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Intertidal Responses to ENSO Patterns

Evie L. Andrade

Scripps College

Intertidal Responses to ENSO Patterns

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Evie Leilin Andrade

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Abstract

ENSO (the El Nino-Southern Oscillation) is a periodic ocean phenomenon that results in warm periods (El Nino) and cooling periods (La Nina). ENSO influences the upwelling patterns along the California Coast and by extension, the ability of marine invertebrate larvae to recruit back to shore. During La Nina years, when upwelling is strengthened, the rising deep sea water causes offshore advection that diverts mobile larvae away from the intertidal habitats which the adults inhabit. Contrastingly, El Nino periods weaken upwelling and could increase larval recruitment. I tested the relationship between ENSO state and larval recruitment by analyzing a 10-year time series of mussel (*Mytilus californianus*) and barnacle (*Chthamalus spp/Balanus glandula*) populations with a Mixed-Model ANOVA; shifts in population size served as an indicator of changes in recruitment. I also tested for differences in the effect of ENSO among three regions: CA North, CA Central, and CA South. The results reveal that barnacles (*Chthamalus spp*/*Balanus glandula*) are more sensitive to ENSO conditions while mussels (*Mytilus californianus*) are not affected by it. Barnacle percent cover increases by 0.200% for each unit increase in the ENSO value index. Despite this minuscule increase, the experiment does provide proof that ENSO's effect on upwelling influences larvae recruitment for certain intertidal species. Understanding how ENSO influences barnacle percent cover shows that certain species are sensitive to extreme weather events and these induced alterations to percent cover could influence the surrounding ecological structure.

Introduction

The El Nino-Southern Oscillation (ENSO) is a 12-month long phenomenon that occurs when interactions between the atmosphere and ocean result in a warming period, an El Nino, or a cooling period, a La Nina (Yocom et al., 2010; NOAA Climate.gov, 2020). During these periods, changes in sea surface temperature (SST), atmosphere and ocean processes, and warm water accumulation occur in the Pacific's equatorial region. Though ENSO events are identified as changes in the tropical Pacific, they have a cascading effect and can alter the salinity, temperature, and circulation in different parts of the California Coastline (Connolly et Roughgarden, 1999). This means that California intertidal fauna and their surrounding environment can be susceptible to ENSO conditions.

ENSO affects the coastline or intertidal habitat, and upwelling has a prominent role in this relationship. Upwelling occurs when both Coriolos effect and the earth's circulation displace warm SST water offshore, and deep, cold water comes up to take its place. In the Pacific Ocean, upwelling typically occurs in the East Pacific, such as the California Coastline, while warm surface water gets displaced to the West Pacific (Broitman et al., 2008). During an El Nino event, the decreased equatorward winds and weakened upwelling will allow warm water to accumulate along the California Coastline (Jacox et al., 2015). As for La Nina, the phenomenon strengthens the normal upwelling process described by the Broitman et al. (2008) study.

ENSO influence on upwelling likely affects larvae recruitment for California intertidal populations. Though intertidal species such as mussels and barnacles are sessile adults, their larvae counterparts are mobile; the latter travel through ocean circulation (Murosaki et al., 2012; Pfeiffer-Herbert et al., 2007). However, this tactic subjects them to upwelling activity. When warm surface water gets displaced, it is called offshore advection; the process prevents larvae from reaching the shore. El Nino reduces upwelling and by extension, it is hypothesized to increase larvae recruitment and strengthen population growth (Connolly et al., 1999; Harley et al., 2006). In contrast, La Nina can catalyze both upwelling and offshore advention. As a result, planktonic larvae is diverted away from the intertidal area (Jacox et al., 2015; Harley et al., 2006).

Studies, such as the Connolly and Roughgarden (1999), provide evidence for an existing correlation between ENSO and intertidal fauna population size. Their study reveals that the decreased upwelling caused by the 1997 El Nino resulted in a higher recruitment of barnacle larvae. This outcome also implies that a La Nina will have a contrasting effect since it intensifies the upwelling process. However, their research does not cover El Nino over a longer time scale, test the effects of La Nina on barnacle recruitment, nor does it analyze other species besides barnacles. Having a single El Nino event to represent the overarching relationship does not provide sufficient data.

