Appendix A

Evaluation of Anthropogenic Impacts on the San Diego Coastal Kelp Forest Ecosystem (Biennial Project Report)

2018–2019

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Appendix A. Evaluation of Anthropogenic Impacts on the San Diego Coastal Kelp Forest

Executive Summary

The City of San Diego (City) may be the most "ocean oriented" city in the world. The kelp forests off San Diego provide habitat to hundreds of species and are the focus of millions of dollars of commercial and recreational fishing. In fact, the Point Loma kelp forest is the largest kelp forest in the world and supports perhaps the most valuable commercial and recreational coastal fisheries in southern California. It is one of the most important areas for recreational diving in the country. Like coral reefs, kelp forests are one of the most charismatic marine communities, and because they are the most intensively studied kelp forests ecosystems worldwide, San Diego's kelp forests are an icon of the habitat. They represent the charismatic and valuable habitat in the minds of people worldwide. However, environmental perturbations associated with climate change are altering the local kelp forests in such a way that the giant kelp (*Macrocystis pyrifera*) itself may eventually disappear. Localized human impacts such as waterborne pollution can potentially accelerate this loss if not properly managed by interfering with kelp forest recovery after larger scale ocean climate disturbances.

Kelp forests are highly productive, characterized by the rapid growth of their structural species, *Macrocystis pyrifera*, whose rate of primary production can exceed that of tropical rain forests (Towle and Pearse 1973). Giant kelp forests provide food and shelter for a host of fishes and invertebrates as well as cohabiting species of algae. These forests occupy the inner margins of the continental shelf and offshore islands extending from the offshore edge of tidepools to depths as great as thirty meters off southern California. Kelp forests also host a range of economically and aesthetically important consumptive and non-consumptive human activities including boating, recreational fishing, spearfishing, SCUBA diving, and the commercial harvest of finfishes, invertebrates, and algae. The kelp forests off Point Loma and La Jolla are among the most important commercial fishing grounds for the red sea urchin (*Mesocentrotus franciscanus*) and spiny lobster (*Panulirus interruptus*) fisheries off California. The kelp forests of La Jolla and Point Loma are the largest contiguous kelp forests off the western coast of the U.S. They host complex marine communities supported by their eponymous species, giant kelp (*M. pyrifera*), which provides structure and food for hundreds of species of fish and invertebrates.

Kelp forests off southern California are subjected to both natural and human-induced disturbance. El Niño Southern Oscillations (ENSO) are the primary ocean climate mode that affects kelp abundance, growth, and reproduction along the west coast of the Americas. Positive ENSOs known as El Niño are associated with warm water, depressed concentrations of nitrate (the principal nutrient limiting giant kelp), and a more energetic storm environment off southern California. Both phenomena can severely stress giant kelp and accompanying species of algae. The opposite conditions occur during negative ENSO events, termed La Niña, enhancing both the growth and reproduction of kelps. Together, the two ocean climate modes drive the greatest amount of annual variability in surface canopy cover of *Macrocystis pyrifera* off southern and Baja California. The periodicity of El Niño is variable, typically occurring at 3–5 year intervals and persisting for <1 year. Kelp forests wax and wane over these cycles, experiencing high mortality during El Niño with recovery afterwards. Rates of recovery depend on growth conditions after an El Niño ebbs. The kelp forests off San Diego have been studied by researchers at the Scripps Institution of Oceanography (SIO), of UC San Diego, since the 1950s, and baseline data began in the 1970s. Currently, kelps and associated animals are monitored at twenty permanent study sites located among the Point Loma, La Jolla, and North County kelp forests.

