, and different species have different needs and tolerances. For example, the pace of change might dominate production and the spatial patterns might change more dramatically in other areas. The framework we have developed, however, can be applied in a case by case basis, to explore if a particular marine spatial plan based on conditions and uses today will remain effective or need to be restructured to be more climate resilient going forward.

E. CONCLUSIONS

Developing well-designed marine spatial plans in the present has many potential environmental, economic and social benefits. Fortunately, in our case study, optimal areas for conditions today remain productive choices despite many future effects of climate variability and climate change. This brings some confidence for the feasibility of aquaculture farms over the coming decades. Whether this site resilience in the face of climate change holds for other locations remains to be tested.

Selecting species with thermal ranges that are resilient to future conditions is one practical strategy to adapt to climate change. The SCB is located towards the equatorward geographical distribution limit of Mediterranean mussels (Shinen et al., 2009) and is in the middle of the distributional range of giant kelp (Edwards et al., 2005; Ramírez-Valdez et al., 2017). Average productivity for these species is likely to decrease significantly over the next century. On the other hand, aquaculture for the candidate fish species in this study is currently optimal in the southern region of the SCB and becomes more productive over time all across the SCB – expanding profitable locations for cultivation in the future.

Although the overall site rankings of average aquaculture production stay relatively consistent over many decades, interannual variability across the region changes substantially. Interannual variability is greatest for kelp, followed by mussels. Both depend heavily on nutrients provided by the environment. Since fish productivity is not dependent on food availability, its dynamics are less variable over time. These conclusions are drawn for a set of three species in a particular geographic region, but our framework is designed to forecast the effects of future climate dynamics on the productivity and economic gains from aquaculture in coastal settings across the globe.

F. SUPPLEMENTAL INFORMATION

Primary productivity trend analysis

Timeseries of yearly average California Current Primary Organic Carbon Production of the models used (GFDL, HAD, IPSL) for the California current do not seem to have a strong trend (Figure 28). Although anomalies plot show a slight negative trend for the HAD model in particular, the CMIP5 Ensemble confirms that the negative trend is not very marked and while some models might have a stronger trend, along the coast and the scale of the southern California Bight, these trends can be noisy (Figure 29). Spatial plots show a decline productivity in the SCB comparing to historical periods (2006-2050 and 2050 to 2099) in most models and the ensemble (Figure 30).

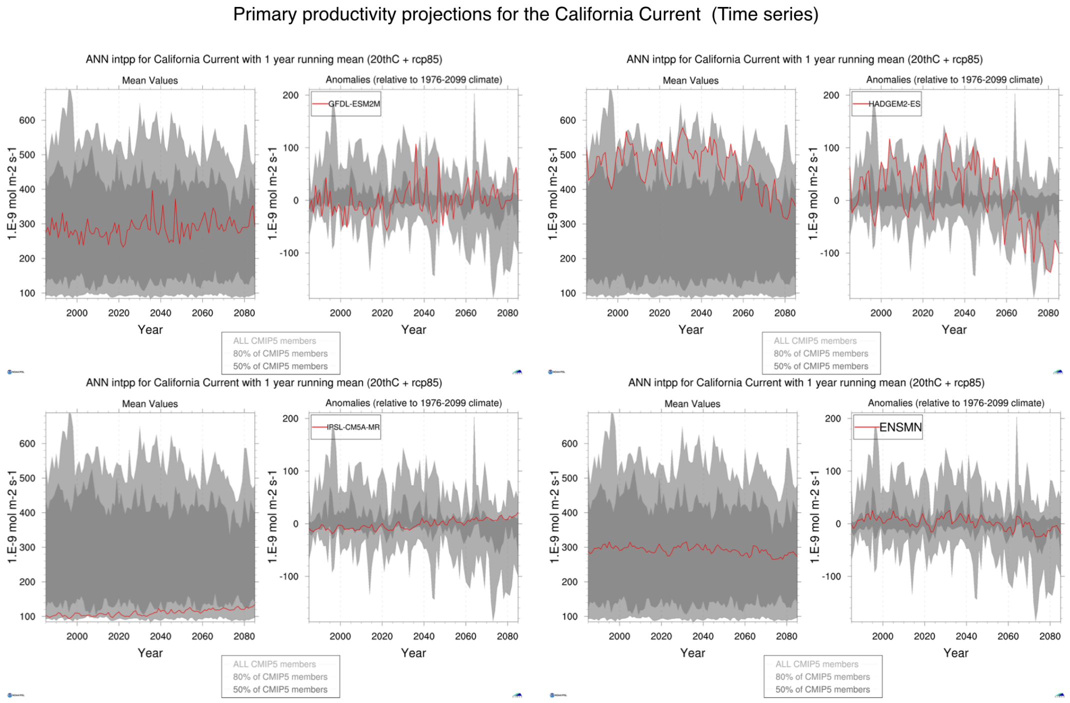


Figure 28. Primary productivity projections for the California Current (time series). Data available and Figures plotted using the NOAA PSL website https://psl.noaa.gov/ipcc/ocn/timeseries.html. Caption generated by website: "Timeseries of yearly average California Current Primary Organic Carbon Production by All Types of Phytoplankton for the 1976-2099 period. The simulations are forced using historical emission (1976 to 2005) and RCP8.5 scenario for future projection (2006 to 2099). A 1-year running mean is applied. Figures show, in colors, GFDL-ESM2M ,HADGEM2-ES, IPSL-CM5A-MR and ENSMN ensemble mean, in light grey, the spread of all the CMIP5 models, and in medium grey, and dark grey, 80% and 50% the spread of all the CMIP5 members, respectively. Left panel shows the mean values and right panel shows the anomalies relative to the 1976-2099 climatology".

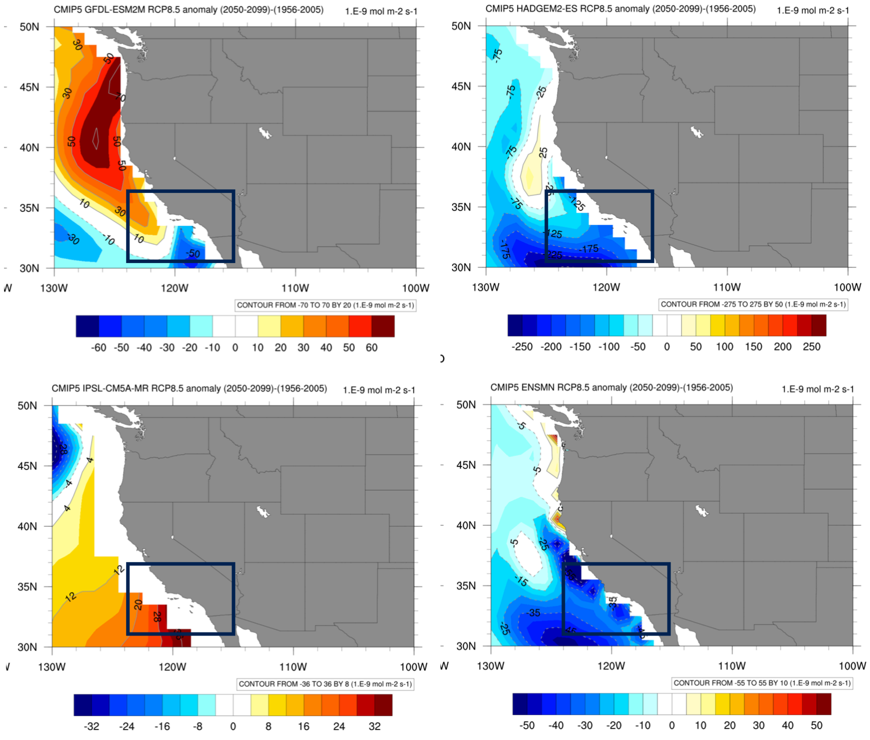


Figure 29. Primary productivity projections for the California Current (maps). Data available and Figures plotted using the NOAA PSL website https://psl.noaa.gov/ipcc/ocn/ccwp.html for CMIP5 maps. Caption: "Primary Organic Carbon Production by All Types of Phytoplankton for GFDL-ESM2M, HADGEM2-ES, IPSL-CM5A-MR and ENSMN interpolated on a 1x1 grid for the entire year; Difference in the mean climate in the future time period (RCP8.5: 2050-2099) compared to the historical reference period (1956-2005)". Rectangle shows the domain of the SCB.