I sought to test if the effects of ENSO on recruitment would alter adult abundance of two common intertidal invertebrates, mussels and barnacles, along the California Coast. More specifically, I will test whether an El Nino event increases mussel and barnacle population percent cover by the end of the 12 months and whether a La Nina produces a contrasting effect.

Also, I tested whether latitudinal differences influenced the relationship between ENSO conditions and percent cover. This is because lower latitudinal regions, such as Southern California, could be more susceptible to ENSO events (Jacox et al., 2015). I expected that lower latitude regions will experience a stronger ENSO event while higher latitude regions will experience a weaker one.

Methods

Data Collection

The UC Santa Cruz MARINe (Multi-Agency Rocky Intertidal Network) is a collaboration of academic and government agencies that conduct a long-term annual survey of marine species from Alaska to Mexico. I selected the *Mytilus californianus* and *Chthamalus spp/Balanus glandula* as the specimens for my project; the survey data spanned from 2005 to 2015. The *Mytilus californianus* is a mussel species while the *Chthamalus spp/Balanus glandula* are a group of barnacle species. These groups were selected because they were present in the experiment's sites and throughout the California Coast (Broitman et al., 2008; MARINe, 2020).

I used the data to select nine sites with three in each georegion (CA North, CA Central, and CA South georegion) or location where the temperature and data were collected. The selection process required adjustments to limit interfering variables. All nine sites share similar habitat features, such as uneven sloped terrain and a variety of bedrock; the similarity of the habitat structures ensures that the populations were in comparable environments throughout the experiment. Next, the sites contained plots where mussels and barnacles were present in their own targeted and dominant assemblage. This factor eliminated competition between barnacles and mussels as an interfering variable in population size. Finally, the sites were selected based on the seasonal sampling and availability. For example, the MARINe database contained summer percent cover data for most of the sites in the CA North region, but it had limited percent cover for the spring, fall, and winter season. Table 1 shows that CA North features summer population data while the CA Central and South georegions feature spring population data.

Table 1. Selected sites, with description, for each of the CA regions.

Region	Site Name	Latitude & Longitude (order)	Survey Year	Season Sampled
CA North	Cape Mendocino	41.69000 N -124.1426 W	2005-2015	Summer
CA North	Damnation Creek	41.65249 N -124.1278 W	2005-2015	Summer
CA North	Enderts	40.34100 N -124.3632 W	2005-2015	Summer
CA Central	Hazards	35.28966 N -120.8833 W	2005-2015	Spring
CA Central	Occulto	34.88122 N -120.6395 W	2005-2015	Spring
CA Central	Point Sierra Nevada	35.72883 N -121.3187 W	2005-2015	Spring
CA South	Arroyo Hondo	34.47344 N -120.1454 W	2005-2015	Spring
CA South	Carpinteria	34.38703 N -119.5141 W	2005-2015	Spring
CA South	Mussel Shoals	34.35548 N -119.4407 W	2005-2015	Spring

The sites for each region served as georegion replicates to strengthen the data's reliability and the accuracy of population response to ENSO. Also, having three regions that span through the California Coastline helps make the sample more representative of the mussel and barnacle populations distributed there. This prevents the experiment from favoring one location and accounts for latitudinal differences influencing a population's response to El Nino periods.

ENSO Index

Generally, La Nina and El Nino are periodic weather phenomena that are identified by extreme shifts from the long-term average SST of the tropical Pacific. If the tropical Pacific SST experiences an increase larger than 0.5 ℃ from the long-term monthly averages, then it is an El Nino. If it experiences a decrease less than -0.5 ℃, then it is a La Nina. This warming or cooling must persist for "five consecutive overlapping three month periods" to be considered a La Nina or an El Nino (noaa.gov, 2016). For example, January/February/March, February/March/April, March/April/May, April/May/June, and May/June/July would be a sequence that fits the description. The 12-month period ran from 2005 to 2015 and was finished to precede the following spring interval: February/March/April.