During the current reporting period (2018–2019), the kelp forests off California have been recovering from severe temperature and nutrient stress that began in late 2013 and persisted until the spring of 2017. This lengthened period of stress was due to the combination of two consecutive ocean climate events. An anomalous surface warm pool extended across much of the NE Pacific from 2014–2015. This warm pool, unique in the climate record of the NE Pacific, was coined the BLOB and resulted from large scale wind patterns in the NE Pacific. This causative forcing is therefore different in nature and scale than ENSO cycles which are caused by anomalous winds along the equatorial Pacific. A strong El Niño occurred during fall of 2015 and the winter of 2016 just as the BLOB dissipated. Together, these consecutive warm periods are now referred to as the NE Pacific marine heat wave, and manifested as the longest and warmest period ever observed in the 104-year-old sea surface temperature record at the SIO pier. Cooler conditions returned to the equatorial eastern Pacific and the Southern California Bight (SCB) by late 2016. The spring upwelling seasons of 2017–2019 brought cool nutrient-laden waters up onto the inner continental shelf of southern California creating favorable conditions for giant kelp recovery. However, the variability of El Niño climate cycles is superimposed onto a larger scale trend of increasing ocean temperatures within the California Current System and the world's oceans generally, and it is likely that conditions supportive of giant kelp growth and reproduction will decrease in frequency and duration over the next century. As a result, deleterious effects due to climate are likely within the next decade. This will result in an increased susceptibility to anthropogenic stress and an overall decreased resilience after heat wave disturbances as the century progresses. Presently, however, there is no evidence of direct human stress on the marine algae of San Diego County due to wastewater discharge from the Point Loma Ocean Outfall (PLOO).

The marine heat wave and associated depressed nutrient conditions decimated *Macrocystis pyrifera* and cohabiting algal species off San Diego. Pooled across 20 kelp forest sites off San Diego, densities of adult *M. pyrifera* were reduced by more than 90%. Unlike previous warm events attributed to El Niño, the coupled marine heat wave resulted in warming and low nutrient exposure of understory kelp species for prolonged periods of time leading to dramatic reductions of those species in addition to giant kelp. The BLOB persisted longer than a typical El Niño and kelps did not recover after the warm pool dissipated because of the stress induced by the following El Niño of 2016. The two events affected kelp at the study sites differently, and the historic pattern of synchronized mortality and recovery was disrupted. Growth conditions returned to normal with the onset of mild La Niña conditions in the spring of 2017. Rates of giant kelp recovery have since varied among study sites and were initially slower than previous recovery periods and non-existent at some study sites. Surface canopy cover in some areas was precluded by increases in understory species density. Some of these areas will likely remain devoid of giant kelp canopy for years since understory species are long-lived and competitively interfere with giant kelp recruitment. Favorable conditions for kelp growth and reproduction returned with the 2018 spring upwelling season and continued through 2019. Numerous study sites experienced significant giant kelp recruitment that has successfully matured. However, the giant kelp canopy off San Diego County remains patchy due to a combination of competition with understory species in the shallower margins of the kelp forests and a lack of recruitment in many deeper areas through early 2018, likely due to decreased light levels caused by phytoplankton blooms. Giant kelp is presently recovering in those areas as the deeper sites experienced recruitment in 2018 and 2019.

An anomalously warm surface layer, limited to the upper 3–5 meters of the ocean's surface, bathed much of the southern California coast during the summer of 2018. Sea surface temperatures reached 27°C, exceeding the all-time high temperature record for the SIO Pier sea surface temperature series by ~2°C. Summer surface temperature maxima in this record are typically ~23°C. This surface warm pool degraded the giant kelp canopy tissue, which was mostly lost from the offshore forests and drifted onto nearby beaches. However, cooler temperatures persisted closer to the bottom, and most of the giant kelp plants in the initial recovery cohorts of 2017 and 2018 survived and regrew to the surface when the warm pool dissipated by the fall of 2018. The marine heat wave decimated what remained of the North County kelp forests and the warm surface anomaly resulted in almost total loss of giant kelp within these forests. Recruitment in these forests has been extremely limited and unsuccessful.