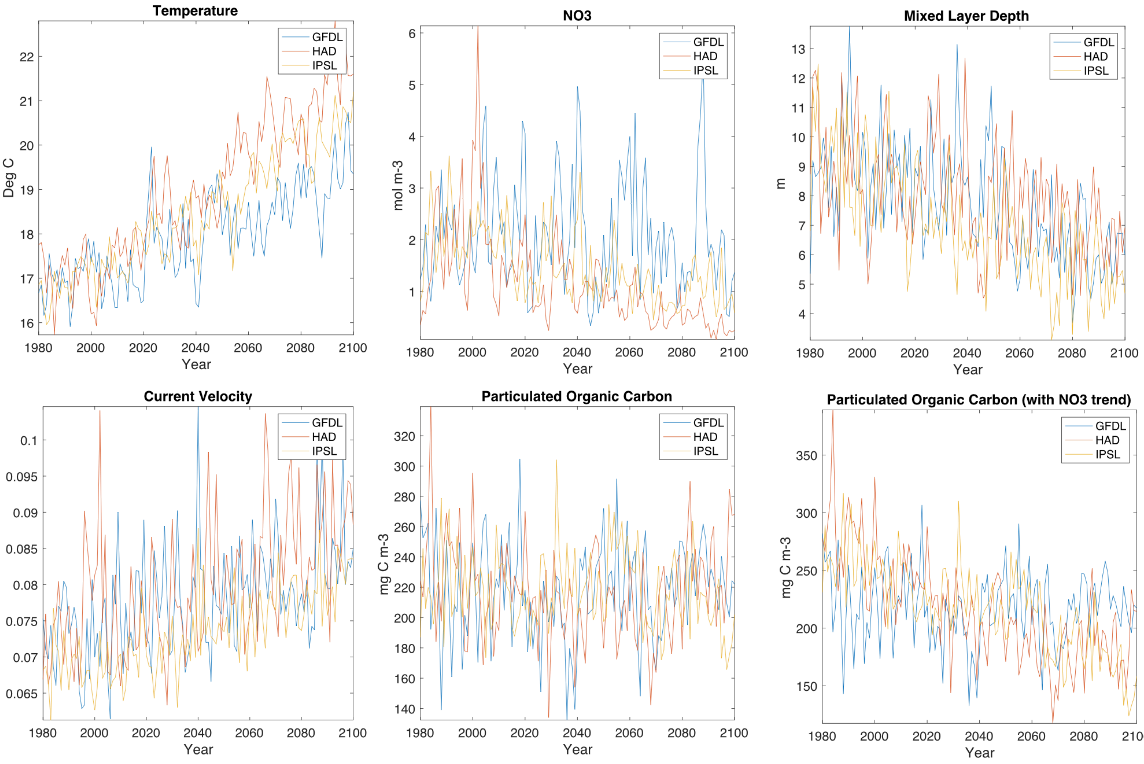


Figure 30. Time series of environmental forcing used to run aquaculture models, separated by model (GFDL, HAD, IPSL). Last two panels show POC reconstructed with the LIM model. However, the development of the LIM model required to detrend the SST data. We assumed that in this region nitrates are proportional to POC. We added the NO_3 trend to the POC data to be consistent. The trend component of the NO_3 was added to the POC by calculating trend and relative amplitude in the NO_3 . The trend and relative amplitude of NO_3 data are normalized to generate an equivalent trend properly scaled to POC.

REFERENCES

Airamé, S., Dugan, J. E., Lafferty, K. D., Leslie, H., McArdle, D. A., & Warner, R. R. (2003). Applying ecological criteria to marine reserve design: A case study from the California Channel Islands. . *Ecological Applications, 13*(sp1), 170-184. doi:10.1890/1051-0761(2003)013[0170:AECTMR]2.0.CO;2

Alamar, M., Estruch, V., Pastor, J., & Vidal, A. (2016). Modelo aleatorio de crecimiento CCT biparamétrico. *Revista AquaTIC*(13).

Allen, P. J., Brokordt, K., Oliva, M., Alveal, K., Flores, H., & Álvarez, C. A. (2021). Physiological insights for aquaculture diversification: Swimming capacity and efficiency, and metabolic scope for activity in cojinoba Seriolella violacea. *Aquaculture, 531*, 735968. doi:https://doi.org/10.1016/j.aquaculture.2020.735968

Alleway, H. K., Gillies, C. L., Bishop, M. J., Gentry, R. R., Theuerkauf, S. J., & Jones, R. (2019). The Ecosystem Services of Marine Aquaculture: Valuing Benefits to People and Nature. *BioScience, 69*(1), 59-68. doi:10.1093/biosci/biy137

Anderson, D. M., Fensin, E., Gobler, C. J., Hoeglund, A. E., Hubbard, K. A., Kulis, D. M., Landsberg, J. H., Lefebvre, K. A., Provoost, P., Richlen, M. L., Smith, J. L., Solow, A. R., & Trainer, V. L. (2021). Marine harmful algal blooms (HABs) in the United States: History, current status and future trends. *Harmful Algae, 102*, 101975. doi:https://doi.org/10.1016/j.hal.2021.101975

Anestis, A., Lazou, A., Pörtner, H. O., & Michaelidis, B. (2007). Behavioral, metabolic, and molecular stress responses of marine bivalve Mytilus galloprovincialis during long-term acclimation at increasing ambient temperature. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology, 293*(2), R911-R921. doi:10.1152/ajpregu.00124.2007

Aura, C. M., Musa, S., Osore, M. K., Kimani, E., Alati, V. M., Wambiji, N., Maina, G. W., & Charo-Karisa, H. (2017). Quantification of climate change implications for water-based management: A case study of oyster suitability sites occurrence model along the Kenya coast. *Journal of Marine Systems, 165*, 27-35. doi:http://dx.doi.org/10.1016/j.jmarsys.2016.09.007

Bakun, A., Black, B. A., Bograd, S. J., García-Reyes, M., Miller, A. J., Rykaczewski, R. R., & Sydeman, W. J. (2015). Anticipated Effects of Climate Change on Coastal Upwelling Ecosystems. *Current Climate Change Reports, 1*(2), 85-93. doi:10.1007/s40641-015-0008-4

Barsley, W., De Young, C & Brugère, C. (2013). *Vulnerability assessment methodologies: an annotated bibliography for climate change and the fisheries and aquaculture sector*. Retrieved from Rome, Italy.

Bell, J. D., Ganachaud, A., Gehrke, P. C., Griffiths, S. P., Hobday, A. J., Hoegh-Guldberg, O., Johnson, J. E., Le Borgne, R., Lehodey, P., Lough, J. M., Matear, R. J., Pickering, T. D., Pratchett, M. S., Gupta, A. S., Senina, I., & Waycott, M. (2013). Mixed responses of tropical Pacific fisheries and aquaculture to climate change. *Nature Clim. Change, 3*(6), 591-599. doi:10.1038/nclimate1838

Bell, T. W., Cavanaugh, K. C., Reed, D. C., & Siegel, D. A. (2015). Geographical variability in the controls of giant kelp biomass dynamics. *Journal of Biogeography, 42*(10), 2010-2021. doi:10.1111/jbi.12550

Besson, M., de Boer, I. J. M., Vandeputte, M., van Arendonk, J. A. M., Quillet, E., Komen, H., & Aubin, J. (2017). Effect of production quotas on economic and environmental values of growth rate and feed efficiency in sea cage fish farming. *PLOS ONE, 12*(3), e0173131. doi:10.1371/journal.pone.0173131

Besson, M., Vandeputte, M., van Arendonk, J. A. M., Aubin, J., de Boer, I. J. M., Quillet, E., & Komen, H. (2016). Influence of water temperature on the economic value of growth rate in fish farming: The case of sea bass (Dicentrarchus labrax) cage farming in the Mediterranean. *Aquaculture, 462*, 47-55. doi:https://doi.org/10.1016/j.aquaculture.2016.04.030

Blanchette, C. A., Melissa Miner, C., Raimondi, P. T., Lohse, D., Heady, K. E. K., & Broitman, B. R. (2008). Biogeographical patterns of rocky intertidal communities along the Pacific coast of North America. *Journal of Biogeography, 35*(9), 1593-1607. doi:10.1111/j.1365-2699.2008.01913.x

Bograd, S. J., Buil, M. P., Lorenzo, E. D., Castro, C. G., Schroeder, I. D., Goericke, R., Anderson, C. R., Benitez-Nelson, C., & Whitney, F. A. (2015). Changes in source waters to the Southern California Bight. *Deep Sea Research Part II: Topical Studies in Oceanography, 112*, 42-52. doi:https://doi.org/10.1016/j.dsr2.2014.04.009

Bograd, S. J., Castro, C. G., Di Lorenzo, E., Palacios, D. M., Bailey, H., Gilly, W., & Chavez, F. P. (2008). Oxygen declines and the shoaling of the hypoxic boundary in the California Current. *Geophysical Research Letters, 35*(12). doi:https://doi.org/10.1029/2008GL034185

Bograd, S. J., & Lynn, R. J. (2001). Physical-biological coupling in the California Current during the 1997–99 El Niño-La Niña Cycle. *Geophysical Research Letters, 28*(2), 275-278. doi:10.1029/2000GL012047

Bograd, S. J., & Lynn, R. J. (2003). Long-term variability in the southern California Current System. *Deep Sea Research Part II: Topical Studies in Oceanography, 50*(14), 2355-2370.

Bond, N. A., Cronin, M. F., Freeland, H., & Mantua, N. (2015). Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophysical Research Letters, 42*(9), 3414-3420. doi:https://doi.org/10.1002/2015GL063306

Bonino, G., Di Lorenzo, E., Masina, S., & Iovino, D. (2019). Interannual to decadal variability within and across the major Eastern Boundary Upwelling Systems. *Scientific Reports, 9*(1), 19949. doi:10.1038/s41598-019-56514-8

Bostock, J., McAndrew, B., Richards, R., Jauncey, K., Telfer, T., Lorenzen, K., Little, D., Ross, L., Handisyde, N., Gatward, I., & Corner, R. (2010). Aquaculture: global status and trends. *Philosophical Transactions of the Royal Society B: Biological Sciences, 365*(1554), 2897.