This choice also assumes that after the late summer, early fall spike in barnacle and mussel recruitment, the mature phase will be completed and contribute to the percent cover while the ENSO event takes place (Murosaki et al., 2012; Broitman et al., 2008). Due to this choice, I started my ENSO period a month or two earlier--between February to April--from the season the MARINe percent cover was collected so I could address hypothetical lag and development in between the ENSO period and population data collection.

After calculating the ENSO index (the average deviation from the expected tropical Pacific SST), I classified them with an ENSO condition and juxtaposed them with their respective year. The following results are shown on Table 2. Note, I did not just use the average SST anomaly to determine the El Nino condition. I also took into account the frequency of +/-0.5 ℃ intervals. For example, 2006 was classified as a weak El Nino and had a higher value than 2014's -0.292 ℃, but NOAA's Oceanic Nino Index shows that it had more instances of <-0.5 ℃

SST anomalies while 2006 still remained close to the long-term average (noaa.gov, 2001). I addressed the intensity of the El Nino and La Nina periods beforehand, based on the following.

1. Having exactly five three-month periods of the phenomenon is a neutral ENSO period
2. Having more than five three-month periods is a stronger phenomenon
3. Having less than five three-month periods with minor overlap is a weaker phenomenon

Table 2. Average SST anomaly value with respective year and ENSO classification.

Year	**SST (Celcius)**	**Classification**
2005	0.475	El Nino
2006	-0.167	Weak La Nina
2007	0.225	Weak El Nino
2008	-0.867	Strong La Nina
2009	-0.617	Strong La Nina
2010	0.625	Strong El Nino
2011	-0.842	Strong La Nina
2012	-0.708	Strong La Nina
2013	-0.0667	No ENSO
2014	-0.292	No ENSO
2015	0.292	Weak El Nino

Statistical Analysis

I used two separate, two-factor Mixed Model ANOVAs to test the effect of ENSO condition and georegion on the mussel and barnacle percent cover. The analyses were conducted in R-studio with the lmer function and package (RStudio Team, 2020). The two fixed variables for the experiment are ENSO index averages and georegion locations (CA North, CA Central, and CA South). The averages were treated as continuous data while the georegions were treated as categorical data.

The other variables in the experiment included the randomly selected sites and the responding percent cover for barnacles and mussels. In contrast to the fixed variables, the nine sites were randomly selected out of a given set and not predetermined prior to the experiment. As for the responding variable, I arcsine-transformed the percent cover data to meet normality assumption for the ANOVA test.

Results

Barnacles

The barnacle data responds more sensitively to ENSO conditions; this indicates that ENSO-induced upwelling influences their recruitment patterns (DF: 1, F-value: 4.05, Pr>F: 0.0448). Furthermore, georegions do not influence ENSO intensity (DF: 2, F-value: 0.0377, Pr>F: 0.963) or have a direct relationship with the barnacle percent cover (DF: 2, F-Value: 0.388, Pr>F: 0.694).

These findings can be reinforced by Figures 1 and 2; they feature the responding barnacle percent cover with the ENSO conditions described in Table 2. In Figure 2, the x-axis consists of the Table 2's SST values with red representing an El Nino while the blue represents a La Nina.

Figure 1 features the Table 2's ENSO conditions; red and blue still represent the same thing, but a darker hue represents a stronger period while a lighter hue indicates a weaker one. Both of these figures show that the nine sites' barnacle percent cover varies with ENSO value. There are drastic shifts between percent covers, such as the 40% to 10% to 75% percent cover shifts Mussel Shoal experienced from 2005 to 2006 to 2007 respectively.

It is important to note that despite the P-value and the variance among sites, the overall influence is not physically noticeable. The slope value for Figure 2 is 0.20; this means that the general percent cover change for each unit increase in the ENSO index is only 0.20%.

Table 3. Mixed Model ANOVA summary for Barnacles and Mussels.