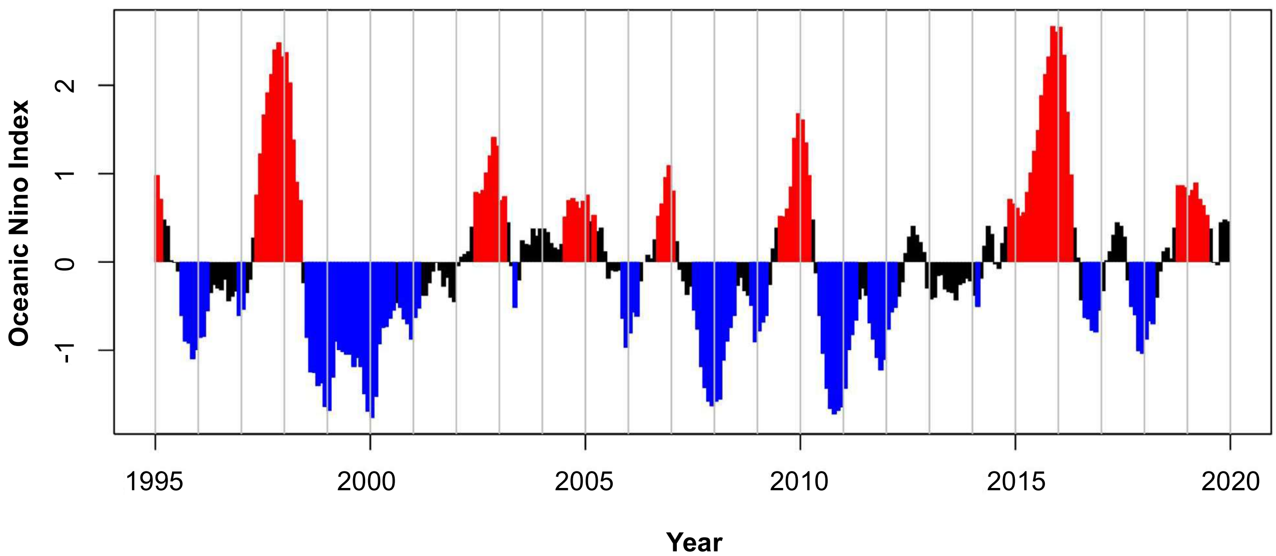
Presently, giant kelp densities are ~20% of their all-time historic highs when averaged across the longest observed study sites off Point Loma (since 1983). Giant kelp stipe densities (the metric most related to surface canopy cover) is presently ~47% of the all-time high, which was observed in 2012. Giant kelp densities are currently the greatest in the northern and central portions of the Point Loma kelp forest, and the southern portions of the La Jolla kelp forest. Giant kelp densities are near, or at, zero in all North County kelp forests, including areas off Del Mar, Solana Beach, and Cardiff.

Diseases in many invertebrates, including sea urchins (echinoids) and predatory seastars (asteroids), are common during warm events. Mass mortality of red (*Mesocentrotus franciscanus*) and purple sea urchins (*Strongylocentrotus purpuratus*) and seastars in the genus *Pisaster*, began off San Diego in 2014 and extended through 2017. This resulted in the disappearance, or near-disappearance, of these species from our study sites and from the kelp forests generally. Further, little to no recruitment of sea urchins was observed until the fall of 2017. Sea urchins are primary herbivores of giant kelp and can overgraze giant kelp and associated algal species given the right conditions. They are capable of precluding kelp recovery, and overgrazed areas, known as barrens, can persist in some areas for decades. The kelp recovery that began in 2017 and continued into 2018 has not been affected by these young sea urchin cohorts due to their low adult densities and small size. However, the 2017–2018 sea urchin cohort may eventually overgraze some areas off San Diego as this cohort emerges from nursery habitat and begins to actively forage. This cohort could lead to overgrazing in some areas of the kelp forests especially in south Point Loma where a unique combination of topography and turbidity emanating from San Diego Bay contribute to resilient barrens. Some recruitment of the seastars *Pisaster giganteus* and *Patiria miniata*, two important kelp forest predators, has been observed off Point Loma and La Jolla. However, adult densities are presently near zero and it is difficult to predict whether the initial bouts of post-disease recruitment will be adequate to recover their populations anytime soon.