Brander, K., Cochrane, K., Barange, M., & Soto, D. (2017). Climate Change Implications for Fisheries and Aquaculture. *Climate Change Impacts on Fisheries and Aquaculture*, 45-62. doi:https://doi.org/10.1002/9781119154051.ch3

Bray, N. A., Keyes, A., & Morawitz, W. M. L. (1999). The California Current system in the Southern California Bight and the Santa Barbara Channel. *Journal of Geophysical Research: Oceans, 104*(C4), 7695-7714. doi:10.1029/1998JC900038

Briggs, J. C., & Bowen, B. W. (2011). A realignment of marine biogeographic provinces with particular reference to fish distributions. *Journal of Biogeography, 39*(1), 12-30. doi:10.1111/j.1365-2699.2011.02613.x

Brugere, C. a. D. Y., Cassandra. (2015). *Assessing climate change vulnerability in fisheries and aquaculture: Available methodologies and their relevance for the sector* Retrieved from Rome, Italy: http://www.fao.org/3/a-i5109e.pdf

Bryniarski, A. (2015). *California Aquaculture Law Symposium: Summary Report*. Retrieved from https://law.ucla.edu/~/media/Files/UCLA/Law/Pages/Publications/RES_PUB_California_Aquaculture_Report.ashx

Brzezinski, M. A., D.C. Reed, S. Harrer, A. Rassweiler, J.M. Melack, B.M. Goodridge, and J.E. Dugan (2013). Multiple sources and forms of nitrogen sustain year-round kelp growth on the inner continental shelf of the Santa Barbara Channel. *Oceanography, 26*(3), 114–123. doi:https://doi.org/10.5670/oceanog.2013.53

CalCOFI. (2016). *STATE OF THE CALIFORNIA CURRENT 2015–16: COMPARISONS WITH THE 1997–98 EL NIÑO*. Retrieved from https://par.nsf.gov/servlets/purl/10025363

CaliforniaSeaGrant. (2015). How can we grow aquaculture in California? Retrieved from https://caseagrant.ucsd.edu/news/how-can-we-grow-aquaculture-in-california

Callaway, R., Shinn, A. P., Grenfell, S. E., Bron, J. E., Burnell, G., Cook, E. J., Crumlish, M., Culloty, S., Davidson, K., Ellis, R. P., Flynn, K. J., Fox, C., Green, D. M., Hays, G. C., Hughes, A. D., Johnston, E., Lowe, C. D., Lupatsch, I., Malham, S., Mendzil, A. F., Nickell, T., Pickerell, T., Rowley, A. F., Stanley, M. S., Tocher, D. R., Turnbull, J. F., Webb, G., Wootton, E., & Shields, R. J. (2012). Review of climate change impacts on marine aquaculture in the UK and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems, 22*(3), 389-421. doi:10.1002/aqc.2247

Camus, C., Infante, J., & Buschmann, A. H. (2019). Revisiting the economic profitability of giant kelp Macrocystis pyrifera (Ochrophyta) cultivation in Chile. *Aquaculture, 502*, 80-86. doi:https://doi.org/10.1016/j.aquaculture.2018.12.030

Canada, G. o. (2006). *An Economic Analysis of the Mussel Industry in Prince Edward Island, Gulf Region*. Moncton, New Brunswick Retrieved from http://www.dfo-mpo.gc.ca/Library/328179-e.pdf.

Carr, M.-E. (2001). Estimation of potential productivity in Eastern Boundary Currents using remote sensing. *Deep Sea Research Part II: Topical Studies in Oceanography, 49*(1), 59-80. doi:https://doi.org/10.1016/S0967-0645(01)00094-7

Carroll, M. L., Johnson, B. J., Henkes, G. A., McMahon, K. W., Voronkov, A., Ambrose, W. G., & Denisenko, S. G. (2009). Bivalves as indicators of environmental variation and potential anthropogenic impacts in the southern Barents Sea. *Marine Pollution Bulletin, 59*(4-7), 193-206. doi:10.1016/j.marpolbul.2009.02.022

Cavanaugh, K. C., Reed, D. C., Bell, T. W., Castorani, M. C. N., & Beas-Luna, R. (2019). Spatial Variability in the Resistance and Resilience of Giant Kelp in Southern and Baja California to a Multiyear Heatwave. *Frontiers in Marine Science, 6*, 413.

Cavanaugh, K. C., Siegel, D. A., Reed, D. C., & Dennison, P. E. (2011). Environmental controls of giant-kelp biomass in the Santa Barbara Channel, California. *Marine Ecology Progress Series, 429*, 1-17.

Cayan, D. R., Redmond, K. T., & Riddle, L. G. (1999). ENSO and Hydrologic Extremes in the Western United States. *Journal of Climate, 12*(9), 2881-2893. doi:10.1175/1520-0442(1999)012<2881:EAHEIT>2.0.CO;2

Celis Plá, P., & Alveal, K. (2012). Development of Macrocystis pyrifera from spores and gametes on artificial substrate: Algal production in a surface culture. *Latin american journal of aquatic research, 40*, 292-299.

Chenillat, F., Rivière, P., Capet, X., Di Lorenzo, E., & Blanke, B. (2012). North Pacific Gyre Oscillation modulates seasonal timing and ecosystem functioning in the California Current upwelling system. *Geophysical Research Letters, 39*(1). doi:https://doi.org/10.1029/2011GL049966

Cheung, W. W. L., Lam, V. W. Y., Sarmiento, J. L., Kearney, K., Watson, R. E. G., Zeller, D., & Pauly, D. (2010). Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology, 16*(1), 24-35. doi:10.1111/j.1365-2486.2009.01995.x

Chhak, K., & Di Lorenzo, E. (2007). Decadal variations in the California Current upwelling cells. *Geophysical Research Letters, 34*(14). doi:10.1029/2007GL030203

Chivers, S. J., Perryman, W. L., Lynn, M. S., Gerrodette, T., Archer, F. I., Danil, K., Berman-Kowalewski, M., & Dines, J. P. (2015). Comparison of reproductive parameters for populations of eastern North Pacific common dolphins: Delphinus capensis and D. delphis. *Marine Mammal Science, 32*(1), 57-85. doi:10.1111/mms.12244

Cho, C. Y. (1992). Feeding systems for rainbow trout and other salmonids with reference to current estimates of energy and protein requirements. *Aquaculture, 100*(1-3), 107-123.

Clavelle, T., Lester, S. E., Gentry, R., & Froehlich, H. E. (2019). Interactions and management for the future of marine aquaculture and capture fisheries. *Fish and Fisheries, 20*(2), 368-388. doi:https://doi.org/10.1111/faf.12351

Clements, J. C., & Chopin, T. (2017). Ocean acidification and marine aquaculture in North America: potential impacts and mitigation strategies. *Reviews in Aquaculture, 9*(4), 326-341. doi:https://doi.org/10.1111/raq.12140

Cochrane, K., De Young, C., Soto, D., & Bahri, T. (2009). Climate change implications for fisheries and aquaculture. *FAO Fisheries and aquaculture technical paper, 530*, 212.

Cohen, J. (2017). Cultivating Marine Biomass. Retrieved from http://www.news.ucsb.edu/2017/018267/cultivating-marine-biomass

Commission, C. F. a. G. (2018). *Santa Barbara Mariculture Company Continued Shellfish Aquaculture Operations on State Water Bottom Lease Offshore Santa Barbara, California*. Sacramento, USA Retrieved from https://nrm.dfg.ca.gov/documents/docviewer.aspx.

Cook, A. M., Duston, J., & Bradford, R. G. (2006). Thermal tolerance of a northern population of striped bass Morone saxatilis. *Journal of Fish Biology, 69*(5), 1482-1490. doi:https://doi.org/10.1111/j.1095-8649.2006.01211.x

Correa, T., Gutiérrez, A., Flores, R., Buschmann, A. H., Cornejo, P., & Bucarey, C. (2016). Production and economic assessment of giant kelp Macrocystis pyrifera cultivation for abalone feed in the south of Chile. *Aquaculture Research, 47*(3), 698-707. doi:10.1111/are.12529

Coutant, C. C. (1990). Temperature-Oxygen Habitat for Freshwater and Coastal Striped Bass in a Changing Climate. *Transactions of the American Fisheries Society, 119*(2), 240-253. doi:10.1577/1548-8659(1990)119<0240:THFFAC>2.3.CO;2

Couture, J. L., Froehlich, H. E., Buck, B. H., Jeffery, K. R., Krause, G., Morris Jr, J. A., Pérez, M., Stentiford, G. D., Vehviläinen, H., & Halpern, B. S. (2021). Scenario analysis can guide aquaculture planning to meet sustainable future production goals. *ICES Journal of Marine Science*. doi:10.1093/icesjms/fsab012

Craig, R. K. (2019). Fostering adaptive marine aquaculture through procedural innovation in marine spatial planning. *Marine Policy, 110*, 103555. doi:https://doi.org/10.1016/j.marpol.2019.103555

Daley, M. D., Anderson, Jack W., Reish, D.J., Gorsline D.S. Anderson Pages. (1993). The Southern California Bight, Background and Setting In D. J. R. Murray D. Dailey, Jack W. Anderson (Ed.), *Ecology of the Southern California Bight: a synthesis and interpretation* (pp. 1-18). Berkeley and Los Angeles, California, USA: University of California Press.