Effect	SS	MS	DF	F-Value	Pr (>F)
Barnacle					
georegion	0.0510	0.0255	2	0.388	0.694
ENSO	0.266	0.267	1	4.05	0.0448
georegion × ENSO	0.00497	0.00248	2	0.0377	0.963
Mussel					
georegion	0.592	0.296	2	4.68	0.0593
ENSO	0.00378	0.00378	1	0.0598	0.807
georegion × ENSO	0.128	0.0642	2	1.02	0.362

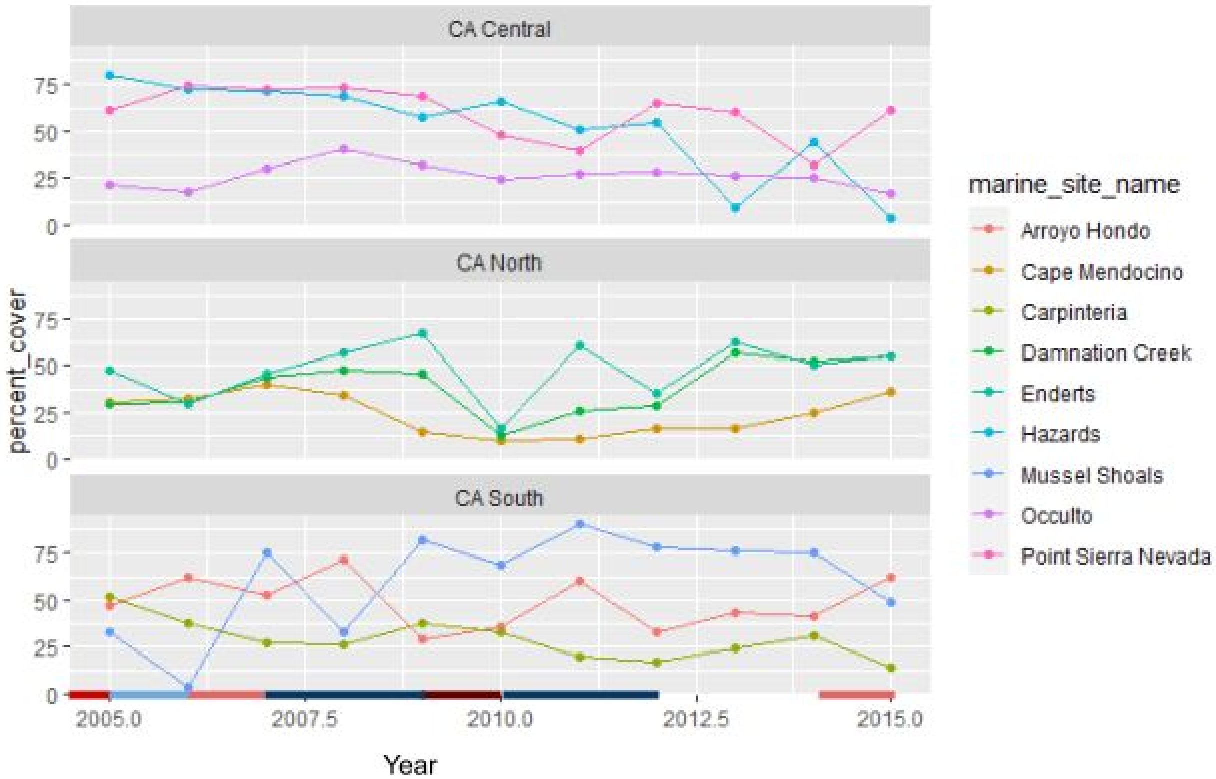

Figure 1. Features the years from 2005 to 2015 and their corresponding, annual barnacle percent cover; x-axis is color-coded with ENSO conditions.