Abalone, another important kelp forest grazer and the target of a once extensive fishery, depend primarily on giant kelp for food. Abalone once supported a large recreational and commercial fishery off southern California until all harvest was closed in 1996 due to depletion from overfishing and disease associated with warm periods. Abalone off San Diego County suffered further mortality during and after the warm event of 2014–2016 due to disease and lack of food. Abundances of all abalone species at the study sites off La Jolla and Point Loma have since declined to near zero with the exception of pink abalone (*Haliotis corrugata*) where there has been some recovery at the two shallowest study sites that began around 2010.

The La Niña conditions that occurred during 2017 and 2018 and resulted in kelp recovery off San Diego County shifted to El Niño conditions in the eastern equatorial Pacific. However, conditions have since been neutral, and no El Niño is forecast through all of 2020. The mild equatorial El Niño of 2019 did not prevent spring upwelling in 2019, and bottom temperatures have remained conducive for kelp recruitment and growth since the fall of 2017. Giant kelp off San Diego County should continue to increase in aerial cover through the spring and early summer of 2020.

Sargassum horneri, an invasive algal species that has replaced patches of giant kelp in some protected kelp forests off southern California, was first observed in the kelp forests off San Diego in 2014. By 2018, this species had been observed at 13 of



Appendix A.1

Barplot of the Oceanic Nino Index (ONI) since 1995. Red bars indicate El Niño conditions, blue bars indicate La Nina conditions, and black bars indicate ENSO neutral conditions (data from NOAA, 2020). The ONI index is based on equatorial sea surface temperatures in the Eastern Pacific.

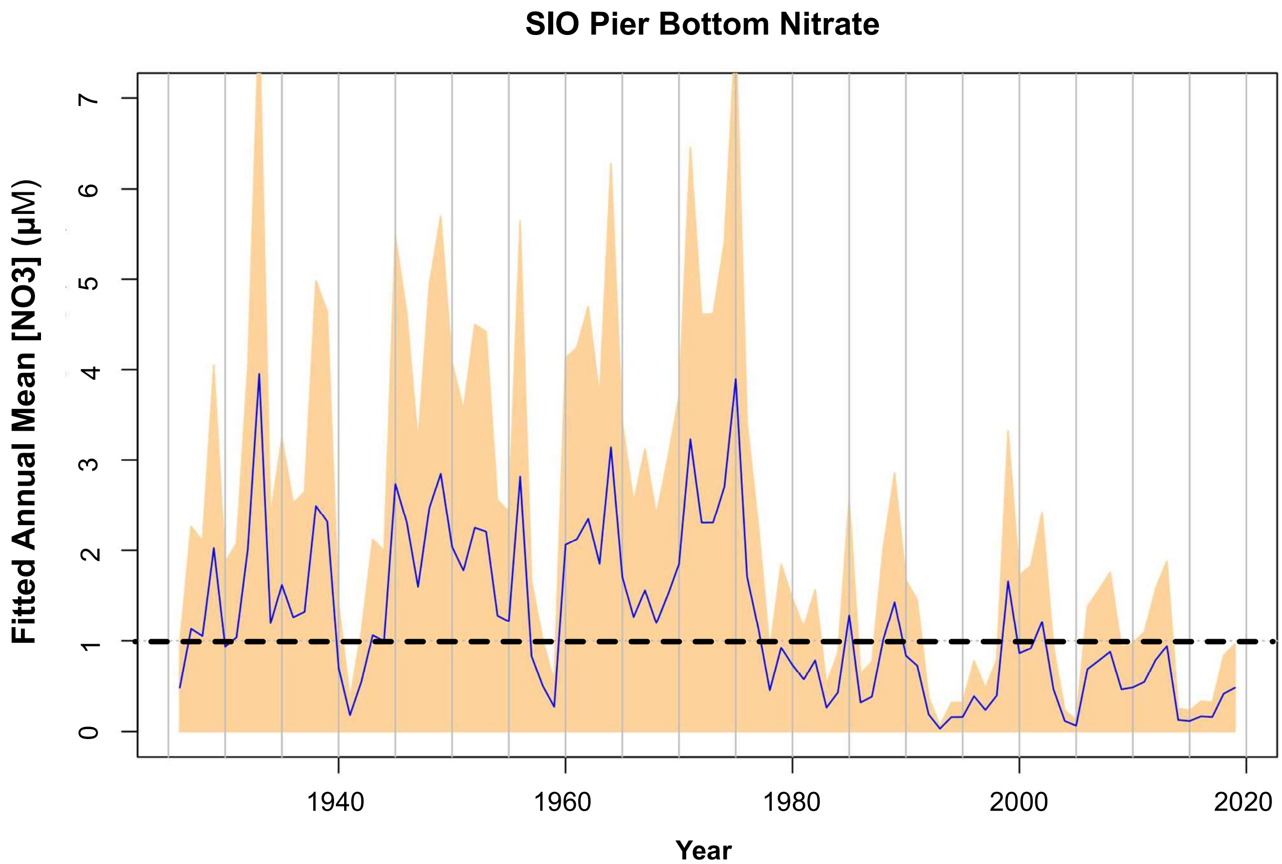
20 study sites, most densely off the deeper portions of the La Jolla kelp forest. However, it has not appeared at any of the remaining study sites through 2019, and has not increased in coverage at the sites where it has been observed. Therefore, this species may not pose as great a risk to San Diego County forests as it has to protected kelp forests off some of the California Channel Islands and mainland.