Davis, K. B. (2004). Temperature affects physiological stress responses to acute confinement in sunshine bass (Morone chrysops×Morone saxatilis). *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology, 139*(4), 433-440. doi:https://doi.org/10.1016/j.cbpb.2004.09.012

Del Rio-Zaragoza, O. B., Cavalheiro Araújo, B., & Viana, M. T. (2021). Health status evaluation of striped bass (Morone saxatilis) exposed to low temperature in sea cage culture during the grow-out. *Aquaculture Research, 52*(6), 2435-2445. doi:https://doi.org/10.1111/are.15093

Deser, C., Alexander, M. A., Xie, S.-P., & Phillips, A. S. (2009). Sea Surface Temperature Variability: Patterns and Mechanisms. *Annual review of marine science, 2*(1), 115-143. doi:10.1146/annurev-marine-120408-151453

Di Lorenzo, E. (2003). Seasonal dynamics of the surface circulation in the Southern California Current System. *Deep Sea Research Part II: Topical Studies in Oceanography, 50*(14), 2371-2388. doi:https://doi.org/10.1016/S0967-0645(03)00125-5

Di Lorenzo, E., Cobb, K. M., Furtado, J. C., Schneider, N., Anderson, B. T., Bracco, A., Alexander, M. A., & Vimont, D. J. (2010). Central Pacific El Niño and decadal climate change in the North Pacific Ocean. *Nature Geoscience, 3*(11), 762-765. doi:10.1038/ngeo984

Di Lorenzo, E., Fiechter, J., Schneider, N., Bracco, A., Miller, A. J., Franks, P. J. S., Bograd, S. J., Moore, A. M., Thomas, A. C., Crawford, W., Peña, A., & Hermann, A. J. (2009). Nutrient and salinity decadal variations in the central and eastern North Pacific. *Geophysical Research Letters, 36*(14). doi:10.1029/2009GL038261

Di Lorenzo, E., Liguori, G., Schneider, N., Furtado, J. C., Anderson, B. T., & Alexander, M. A. (2015). ENSO and meridional modes: A null hypothesis for Pacific climate variability. *Geophysical Research Letters, 42*(21), 9440-9448. doi:https://doi.org/10.1002/2015GL066281

Di Lorenzo, E., M. D. Ohman and S. Lluch-Cota (2018). Tendency for global-scale climate synchrony in marine populations. *Nature Climate Change*(submitted).

Di Lorenzo, E., Miller, A. J., Schneider, N., & McWilliams, J. C. (2005). The Warming of the California Current System: Dynamics and Ecosystem Implications. *Journal of Physical Oceanography, 35*(3), 336-362. doi:10.1175/JPO-2690.1

Di Lorenzo, E., & Ohman, M. D. (2013). A double-integration hypothesis to explain ocean ecosystem response to climate forcing. *Proceedings of the National Academy of Sciences, 110*(7), 2496. doi:10.1073/pnas.1218022110

Di Lorenzo, E., Schneider, N., Cobb, K. M., Franks, P. J. S., Chhak, K., Miller, A. J., McWilliams, J. C., Bograd, S. J., Arango, H., Curchitser, E., Powell, T. M., & Rivière, P. (2008). North Pacific Gyre Oscillation links ocean climate and ecosystem change. *Geophysical Research Letters, 35*(8). doi:10.1029/2007GL032838

Diana, J. S., Egna, H. S., Chopin, T., Peterson, M. S., Cao, L., Pomeroy, R., Verdegem, M., Slack, W. T., Bondad-Reantaso, M. G., & Cabello, F. (2013). Responsible Aquaculture in 2050: Valuing Local Conditions and Human Innovations Will Be Key to Success. *BioScience, 63*(4), 255-262. doi:10.1525/bio.2013.63.4.5

Diaz, I. (2018). *Datos Abiertos de Producción Acuícola y Pesquera, 2014* Retrieved from: https://datos.gob.mx/busca/dataset/produccion-pesquera

DiGiacomo, P. M., & Holt, B. (2001). Satellite observations of small coastal ocean eddies in the Southern California Bight. *Journal of Geophysical Research: Oceans, 106*(C10), 22521-22543. doi:10.1029/2000JC000728

Doney, S. C., Ruckelshaus, M., Emmett Duffy, J., Barry, J. P., Chan, F., English, C. A., Galindo, H. M., Grebmeier, J. M., Hollowed, A. B., & Knowlton, N. (2012). Climate change impacts on marine ecosystems. *Annual review of marine science, 4*, 11-37.

Du, X., Hendy, I., Hinnov, L., Brown, E., Schimmelmann, A., & Pak, D. (2020). Interannual Southern California Precipitation Variability During the Common Era and the ENSO Teleconnection. *Geophysical Research Letters, 47*(1), e2019GL085891. doi:https://doi.org/10.1029/2019GL085891

Edwards, M. S., & Hernández-Carmona, G. (2005). Delayed recovery of giant kelp near its southern range limit in the North Pacific following El Niño. *Marine Biology, 147*(1), 273-279. doi:10.1007/s00227-004-1548-7

Eppley, R. W. (1992). Chlorophyll, photosynthesis and new production in the Southern California Bight. *Progress in Oceanography, 30*(1), 117-150. doi:https://doi.org/10.1016/0079-6611(92)90010-W

Fagan, A. J., Moreno, A. R., & Martiny, A. C. (2019). Role of ENSO Conditions on Particulate Organic Matter Concentrations and Elemental Ratios in the Southern California Bight. *Frontiers in Marine Science, 6*, 386.

FAO. (2016). *The State of World Fisheries and Aquaculture 2016. Contributing to food security and nutrition for all.* Retrieved from

FAO. (2017) The 2030 Agenda and the Sustainable Development Goals: The challenge for aquaculture development and management. In. *FAO Fisheries and Aquaculture Circular No. 1141*. Rome, Italy.

Fernández, P. A., Gaitán-Espitia, J. D., Leal, P. P., Schmid, M., Revill, A. T., & Hurd, C. L. (2020). Nitrogen sufficiency enhances thermal tolerance in habitat-forming kelp: implications for acclimation under thermal stress. *Scientific Reports, 10*(1), 3186. doi:10.1038/s41598-020-60104-4

Filgueira, R., Guyondet, T., Comeau, L. A., & Grant, J. (2014). A fully-spatial ecosystem-DEB model of oyster (Crassostrea virginica) carrying capacity in the Richibucto Estuary, Eastern Canada. *Journal of Marine Systems, 136*, 42-54. doi:https://doi.org/10.1016/j.jmarsys.2014.03.015

Filgueira, R., Guyondet, T., Comeau, L. A., & Tremblay, R. (2016). Bivalve aquaculture-environment interactions in the context of climate change. *Global Change Biology, 22*(12), 3901-3913.

Fram, J. P., Stewart, H. L., Brzezinski, M. A., Gaylord, B., Reed, D. C., Williams, S. L., & MacIntyre, S. (2008). Physical pathways and utilization of nitrate supply to the giant kelp, Macrocystis pyrifera. *Limnology and Oceanography, 53*(4), 1589-1603. doi:https://doi.org/10.4319/lo.2008.53.4.1589

Froehlich, H. E., Gentry, R. R., & Halpern, B. S. (2016). Synthesis and comparative analysis of physiological tolerance and life-history growth traits of marine aquaculture species. *Aquaculture, 460*, 75-82. doi:http://doi.org/10.1016/j.aquaculture.2016.04.018

Froehlich, H. E., Gentry, R. R., & Halpern, B. S. (2018). Global change in marine aquaculture production potential under climate change. *Nature Ecology & Evolution, 2*(11), 1745-1750. doi:10.1038/s41559-018-0669-1

Froehlich, H. E., Gentry, R. R., Rust, M. B., Grimm, D., & Halpern, B. S. (2017). Public Perceptions of Aquaculture: Evaluating Spatiotemporal Patterns of Sentiment around the World. *PLOS ONE, 12*(1), e0169281. doi:10.1371/journal.pone.0169281

Fry, J. P., Mailloux, N. A., Love, D. C., Milli, M. C., & Cao, L. (2018). Feed conversion efficiency in aquaculture: do we measure it correctly? *Environmental Research Letters, 13*(2), 024017. doi:10.1088/1748-9326/aaa273

Fumo, J. T., Carter, M. L., Flick, R. E., Rasmussen, L. L., Rudnick, D. L., & Iacobellis, S. F. (2020). Contextualizing Marine Heatwaves in the Southern California Bight Under Anthropogenic Climate Change. *Journal of Geophysical Research: Oceans, 125*(5), e2019JC015674. doi:https://doi.org/10.1029/2019JC015674

García-Reyes, M., Sydeman, W. J., Schoeman, D. S., Rykaczewski, R. R., Black, B. A., Smit, A. J., & Bograd, S. J. (2015). Under Pressure: Climate Change, Upwelling, and Eastern Boundary Upwelling Ecosystems. *Frontiers in Marine Science, 2*, 109.

Gaylord, B., Emily Rivest, Tessa Hill, Eric Sanford, Priya Shukla, Aaron Ninokawa. . (2018). *California Mussels as Bio-Indicators of the Ecological Consequences of Global Change: Temperature, Ocean Acidification, and Hypoxia*. Retrieved from

Gentry, R. R., Froehlich, H. E., Grimm, D., Kareiva, P., Parke, M., Rust, M., Gaines, S. D., & Halpern, B. S. (2017). Mapping the global potential for marine aquaculture. *Nature Ecology & Evolution, 1*(9), 1317-1324. doi:10.1038/s41559-017-0257-9

Gobler, C. J., Doherty, O. M., Hattenrath-Lehmann, T. K., Griffith, A. W., Kang, Y., & Litaker, R. W. (2017). Ocean warming since 1982 has expanded the niche of toxic algal blooms in the North Atlantic and North Pacific oceans. *Proceedings of the National Academy of Sciences, 114*(19), 4975. doi:10.1073/pnas.1619575114

Grant, C. G., B.; Ho, D.; Read, E.; Winslow, E. (2017). *Planning and Incentivizing Native Olympia Oyster Restoration in Southern California.* (Masters Thesis), University of California Santa Barbara,

Grebe, G. S., Byron, C. J., Gelais, A. S., Kotowicz, D. M., & Olson, T. K. (2019). An ecosystem approach to kelp aquaculture in the Americas and Europe. *Aquaculture Reports, 15*, 100215. doi:https://doi.org/10.1016/j.aqrep.2019.100215

Gruber, N. (2011). Warming up, turning sour, losing breath: ocean biogeochemistry under global change. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 369*(1943), 1980.