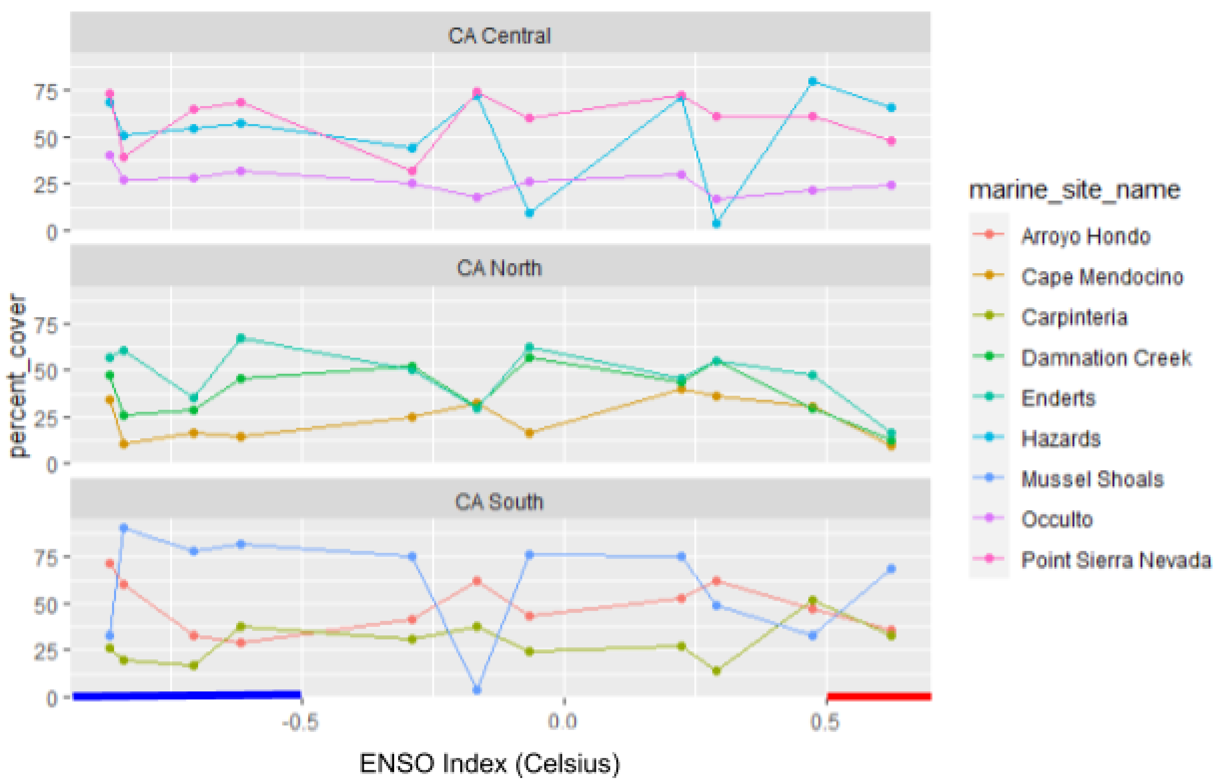

Figure 2. Barnacle percent cover with ENSO index values from Table 2.

Mussels

Table 3 reveals that mussels are not influenced by ENSO conditions from 2005 to 2015 (DF: 1, F-value: 0.0598, Pr>F: 0.807). By extension, georegions do not directly influence the mussel percent cover (DF: 2, F-value: 4.68, Pr>F:0.0593) or affect the ENSO conditions (DF: 2, F-value: 1.02, Pr>F: 0.362). The overall slope, for Figure 4, between the ENSO index and percent cover is only 0.00407.

Figures 3 and 4 stress the fact that most of the mussel populations generally remain the same regardless of the changes in ENSO conditions; color code on the Figure 3 x-axis is the same as Figure 1, and color code on the Figure 4 x-axis is the same as Figure 2. Figure 3 shows that the percent cover remains the same throughout the duration of the experiment, and this is prominent in the CA North and CA Central regions. For example, mussel percent cover in Point Sierra Nevada is within the 75 to 85 % range while areas like Damnation Creek have maintained close to 90% each year. True, there are some shifts in percent cover in the CA South sites, but these changes are only prominent in two (Carpinteria and Mussel Shoals) out of the nine sites in Figure 3. Most of the sites do not respond sensitively to the ENSO conditions.

Figure 4 also features minor instances in percent cover shift, but the general trends are linear in comparison to the barnacles in Figure 2. This can be shown with the difference of barnacle and mussel populations in the Hazards site (in CA Central). In Figure 2, barnacle percent cover along the ENSO index-axis shifts from values ranging from less than 25% to 75% at most. In contrast, Hazards site percent cover ranges between 25 to 38% for Figure 4. Furthermore, the slope value for Figure 4 is lower since it has a 0.004 value, showing that mussels percent cover has a weaker relationship with the ENSO index while barnacles maintain a stronger one.