Introduction

Kelp forests are susceptible to human disturbance because of their proximity to urbanized coasts exposing them to overfishing, polluted surface and groundwater discharge, as well as the discharge of wastewater. Perhaps the largest effect is that due to increased turbidity which limits light penetration for kelps to grow, germinate, and reproduce (Clendenning and North 1960). Dramatic reductions in kelp forest canopy off Palos Verdes have been attributed to the combined effects of wastewater disposal and an energetic El Niño in the late 1950s (Grigg 1978). Nearshore turbidity, due to wastewater discharge, has since been mitigated by increasing the offshore distances and depths of discharge, and improved outfall design (Roberts 1991). Beach replenishment can also negatively impact kelp forests via sedimentation and burial. This has been observed at kelp forests off northern San Diego County where replenished sediments erode from beaches and partially bury the low relief kelp supporting habitat as eroded sediments redistribute offshore.

The PLOO discharges advanced primary treated wastewater through a deep-water open ocean outfall. The PLOO was extended into deeper waters in 1993, and presently discharges treated wastewater ~7.2 km offshore in marine waters ~98 m deep. The PLOO is situated approximately 5 km offshore of the outer edge of the Point Loma kelp forest. Due to its proximity, wastewater discharge through the PLOO presents at the very least a perceived risk to the health of the nearby kelp forest community off Point Loma. Local human risks to kelp forests can magnify risks posed by larger scale natural disturbances by reducing the resilience of kelp forests after episodic natural disturbances.

Kelp forests in southern California are disturbed naturally by ocean climate variability that occurs on an interannual (ENSO) (Appendix A.1) and



Appendix A.2

Time series of annual mean nitrate concentrations estimated from daily temperature and salinity sampled at the base of the Scripps Institution of Oceanography Pier (see Parnell et al., 2010 for details). Dotted gray line indicates the minimum nitrate threshold (1 µM) for the growth of giant kelp (*M. pyrifera*). Peach area indicates the 95% confidence limits.

decadal cycle (Pacific Decadal Oscillation - PDO). Positive phases of both ocean climate cycles are associated with a deepened thermocline limiting nutrient delivery to the inner shelf that is necessary for kelp growth and reproduction. These cycles are also associated with increased storm energy which causes giant kelp mortality via plant detachment and abrasion (Seymour et al. 1989). The northeastern Pacific experienced a profound shift in the late 1970s in which the main ocean thermocline deepened, resulting in a steep reduction in nitrate concentrations along the SCB that still persists (Parnell et al. 2010) (Appendix A.2). Concentrations of nitrate, the main limiting nutrient for kelp growth in southern California switched from being conducive for kelp growth most years prior to the shift, with the exception of the most intense El Niño events, to being less adequate most of the time (Parnell et al. 2010) with the exception of strong negative ENSO phases known as La Niña. The ecology of kelp forests off San Diego has changed fundamentally due to the increased frequency of natural disturbance resulting in a demographic shift towards younger and smaller *Macrocystis pyrifera* individuals (Parnell et al. 2010).