Guyondet, T., Comeau, L. A., Bacher, C., Grant, J., Rosland, R., Sonier, R., & Filgueira, R. (2015). Climate Change Influences Carrying Capacity in a Coastal Embayment Dedicated to Shellfish Aquaculture. *Estuaries and Coasts, 38*(5), 1593-1618. doi:10.1007/s12237-014-9899-x

Hallegraeff, G. M. (2010). Ocean climate change, phytoplankton community responses and harmful algal blooms: a formidable predictive challenge. *Journal of Phycology, 46*(2), 220-235. doi:10.1111/j.1529-8817.2010.00815.x

Handisyde, N. T., Ross, L. G., Badjeck, M. C., & Allison, E. H. (2006). The effects of climate change on world aquaculture: a global perspective. *Aquaculture and Fish Genetics Research Programme, Stirling Institute of Aquaculture. Final Technical Report, DFID, Stirling. 151pp*.

Harms, S., & Winant, C. D. (1998). Characteristic patterns of the circulation in the Santa Barbara Channel. *Journal of Geophysical Research: Oceans, 103*(C2), 3041-3065. doi:https://doi.org/10.1029/97JC02393

Harrold, C., & Reed, D. C. (1985). Food Availability, Sea Urchin Grazing, and Kelp Forest Community Structure. *Ecology, 66*(4), 1160-1169. doi:https://doi.org/10.2307/1939168

Hauri, C., Gruber, N., Vogt, M., Doney, S., Feely, R., Lachkar, Z., Leinweber, A., McDonnell, A., Münnich, M., & Plattner, G. (2012). Spatiotemporal variability and long-term trends of ocean acidification in the California Current System. *Biogeosciences, 10*, 193-216.

Hilbish, T. J., Brannock, P. M., Jones, K. R., Smith, A. B., Bullock, B. N., & Wethey, D. S (2010). Historical changes in the distributions of invasive and endemic marine invertebrates are contrary to global warming predictions: the effects of decadal climate oscillations. *Journal of Biogeography, 37*(3), 423-431. doi:https://doi.org/10.1111/j.1365-2699.2009.02218.x

Hobday, A. J., Spillman, C. M., Paige Eveson, J., & Hartog, J. R. (2016). Seasonal forecasting for decision support in marine fisheries and aquaculture. *Fisheries Oceanography, 25*, 45-56. doi:10.1111/fog.12083

Holbrook, S. J., Schmitt, R. J., & Stephens, J. S. (1997). Changes in an assemblage or temperate reef fishes associated with a climate shift *Ecological Applications, 7*(4), 1299-1310. doi:10.1890/1051-0761(1997)007[1299:CIAAOT]2.0.CO;2

Howard, E. M., Penn, J. L., Frenzel, H., Seibel, B. A., Bianchi, D., Renault, L., Kessouri, F., Sutula, M. A., McWilliams, J. C., & Deutsch, C. (2020). Climate-driven aerobic habitat loss in the California Current System. *Science Advances, 6*(20), eaay3188. doi:10.1126/sciadv.aay3188

Howard, M. D. A. S., M.; Caron D.A.; Chao, Yi; Farrara J.D.; Frenzel, H.; Burton J.; Robertson, G.; McLaughlin, K.; Sengupta A. (2014). Anthropogenic nutrient sources rival natural sources on small scales in the coastal waters of the Southern California Bight. *Limnology and Oceanography, 59*(1), 285-297. doi:10.4319/lo.2014.59.1.0285

Hvas, M., Folkedal, O., Imsland, A., & Oppedal, F. (2018). Metabolic rates, swimming capabilities, thermal niche and stress response of the lumpfish, Cyclopterus lumpus. *Biology Open, 7*(9). doi:10.1242/bio.036079

Iles, A. C., Gouhier, T. C., Menge, B. A., Stewart, J. S., Haupt, A. J., & Lynch, M. C. (2012). Climate-driven trends and ecological implications of event-scale upwelling in the

California Current System. *Global Change Biology, 18*(2), 783-796. doi:10.1111/j.1365-2486.2011.02567.x

IPCC. (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Retrieved from Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, :

IPCC. (2019). *Technical Summary. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Retrieved from

Iwama, G. K., & Tautz, A. F. (1981). A Simple Growth Model for Salmonids in Hatcheries. *Canadian Journal of Fisheries and Aquatic Sciences, 38*(6), 649-656. doi:10.1139/f81-087

Jackson, G. A. (1986). Physical Oceanography of the Southern California Bight. In *Plankton Dynamics of the Southern California Bight* (pp. 13-52): Springer-Verlag.

Jacox, M. G., Alexander, M. A., Stock, C. A., & Hervieux, G. (2019). On the skill of seasonal sea surface temperature forecasts in the California Current System and its connection to ENSO variability. *Climate Dynamics, 53*(12), 7519-7533. doi:10.1007/s00382-017-3608-y

Joh, Y., & Di Lorenzo, E. (2017). Increasing Coupling Between NPGO and PDO Leads to Prolonged Marine Heatwaves in the Northeast Pacific. *Geophysical Research Letters, 44*(22), 11,663-611,671. doi:10.1002/2017GL075930

Kahru, M., & Mitchell, B. G. (2000). Influence of the 1997–98 El Niño on the surface chlorophyll in the California Current. *Geophysical Research Letters, 27*(18), 2937-2940. doi:10.1029/2000GL011486

Kapetsky, J. M., Aguilar-Manjarrez, J. & Jenness, J. . (2013). A global assessment of potential for offshore mariculture development from a spatial perspective. *FAO Fisheries and Aquaculture Technical Paper No. 549. Rome, FAO.*, 181.

Kettmann, M. (2015, Apr. 2-9, 2015). Flexing Muscles over Mussels *Santa Barbara Independent 29*.

Kim, H.-J., & Miller, A. J. (2007). Did the Thermocline Deepen in the California Current after the 1976/77 Climate Regime Shift? *Journal of Physical Oceanography, 37*(6), 1733-1739. doi:10.1175/JPO3058.1

Kim, H.-J., Miller, A. J., McGowan, J., & Carter, M. L. (2009). Coastal phytoplankton blooms in the Southern California Bight. *Progress in Oceanography, 82*(2), 137-147. doi:https://doi.org/10.1016/j.pocean.2009.05.002

Kim, S. Y., & Cornuelle, B. D. (2015). Coastal ocean climatology of temperature and salinity off the Southern California Bight: Seasonal variability, climate index correlation, and linear trend. *Progress in Oceanography, 138*, 136-157. doi:https://doi.org/10.1016/j.pocean.2015.08.001

King, J. R., Agostini, V. N., Harvey, C. J., McFarlane, G. A., Foreman, M. G. G., Overland, J. E., Di Lorenzo, E., Bond, N. A., & Aydin, K. Y. (2011). Climate forcing and the California Current ecosystem. *ICES Journal of Marine Science, 68*(6), 1199-1216. doi:10.1093/icesjms/fsr009

Klinger, D. H., Levin, S. A., & Watson, J. R. (2017). The growth of finfish in global open-ocean aquaculture under climate change. *Proceedings of the Royal Society B: Biological Sciences, 284*(1864), 20170834. doi:10.1098/rspb.2017.0834

Kooijman, B., Lika, D., Marques, G., Augustine, S. & Pecquerie, L. (2014). *Add-my-pet Dynamic Energy Budget Database. Entry for Mytilus galloprovincialis*. Retrieved from: https://www.bio.vu.nl/thb/deb/deblab/add_my_pet_old/html/Mytilus_galloprovincialis.html

Kooijman, S. A. L. M. (1986). Energy budgets can explain body size relations. *Journal of Theoretical Biology, 121*(3), 269-282. doi:https://doi.org/10.1016/S0022-5193(86)80107-2

Kooijman, S. A. L. M. (2010). *Dynamic Energy Budget Theory for Metabolic Organisation*: Cambridge University Press.

Kroeker, K. J., Gaylord, B., Hill, T. M., Hosfelt, J. D., Miller, S. H., & Sanford, E. (2014). The Role of Temperature in Determining Species' Vulnerability to Ocean Acidification: A Case Study Using Mytilus galloprovincialis. *PLOS ONE, 9*(7), e100353. doi:10.1371/journal.pone.0100353

Lafferty, K. D. (2004). Fishing for lobsters indirectly increases epidemics in sea urchings. *Ecological Applications, 14*(5), 1566-1573. doi:https://doi.org/10.1890/03-5088

Lagos, N. A., Benítez, S., Duarte, C., Lardies, M. A., Broitman, B. R., Tapia, C., Tapia, P., Widdicombe, S., & Vargas, C. A. (2016). Effects of temperature and ocean acidification on shell characteristics of Argopecten purpuratus: implications for scallop aquaculture in an upwelling-influenced area. *Aquaculture Environment Interactions, 8*, 357-370.

Lam, V. W. Y., Cheung, W. W. L., Reygondeau, G., & Sumaila, U. R. (2016). Projected change in global fisheries revenues under climate change. *Scientific Reports, 6*.