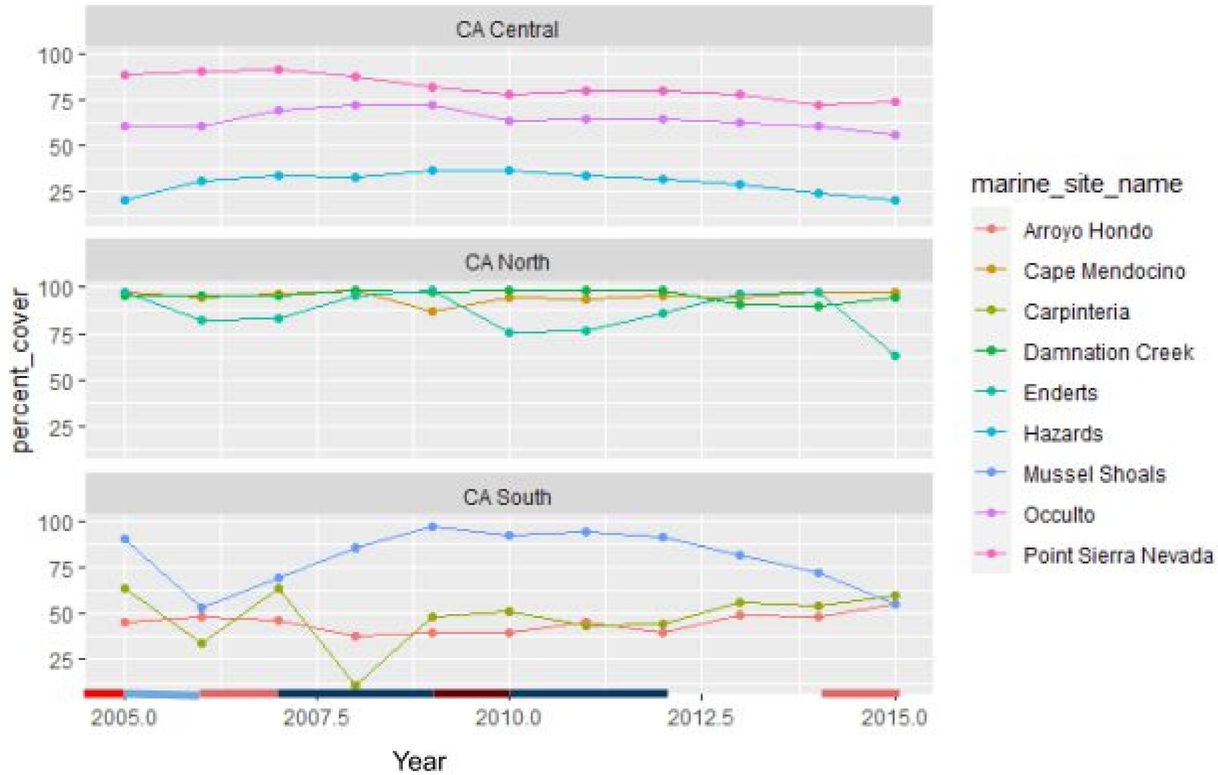

Figure 3. Features the years from 2005 to 2015 and their corresponding, annual mussel percent cover; x-axis is color-coded with ENSO conditions.