Sea urchin overgrazing is another form of natural disturbance within kelp forests (Leighton et al. 1966). Kelps are susceptible to overgrazing when sea urchin densities increase or when sea urchins aggregate into overgrazing fronts. Overgrazing can lead to areas denuded of most or all algae and have been termed barrens. Barrens can be resilient in some areas such as in the southern portion of the Point Loma kelp forest (Parnell 2015), or can alternate with forested periods due to external forcing such as reductions in kelp standing stock as a result of El Niño, sea urchin disease epidemics, and indirectly from human activities including the harvest of important sea urchin predators

(Steneck et al. 2002). Overfishing of sea urchin predators, such as spiny lobsters (*Panulirus interruptus*) and California sheephead wrasse (*Semicossyphus pulcher*) in southern California can lead to outbreaks of sea urchin overgrazing.

A more recent source of disturbance has been the introduction of an invasive alga, *Sargassum horneri*, throughout southern California. This species competes with *Macrocystis pyrifera* for space and light, and is now seasonally dominant in some areas previously dominated by *M. pyrifera*. The most impacted areas include the protected low energy habitats in the lee of islands such as the northern Channel Islands and Santa Catalina Island (Miller et al. 2011). *S. horneri* is now establishing itself in many areas off San Diego County including the kelp forests, bays, and estuaries.

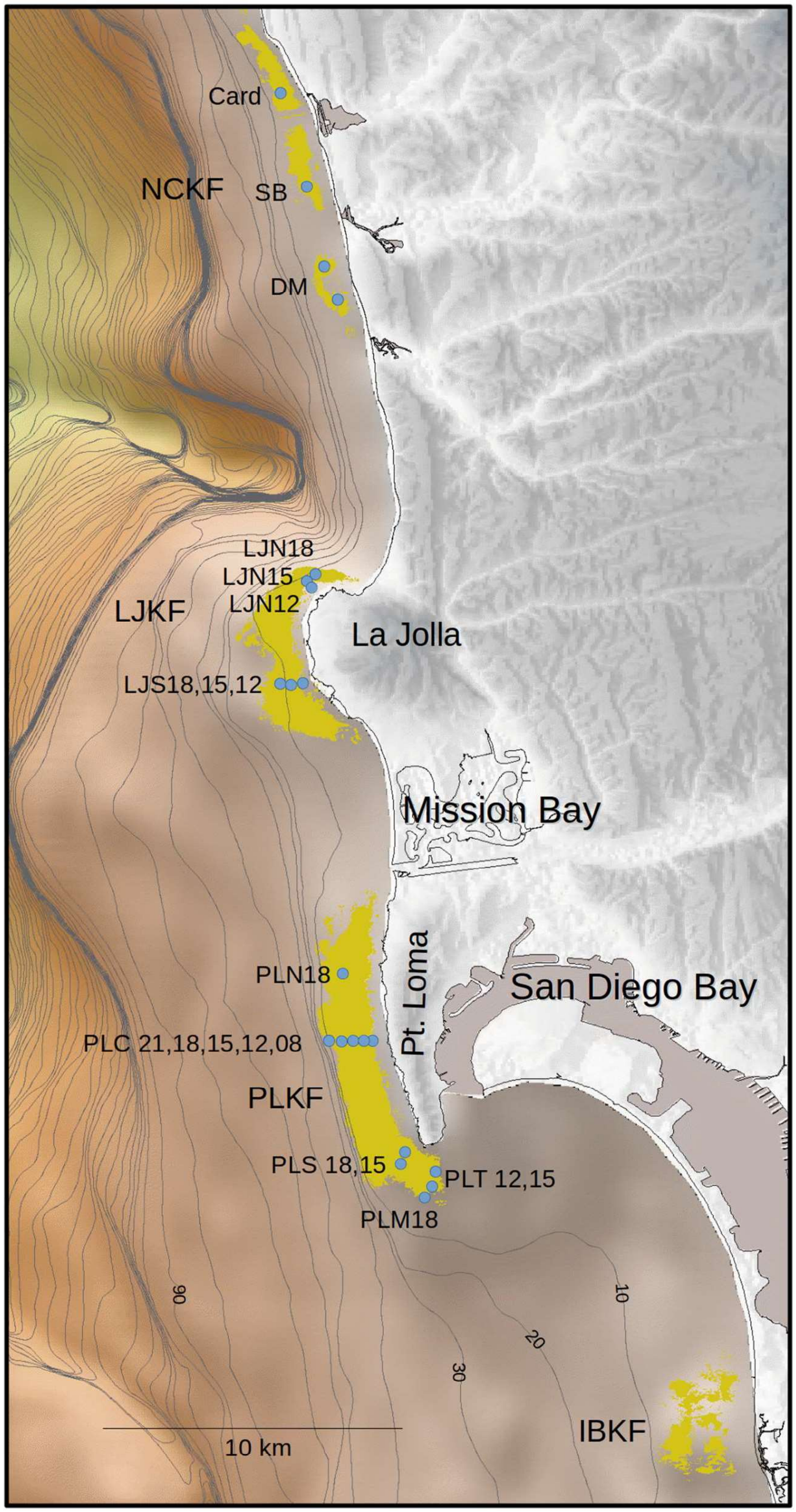
Researchers at SIO have partnered with the City to conduct regular surveys of the kelp forests off San Diego County including the kelp forests off Point Loma, La Jolla and North County. These surveys represent a continuation of ecological studies that began at SIO in the Point Loma (PLKF) and La Jolla (LJKF) kelp forests and continue at some of the sites established in the 1970 and 1980 (Dayton and Tegner 1984). Additional study sites have been established more recently in both kelp forests and in kelp forests off northern San Diego County (North County - NCKF). PLKF and LJKF are the largest contiguous kelp forests off the western United States coast and are historically one of the most studied kelp forest systems in the world.