Lara, C., Saldías, G. S., Tapia, F. J., Iriarte, J. L., & Broitman, B. R. (2016). Interannual variability in temporal patterns of Chlorophyll–a and their potential influence on the supply of mussel larvae to inner waters in northern Patagonia (41–44°S). *Journal of Marine Systems, 155*, 11-18. doi:https://doi.org/10.1016/j.jmarsys.2015.10.010

Lee, C. S., & Ostrowski, A. C. (2001). Current status of marine finfish larviculture in the United States. *Aquaculture, 200*(1), 89-109. doi:http://dx.doi.org/10.1016/S0044-8486(01)00695-0

Lester, S. E., Stevens, J. M., Gentry, R. R., Kappel, C. V., Bell, T. W., Costello, C. J., Gaines, S. D., Kiefer, D. A., Maue, C. C., Rensel, J. E., Simons, R. D., Washburn, L., & White, C. (2018). Marine spatial planning makes room for offshore aquaculture in crowded coastal waters. *Nature Communications, 9*(1), 945. doi:10.1038/s41467-018-03249-1

Levin, L. A., & Breitburg, D. L. (2015). Linking coasts and seas to address ocean deoxygenation. *Nature Climate Change, 5*(5), 401-403. doi:10.1038/nclimate2595

Liguori, G., & Di Lorenzo, E. (2018). Meridional Modes and Increasing Pacific Decadal Variability Under Anthropogenic Forcing. *Geophysical Research Letters, 45*(2), 983-991. doi:10.1002/2017GL076548

Liu, N. N. a. E. D. L. (2018). Mechanisms and Predictability of Pacific Decadal Variability. *Current Climate Change Reports*. doi:https://doi.org/10.1007/s40641-018-0090-5

Liu, Y., Saitoh, S.-I., Radiarta, I. N., Isada, T., Hirawake, T., Mizuta, H., & Yasui, H. (2013). Improvement of an aquaculture site-selection model for Japanese kelp (Saccharinajaponica) in southern Hokkaido, Japan: an application for the impacts of climate events. *ICES Journal of Marine Science, 70*(7), 1460-1470. doi:10.1093/icesjms/fst108

Liu, Y., & Sumaila, U. R. (2007). Economic analysis of netcage versus sea-bag production systems for salmon aquaculture in British Columbia. *Aquaculture Economics & Management, 11*(4), 371-395. doi:10.1080/13657300701727235

Liu, Z., & Di Lorenzo, E. (2018). Mechanisms and Predictability of Pacific Decadal Variability. *Current Climate Change Reports, 4*(2), 128-144. doi:10.1007/s40641-018-0090-5

Lluch-Belda, D., Lluch-Cota, D. B., & Lluch-Cota, S. E. (2005). Changes in marine faunal distributions and ENSO events in the California Current. *Fisheries Oceanography, 14*(6), 458-467.

Lockwood, B. L., & Somero, G. N. (2011). Invasive and native blue mussels (genus Mytilus) on the California coast: The role of physiology in a biological invasion. *Journal of Experimental Marine Biology and Ecology, 400*(1), 167-174. doi:https://doi.org/10.1016/j.jembe.2011.02.022

Lorenz, E. N. (1956). *Empirical orthogonal functions and statistical weather prediction* (1). Retrieved from Cambridge, MA.:

Lovatelli, A., Aguilar-Manjarrez, J. & Soto, D., eds. . (2013). *Expanding mariculture farther offshore: technical, environmental, spatial and governance challenges.* . Retrieved from http://www.fao.org/docrep/018/i3092e/i3092e.pdf

Low, N. H. N., Micheli, F., Aguilar, J. D., Arce, D. R., Boch, C. A., Bonilla, J. C., Bracamontes, M. Á., De Leo, G., Diaz, E., Enríquez, E., Hernandez, A., Martinez, R., Mendoza, R., Miranda, C., Monismith, S., Ramade, M., Rogers-Bennett, L., Romero, A., Salinas, C., Smith, A. E., Torre, J., Villavicencio, G., & Woodson, C. B. (2021). Variable coastal hypoxia exposure and drivers across the southern California Current. *Scientific Reports, 11*(1), 10929. doi:10.1038/s41598-021-89928-4

Lynn, R. J., & Simpson, J. J. (1990). The flow of the undercurrent over the continental borderland off southern California. *Journal of Geophysical Research: Oceans, 95*(C8), 12995-13008. doi:https://doi.org/10.1029/JC095iC08p12995

Maar, M., Saurel, C., Landes, A., Dolmer, P., & Petersen, J. K. (2015). Growth potential of blue mussels (M. edulis) exposed to different salinities evaluated by a Dynamic Energy Budget model. *Journal of Marine Systems, 148*, 48-55. doi:http://dx.doi.org/10.1016/j.jmarsys.2015.02.003

MacLeod, M. J., Hasan, M. R., Robb, D. H. F., & Mamun-Ur-Rashid, M. (2020). Quantifying greenhouse gas emissions from global aquaculture. *Scientific Reports, 10*(1), 11679. doi:10.1038/s41598-020-68231-8

Mantyla, A. W., Bograd, S. J., & Venrick, E. L. (2008). Patterns and controls of chlorophyll-a and primary productivity cycles in the Southern California Bight. *Journal of Marine Systems, 73*(1), 48-60. doi:http://dx.doi.org/10.1016/j.jmarsys.2007.08.001

Martiny, A. C., Vrugt, J. A., Primeau, F. W., & Lomas, M. W. (2013). Regional variation in the particulate organic carbon to nitrogen ratio in the surface ocean. *Global Biogeochemical Cycles, 27*(3), 723-731. doi:https://doi.org/10.1002/gbc.20061

Matzelle, A. J., Sarà, G., Montalto, V., Zippay, M., Trussell, G. C., & Helmuth, B. (2015). A bioenergetics framework for integrating the effects of multiple stressors: opening a 'black box'in climate change research. *American Malacological Bulletin, 33*(1), 150-160.

Mayer, P., Estruch, V., Blasco, J., & Jover, M. (2008). Predicting the growth of gilthead sea bream (Sparus aurata L.) farmed in marine cages under real production conditions using temperature- and time-dependent models. *Aquaculture Research, 39*(10), 1046-1052. doi:10.1111/j.1365-2109.2008.01963.x

McPhee-Shaw, E. E., Siegel, D. A., Washburn, L., Brzezinski, M. A., Jones, J. L., Leydecker, A., & Melack, J. (2007). Mechanisms for nutrient delivery to the inner shelf: Observations from the Santa Barbara Channel. *Limnology and Oceanography, 52*(5), 1748-1766. doi:https://doi.org/10.4319/lo.2007.52.5.1748

Meehl, G. A., Hu, A., & Tebaldi, C. (2010). Decadal Prediction in the Pacific Region. *Journal of Climate, 23*(11), 2959-2973. doi:10.1175/2010JCLI3296.1

Meehl, G. A., Hu, A., & Teng, H. (2016). Initialized decadal prediction for transition to positive phase of the Interdecadal Pacific Oscillation. *Nature Communications, 7*, 11718. doi:10.1038/ncomms11718

Menge, B. A., Chan, F., Nielsen, K. J., Di Lorenzo, E., & Lubchenco, J. (2009). Climatic Variation Alters Supply-Side Ecology: Impact of Climate Patterns on Phytoplankton and Mussel Recruitment. *Ecological Monographs, 79*(3), 379-395.

Menge, B. A., Hacker, S. D., Freidenburg, T., Lubchenco, J., Craig, R., Rilov, G., Noble, M., & Richmond, E. (2011). Potential impact of climate-related changes is buffered by differential responses to recruitment and interactions. *Ecological Monographs, 81*(3), 493-509. doi:10.1890/10-1508.1

Merino, G., Barange, M., Blanchard, J. L., Harle, J., Holmes, R., Allen, I., Allison, E. H., Badjeck, M. C., Dulvy, N. K., Holt, J., Jennings, S., Mullon, C., & Rodwell, L. D. (2012). Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate? *Global Environmental Change, 22*(4), 795-806. doi:http://doi.org/10.1016/j.gloenvcha.2012.03.003

Miller, R. J., Page, H. M., & Brzezinski, M. A. (2013). Ã□Â´13C and Ã□Â´15N of particulate organic matter in the Santa Barbara Channel: drivers and implications for trophic inference. *Marine Ecology Progress Series, 474*, 53-66.

Montalto, V., Sarà, G., Ruti, P. M., Dell'Aquila, A., & Helmuth, B. (2014). Testing the effects of temporal data resolution on predictions of the effects of climate change on bivalves. *Ecological Modelling, 278*, 1-8. doi:https://doi.org/10.1016/j.ecolmodel.2014.01.019

Moore, A. M., Arango, H. G., Broquet, G., Edwards, C., Veneziani, M., Powell, B., Foley, D., Doyle, J. D., Costa, D., & Robinson, P. (2011a). The Regional Ocean Modeling System (ROMS) 4-dimensional variational data assimilation systems: Part II – Performance and application to the California Current System. *Progress in Oceanography, 91*(1), 50-73. doi:https://doi.org/10.1016/j.pocean.2011.05.003

Moore, A. M., Arango, H. G., Broquet, G., Edwards, C., Veneziani, M., Powell, B., Foley, D., Doyle, J. D., Costa, D., & Robinson, P. (2011b). The Regional Ocean Modeling System (ROMS) 4-dimensional variational data assimilation systems: Part III – Observation impact and observation sensitivity in the California Current System. *Progress in Oceanography, 91*(1), 74-94. doi:https://doi.org/10.1016/j.pocean.2011.05.005

Moore, A. M., Arango, H. G., Broquet, G., Powell, B. S., Weaver, A. T., & Zavala-Garay, J. (2011c). The Regional Ocean Modeling System (ROMS) 4-dimensional variational data assimilation systems: Part I – System overview and formulation. *Progress in Oceanography, 91*(1), 34-49. doi:https://doi.org/10.1016/j.pocean.2011.05.004

Moore, S. K., Trainer, V. L., Mantua, N. J., Parker, M. S., Laws, E. A., Backer, L. C., & Fleming, L. E. (2008). Impacts of climate variability and future climate change on harmful algal blooms and human health. *Environmental Health, 7*(Suppl 2), S4-S4. doi:10.1186/1476-069X-7-S2-S4

Morris, J., Olin, P., Riley, K., Schubel, J., Thompson, K., Windham, D. (2015). *Offshore Aquaculture in the Southern California Bight*. Retrieved from

Naylor, R., & Burke, M. (2005). AQUACULTURE AND OCEAN RESOURCES: Raising Tigers of the Sea. *Annual Review of Environment and Resources, 30*(1), 185-218. doi:10.1146/annurev.energy.30.081804.121034

Nezlin, N. P., & DiGiacomo, P. M. (2005). Satellite ocean color observations of stormwater runoff plumes along the San Pedro Shelf (southern California) during 1997–2003. *Continental Shelf Research, 25*(14), 1692-1711. doi:https://doi.org/10.1016/j.csr.2005.05.001

Nezlin, N. P., McLaughlin, K., Booth, J. A. T., Cash Curtis, L., Diehl Dario, W., Davis Kristen, A., Feit, A., Goericke, R., Gully Joseph, R., Howard Meredith, D. A., Johnson, S., Latker, A., Mengel Michael, J., Robertson George, L., Steele, A., Terriquez, L., Washburn, L., & Weisberg Stephen, B. (2017). Spatial and Temporal Patterns of Chlorophyll Concentration in the Southern California Bight. *Journal of Geophysical Research: Oceans, 123*(1), 231-245. doi:10.1002/2017JC013324

National Marine Aquaculture Policy (2011).