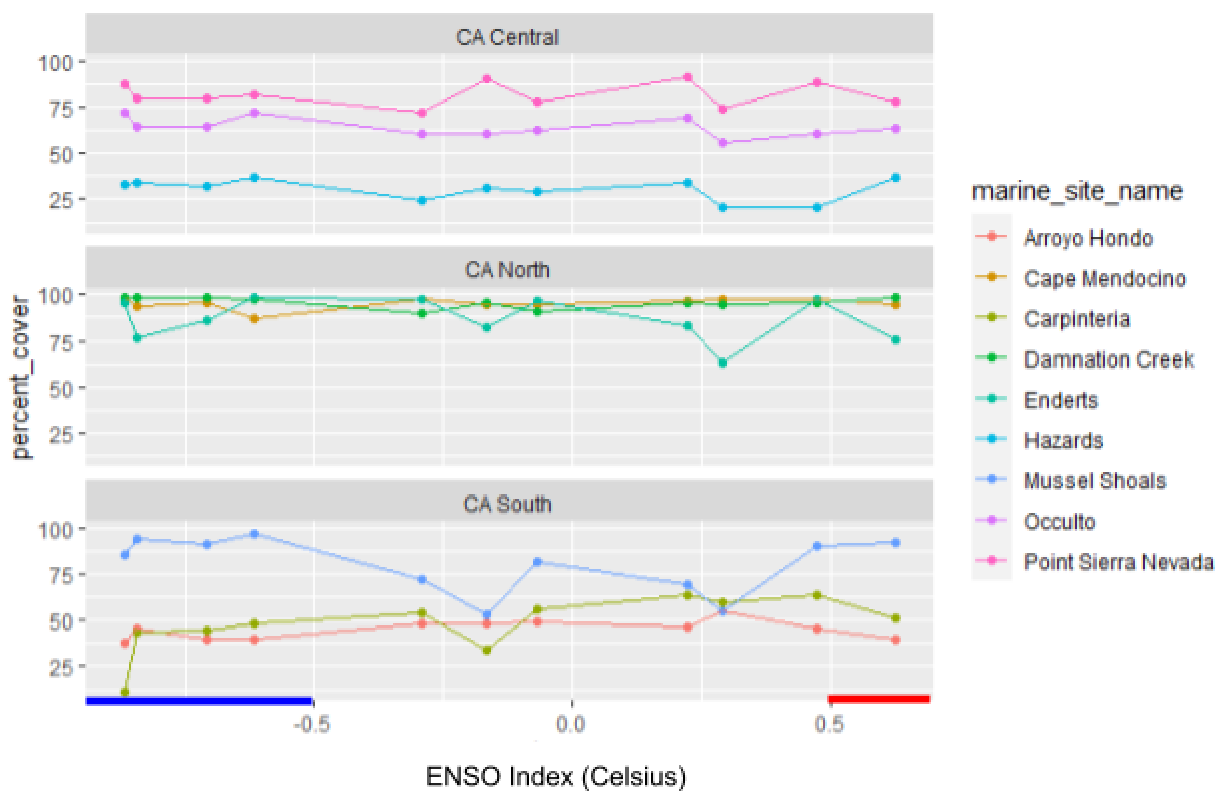

Figure 4. Mussel percent cover to ENSO index values from Table 2.

Discussion

Connolly and Roughgarden (1999) suggested a potential relationship between ENSO and intertidal fauna population size across the California Coastline. I sought to further test their hypotheses by analyzing a decade's worth of adult barnacle and mussel percent cover data from the California Coastline. I expected to find that El Nino years led to increased population sizes while a La Nina strengthened upwelling and decreased population size. The results reveal that only barnacles are affected by ENSO conditions. Since the general percent change with an ENSO unit increase is only 0.2%, ENSO does not drastically increase the population size. Therefore, I found limited evidence for Connolly and Roughgarden's theory.

Tropical ENSO activity on upwelling clearly influences the California Coastline habitat, but only certain species respond to it. In my experiment, barnacle populations in California's north, central, and southern regions respond sensitively to ENSO conditions; its P-value and 0.20 slope value indicate that barnacle population size will increase in response to higher ENSO indices. In contrast, the mussel populations in the same region maintain a consistent population size and do not fluctuate as much, compared to the barnacles. Connolly and Roughgarden (1999) reaffirm ENSO's effects in their barnacle recruitment study: El Nino yields unusually high larvae recruitment in most of the sites that they studied. These results were then juxtaposed with evidence of El Nino increasing recruitment by weakening upwelling: increased onshore flow, downwelling, and anomalously high sea levels present in the area. Though their study was done for one El Nino period and analyzed larvae rather than the adult population, my experiment confirms that ENSO conditions influence barnacle population size and a high ENSO index correlates with a high percent cover. Though the change is minimal, it still exists.