NOAA. (2015). *Fisheries of the United States* Retrieved from Silver Spring, MD:

NOAA. (2016). *Fisheries of the United States 2015*. Retrieved from http://www.st.nmfs.noaa.gov/Assets/commercial/fus/fus15/documents/FUS2015.pdf;

NOAA. (2017). What does Marine Aquaculture look like in the United States? . Retrieved from https://www.fisheries.noaa.gov/insight/marine-aquaculture#what_does_marine_aquaculture_look_like_in_the_united_states?

NOAA. (2020). NOAA Announces Regions for First Two Aquaculture Opportunity Areas under Executive Order on Seafood. Retrieved from https://www.fisheries.noaa.gov/feature-story/noaa-announces-regions-first-two-aquaculture-opportunity-areas-under-executive-order

Oey, L.-Y., Wang, D.-P., Hayward, T., Winant, C., & Hendershott, M. (2001). "Upwelling" and "cyclonic" regimes of the near-surface circulation in the Santa Barbara Channel. *Journal of Geophysical Research: Oceans, 106*(C5), 9213-9222. doi:https://doi.org/10.1029/1999JC000129

Parnell, P. E., Miller, E. F., Cody, C. E. L., Dayton, P. K., Carter, M. L., & Stebbinsd, T. D. (2010). The response of giant kelp (Macrocystis pyrifera) in southern California to low-frequency climate forcing. *Limnology and Oceanography, 55*(6), 2686-2702. doi:https://doi.org/10.4319/lo.2010.55.6.2686

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I. C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Janion-Scheepers, C., Jarzyna, M. A., Jennings, S., Lenoir, J., Linnetved, H. I., Martin, V. Y., McCormack, P. C., McDonald, J., Mitchell, N. J., Mustonen, T., Pandolfi, J. M., Pettorelli, N., Popova, E., Robinson, S. A., Scheffers, B. R., Shaw, J. D., Sorte, C. J. B., Strugnell, J. M., Sunday, J. M., Tuanmu, M.-N., Vergés, A., Villanueva, C., Wernberg, T., Wapstra, E., & Williams, S. E. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science, 355*(6332).

Peterson, J., Griffis, R., Gulf of, A., Zador, S. G., Sigler, M. F., Joyce, J. E., California, C., Hunsicker, M., Bograd, S., Crozier, L. G., McClatchie, S., Morris Jr, J. A., Peterson, W. T., Price, C., Pacific, I., Woodworth-Jefcoats, P. A., Gulf of, M., Karnauskas, M., Muñoz, R., Schueller, A., Kevin Craig, J., Southeast, U. S. A., Bacheler, N., Burton, M. L., Gore, K., Kellison, T., Morris Jr, J. A., Muñoz, R., Price, C., Northeast, U. S. A., Hare, J. A., Friedland, K. D., & Miller, T. J. (2017). Climate Change Impacts on Fisheries and Aquaculture of the United States. *Climate Change Impacts on Fisheries and Aquaculture*, 159-218. doi:https://doi.org/10.1002/9781119154051.ch8

Pouvreau, S., Bourles, Y., Lefebvre, S., Gangnery, A., & Alunno-Bruscia, M. (2006). Application of a dynamic energy budget model to the Pacific oyster, Crassostrea gigas, reared under various environmental conditions. *Journal of Sea Research, 56*(2), 156-167. doi:http://doi.org/10.1016/j.seares.2006.03.007

Pozo Buil, M., Jacox, M. G., Fiechter, J., Alexander, M. A., Bograd, S. J., Curchitser, E. N., Edwards, C. A., Rykaczewski, R. R., & Stock, C. A. (2021). A Dynamically Downscaled Ensemble of Future Projections for the California Current System. *Frontiers in Marine Science, 8*, 324.

Radiarta, I. N., & Saitoh, S.-I. (2008). Satellite-derived measurements of spatial and temporal chlorophyll-a variability in Funka Bay, southwestern Hokkaido, Japan. *Estuarine, Coastal and Shelf Science, 79*(3), 400-408. doi:https://doi.org/10.1016/j.ecss.2008.04.017

Ramírez-Valdez, A., Aburto-Oropeza, O., Arafeh-Dalmau, N., Beas, R., Caselle, J., Castorani, M., Cavanaugh, K., Edwards, M., Hernandez-Carmona, G., Johnson, A., Leslie, H., Montaño-Moctezuma, G., Micheli, F., Palleiro, J., Parnell, P., Reed, D., Sosa-Nishizaki, O., Torre, J., Torres-Moye, G., & Raimondi, P. (2017). Mexico-California Binational Initiative of Kelp Forest Ecosystems and Fisheries. In.

Ray, N. E., Maguire, T. J., Al-Haj, A. N., Henning, M. C., & Fulweiler, R. W. (2019). Low Greenhouse Gas Emissions from Oyster Aquaculture. *Environmental Science & Technology, 53*(15), 9118-9127. doi:10.1021/acs.est.9b02965

Reed, D. C., Rassweiler A Fau - Carr, M. H., Carr Mh Fau - Cavanaugh, K. C., Cavanaugh Kc Fau - Malone, D. P., Malone Dp Fau - Siegel, D. A., & Siegel, D. A. (2011). Wave disturbance overwhelms top-down and bottom-up control of primary production in California kelp forests. *Ecology*
, 91(11), 2108–2116. doi:https://doi.org/10.1890/11-0377.1

Reid, G. K., Gurney-Smith, H. J., Flaherty, M., Garber, A. F., Forster, I., Brewer-Dalton, K., Knowler, D., Marcogliese, D. J., Chopin, T., Moccia, R. D., Smith, C. T., & De Silva, S. (2019). Climate change and aquaculture: considering adaptation potential. *Aquaculture Environment Interactions, 11*, 603-624.

Roemmich, D., & McGowan, J. (1995). Climatic warming and the decline of zooplankton in the California Current. *Science, 267*(5202), 1324.

Rosland, R., Strand, Ø., Alunno-Bruscia, M., Bacher, C., & Strohmeier, T. (2009). Applying Dynamic Energy Budget (DEB) theory to simulate growth and bio-energetics of blue mussels under low seston conditions. *Journal of Sea Research, 62*(2), 49-61. doi:https://doi.org/10.1016/j.seares.2009.02.007

Ruiz Campo, S., & Zuniga-Jara, S. (2018). Reviewing capital cost estimations in aquaculture. *Aquaculture Economics & Management, 22*(1), 72-93. doi:10.1080/13657305.2017.1300839

Sainz, J. F., Di Lorenzo, E., Bell, T. W., Gaines, S., Lenihan, H., & Miller, R. J. (2019). Spatial Planning of Marine Aquaculture Under Climate Decadal Variability: A Case Study for Mussel Farms in Southern California. *Frontiers in Marine Science, 6*, 253.

Saitoh, S.-I., Mugo, R., Radiarta, I. N., Asaga, S., Takahashi, F., Hirawake, T., Ishikawa, Y., Awaji, T., In, T., & Shima, S. (2011). Some operational uses of satellite remote sensing and marine GIS for sustainable fisheries and aquaculture. *ICES Journal of Marine Science, 68*(4), 687-695. doi:10.1093/icesjms/fsq190

Sanchez-Jerez, P., Karakassis, I., Massa, F., Fezzardi, D., Aguilar-Manjarrez, J., Soto, D., Chapela, R., Ávila, P., Macías, J. C., & Tomassetti, P. (2016). Aquaculture's struggle for space: the need for coastal spatial planning and the potential benefits of Allocated Zones for Aquaculture (AZAs) to avoid conflict and promote sustainability. *Aquaculture Environment Interactions, 8*, 41-54.

Sarà, G., Gouhier, T. C., Brigolin, D., Porporato, E. M. D., Mangano, M. C., Mirto, S., Mazzola, A., & Pastres, R. (2018). Predicting shifting sustainability trade-offs in marine finfish aquaculture under climate change. *Global Change Biology, 24*(8), 3654-3665. doi:https://doi.org/10.1111/gcb.14296

Sarà, G., Reid, G. K., Rinaldi, A., Palmeri, V., Troell, M., & Kooijman, S. A. L. M. (2012). Growth and reproductive simulation of candidate shellfish species at fish cages in the Southern Mediterranean: Dynamic Energy Budget (DEB) modelling for integrated multi-trophic aquaculture. *Aquaculture, 324–325*, 259-266. doi:http://doi.org/10.1016/j.aquaculture.2011.10.042

SCCWRP. (1973). *The ecology of the Southern California Bight: Implications for Water Quality Management* Retrieved from http://ftp.sccwrp.org/pub/download/DOCUMENTS/TechnicalReports/010_3yrRptEcoImplicationsWQmgt.pdf

Schiff, K., Greenstein, D., Dodder, N., & Gillett, D. J. (2016). Southern California Bight regional monitoring. *Regional Studies in Marine Science, 4*, 34-46. doi:https://doi.org/10.1016/j.rsma.2015.09.003

Schmid, M., Fernández, P. A., Gaitán-Espitia, J. D., Virtue, P., Leal, P. P., Revill, A. T., Nichols, P. D., & Hurd, C. L. (2020). Stress due to low nitrate availability reduces the biochemical acclimation potential of the giant kelp Macrocystis pyrifera to high temperature. *Algal Research, 47*, 101895. doi:https://doi.org/10.1016/j.algal.2020.101895

Schneider, K. R., Van Thiel, L. E., & Helmuth, B. (2010). Interactive effects of food availability and aerial body temperature on the survival of two intertidal Mytilus species. *Journal of Thermal Biology, 35*(4), 161-166. doi:http://doi.org/10.1016/j.jtherbio.2010.02.003

Schonher, T., & Nicholson, S. E. (1989). The Relationship between California Rainfall and ENSO Events. *Journal of Climate, 2*(11), 1258-1269. doi:10.1175/1520-0442(1989)002<1258:TRBCRA>2.0.CO;2

Sekula-Wood, E., Benitez-Nelson, C., Morton, S., Anderson, C., Burrell, C., & Thunell, R. (2011). Pseudo-nitzschia and domoic acid fluxes in Santa Barbara Basin (CA) from

1993 to 2008. *Harmful Algae, 10*(6), 567-575. doi:http://doi.org/10.1016/j.hal.2011.04.009

Shchepetkin, A. F., & McWilliams, J. C. (2005). The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model. *Ocean Modelling, 9*(4), 347-404. doi:https://doi.org/10.1016/j.ocemod.2004.08.002

Shinen, J., & Morgan, S. (2009). Mechanisms of invasion resistance: competition among intertidal mussels promotes establishment of invasive species and displacement of native species. *Marine Ecology-progress Series - MAR ECOL-PROGR SER, 383*, 187-197. doi:10.3354/meps07982

Shoffler, S. M. (2015). The Promise of Aquaculture. *Edible San Diego*

Smith, J. R., Fong, P., & Ambrose, R. F. (2009). Spatial patterns in recruitment and growth of the mussel Mytilus californianus (Conrad) in southern and northern California, USA, two regions with differing oceanographic conditions. *Journal of Sea Research, 61*(3), 165-173. doi:https://doi.org/10.1016/j.seares.2008.10.009

Smith, T. M., & Reynolds, R. W. (2004). Improved Extended Reconstruction of SST (1854?1997). *Journal of Climate, 17*(12), 2466-2477. doi:10.1175/1520-0442(2004)017<2466:IEROS>2.0.CO;2

Snyder, J. N., Bell, T. W., Siegel, D. A., Nidzieko, N. J., & Cavanaugh, K. C. (2020). Sea Surface Temperature Imagery Elucidates Spatiotemporal Nutrient Patterns for Offshore Kelp Aquaculture Siting in the Southern California Bight. *Frontiers in Marine Science, 7*, 22.

Snyder, M. A., Sloan, L. C., Diffenbaugh, N. S., & Bell, J. L. (2003). Future climate change and upwelling in the California Current. *Geophysical Research Letters, 30*(15), n/a-n/a. doi:10.1029/2003GL017647

Soto, D., Aguilar-Manjarrez, J., Hishamunda, N. . (2008). *Building an ecosystem approach to aquaculture.* (No. 14.). Retrieved from Rome:

Spillman, C. M., & Hobday, A. J. (2014). Dynamical seasonal ocean forecasts to aid salmon farm management in a climate hotspot. *Climate Risk Management, 1*, 25-38. doi:http://dx.doi.org/10.1016/j.crm.2013.12.001

Stone, H. B., Banas, N. S., MacCready, P., Kudela, R. M., & Ovall, B. (2020). Linking Chlorophyll Concentration and Wind Patterns Using Satellite Data in the Central and Northern California Current System. *Frontiers in Marine Science, 7*, 842.

Sumaila, U. R., Cheung, W. W. L., Lam, V. W. Y., Pauly, D., & Herrick, S. (2011). Climate change impacts on the biophysics and economics of world fisheries. *Nature Clim. Change, 1*(9), 449-456.

Sydeman, W. J., Santora, J. A., Thompson, S. A., Marinovic, B., & Lorenzo, E. D. (2013). Increasing variance in North Pacific climate relates to unprecedented ecosystem variability off California. *Global Change Biology, 19*(6), 1662-1675. doi:https://doi.org/10.1111/gcb.12165

Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society, 93*(4), 485-498. doi:https://doi.org/10.1175/BAMS-D-11-00094.1

Thomas, L. R., Clavelle, T., Klinger, D. H., & Lester, S. E. (2019). The ecological and economic potential for offshore mariculture in the Caribbean. *Nature Sustainability, 2*(1), 62-70. doi:10.1038/s41893-018-0205-y

Thomas, Y., Mazurié, J., Alunno-Bruscia, M., Bacher, C., Bouget, J.-F., Gohin, F., Pouvreau, S., & Struski, C. (2011). Modelling spatio-temporal variability of Mytilus edulis (L.) growth by forcing a dynamic energy budget model with satellite-derived environmental data. *Journal of Sea Research, 66*(4), 308-317. doi:https://doi.org/10.1016/j.seares.2011.04.015

Tiller, R., Gentry, R., & Richards, R. (2013). Stakeholder driven future scenarios as an element of interdisciplinary management tools; the case of future offshore aquaculture development and the potential effects on fishermen in Santa Barbara, California. *Ocean & Coastal Management, 73*, 127-135. doi:https://doi.org/10.1016/j.ocecoaman.2012.12.011

Trainer, V. L., Kudela, R. M., Hunter, M. V., Adams, N. G., & McCabe, R. M. (2020). Climate Extreme Seeds a New Domoic Acid Hotspot on the US West Coast. *Frontiers in Climate, 2*, 23.

U.S.CensusBureau. (2010). *United States Census Interactive Map*. Retrieved from https://www.census.gov/2010census/popmap/.

Valentine, J. W. (1966). Numerical analysis of marine molluscan ranges on the extratropical Northeastern Pacific Shelf. . *Limnology and Oceanography, 11*(2), 198-211. doi:10.4319/lo.1966.11.2.0198

Van Haren, R. J. F., & Kooijman, S. A. L. M. (1993). Application of a dynamic energy budget model to Mytilus edulis (L.). *Netherlands Journal of Sea Research, 31*(2), 119-133. doi:https://doi.org/10.1016/0077-7579(93)90002-A

Weisser, M. (2016). The government wants more offshore fish farms, but no one is biting *The Guardian*.

Whitmarsh, D. J., Cook, E. J., & Black, K. D. (2006). Searching for sustainability in aquaculture: An investigation into the economic prospects for an integrated salmon–mussel production system. *Marine Policy, 30*(3), 293-298. doi:https://doi.org/10.1016/j.marpol.2005.01.004

Wildlife, C. D. o. F. a. (2016). *Regulations governing leasing of State water bottoms for Aquaculture* Sacramento, CA: The Natural Resources Agency of California Retrieved from https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=27450&inline.

World-Bank. (2013). *Fish to 2030. Prospects for Fisheries and Aquaculture.* Retrieved from

Xiu, P., Chai, F., Curchitser, E. N., & Castruccio, F. S. (2018). Future changes in coastal upwelling ecosystems with global warming: The case of the California Current System. *Scientific Reports, 8*(1), 2866. doi:10.1038/s41598-018-21247-7

Xu, T., Newman, M., Capotondi, A., & Di Lorenzo, E. (2021). The Continuum of Northeast Pacific Marine Heatwaves and Their Relationship to the Tropical Pacific. *Geophysical Research Letters, 48*(2), 2020GL090661. doi:https://doi.org/10.1029/2020GL090661

Young Cho, C., & Bureau, D. P. (1998). Development of bioenergetic models and the Fish-PrFEQ software to estimate production, feeding ration and waste output in aquaculture. *Aquat. Living Resour., 11*(4), 199-210.

Yuen, J. W., Dempster, T., Oppedal, F., & Hvas, M. (2019). Physiological performance of ballan wrasse (Labrus bergylta) at different temperatures and its implication for cleaner fish usage in salmon aquaculture. *Biological Control, 135*, 117-123. doi:https://doi.org/10.1016/j.biocontrol.2019.05.007

Zacherl, D., Gaines, S. D., & Lonhart, S. I. (2003). The limits to biogeographical distributions: insights from the northward range extension of the marine snail, Kelletia kelletii (Forbes, 1852). *Journal of Biogeography, 30*(6), 913-924. doi:10.1046/j.1365-2699.2003.00899.x

Zeldis, J. R., Howard-Williams, C., Carter, C. M., & Schiel, D. R. (2008). ENSO and riverine control of nutrient loading, phytoplankton biomass and mussel aquaculture yield in Pelorus Sound, New Zealand. *Marine Ecology Progress Series, 371*, 131-142.

Zhu, Z., Qu, P., Fu, F., Tennenbaum, N., Tatters, A. O., & Hutchins, D. A. (2017). Understanding the blob bloom: Warming increases toxicity and abundance of the harmful bloom diatom Pseudo-nitzschia in California coastal waters. *Harmful Algae, 67*, 36-43. doi:https://doi.org/10.1016/j.hal.2017.06.004

Zimmerman, R. C., & Kremer, J. N. (1984). Episodic nutrient supply to a kelp forest ecosystem in Southern California. *Journal of Marine Research, 42*(3), 591-604. doi:10.1357/002224084788506031