I originally hypothesized that lower latitude regions of California would show a stronger ENSO signal. Due to ENSO being stronger at lower latitudes, ENSO intensity should increase with latitudinal decrease (Jacox et al., 2015). However, I found no significant differences among georegions and their influence on the relationship between ENSO conditions and intertidal populations. Connolly and Roughgarden (1999) encountered a similar outcome: all the sites experienced increased recruitment, regardless of georegion. While variation among sites had an apparent influence on barnacle abundance, there is another explanation for this situation. My experiment did feature a latitudinal difference, but it was fairly small, only 7-8 degrees. Furthermore, Connolly and Roughgarden (1999) conducted their study in a 5-degree latitudinal difference, meaning their population sites were closer to each other in comparison to my study. A larger latitudinal range might have made it easier to detect latitudinal differences. This approach was done in the Broitman et al., (2008) and Connolly et al. (2001) studies; they noticed differences in barnacle recruitment when comparing Oregon (a higher latitudinal state) to Southern California. Rather than selecting just three regions along the California Coastline, my experiment could have utilized population data from Oregon, California, and a tropical region within the 20-degree or lower range.

Despite the 0.20 slope value, it is likely that the delayed and prolonged effects of ENSO are present. ENSO is described as a delayed oscillator because entering or transitioning into a certain ENSO phase is not immediate (Wang et Weisberg, 1994). The time lag between phase transitioning can likely prolong the previous phases' effects on intertidal population, even in areas with overlapping ENSO conditions. In Figures 1, the 2005-to-2012-time interval is dominated by strong and frequent La Nina periods; trial areas such as Cape Mendocino, Carpinteria, Damnation Creek, and Occulto experienced less than 50% barnacle percent cover throughout the 2005 to 2015. Additionally, the Hazards site originally started out with a 75% barnacle cover, but over the course of the 2005-to-2012-time interval, the percent cover decreased to the 50% range by 2012 and did not get any higher for the remaining years.

Due to the La Nina dominance and its prolonged effect, the experiment could have been improved and provided clearer results on ENSO's influence. A longer time series of percent cover would have provided more ENSO indices to analyze. The 2005 to 2015 data is biased towards intense and frequent La Nina periods. More annual percent cover and the ENSO index value associated with them could have provided more El Nino and Normal conditions to input to the data set. For example, there was one main instance of a strong El Nino event that took place in 2010. In Figure 1, after the 2010 Strong El Nino, over half of the trials (Arroyo Hondo, Enderts, Damnation Creek, Mussel Shoals, and Point Sierra Nevada) experienced a mild increase in barnacle percent cover, indicating that larvae recruitment may have experienced an increase despite the time interval being dominated by frequent La Nina periods. Integrating percent cover data could have supported or disproved whether El Nino events did improve population size, rather than relying on a singular event like the Connolly and Roughgarden (1999) reading.

Overall, the experiment is a starting point for studying ENSO's influence on California's intertidal population ecology. It proved Connally and Roughgarden's (1999) findings to some extent, but conflicting factors such as close proximity of the regions studied and dominant ENSO conditions affected the experimental outcome. Therefore, using a larger data set and greater distance between sites can improve future attempts of my experiment and provide more concrete results.

Conclusion

ENSO conditions do influence population size of certain species, such as the *Chthamalus/Balanus Glandula* barnacles, by impacting their larvae recruitment; however, the overall effect is minimal. For researchers who want to recreate my experiment, I recommend utilizing a more advanced ANOVA model, a longer timer series for population data, and regions with more distinct latitudinal differences. Barnacle recruitment and population size responding to varying ENSO conditions is an indicator that marine species (that travel through sea currents) and their population sizes can be susceptible to intense weather phenomena. Furthermore, if certain species are affected by ENSO, they could experience more intense environmental stress due to global warming evolving and coinciding with the ENSO process (Latif et Keenlyside, 2009). By utilizing historical data and testing how the population sizes of polyps, fish, sea stars, etc. respond to various ENSO events over given time period, the information can be used to better understand how the shifts in population sizes alter the surrounding coastal environment and develop management strategies to mitigate the negative effect of future ENSO events.

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