Materials and Methods

Algae, invertebrates and bottom temperatures are monitored at twenty permanently established study sites (Appendix A.3). Algae and invertebrates are monitored along four replicate parallel permanent band transects oriented perpendicular to shore (25 x 4 m bands separated 3–5 m apart) except at the DM study site where two sets of band transects are located ~1300 m apart due to the small size and fragmented shape of that forest. The main components of the kelp forest monitoring program include assessments of (1) algal density, growth, reproductive condition and recruitment, (2) invertebrate densities, (3) sea urchin demography (size distributions to monitor for episodic recruitment), and (4) ocean bottom temperature (which is a proxy of ocean nutrient status). The types of data collected and the frequency of collection are listed in Appendix A.4.

Several life stages of *Macrocystis pyrifera* are enumerated to identify recruitment events and follow the fate of recruiting cohorts into adulthood. Survival of recruitment cohorts to adulthood is highly variable and a lack of successful maturation into adulthood indicates changes in the growth environment in the form of stress by temperature and nutrients, grazers, and/or reduced light. Giant kelp life stages include adults (≥ 4 stipes), pre-adults (plants > 1 m tall but with < 4 stipes), bifurcates (a late post recruitment stage indicated by the presence of a split in the apical meristem which represents the primary dichotomous branching event), and pre-bifurcates (very early post settlement stage lacking the initial dichotomous split). The number of stipes is counted and recorded for each adult plant each visit.

Conspicuous macroalgal species/groups are enumerated or percent cover is estimated within 5 x 2 m (10 m^2) contiguous quadrats along the band transect lines at all sites. Reproduction and growth of *Macrocystis pyrifera*, and the understory kelps *Pterygophora californica* and *Laminaria farlowii*, are measured on permanently tagged plants along the central Point Loma study sites. All conspicuous sessile and mobile invertebrates are enumerated annually within the 10 m^2 quadrats during spring. Size frequencies of red (RSU - *Mesocentrotus franciscanus*) and purple (PSU - *Strongylocentrotus purpuratus*) sea urchins are recorded for > 100 individuals of each species located near all of the study sites except for the NCKF sites which do not have adequate densities of sea urchins. Sedimentation is monitored along the NCKF sites by measuring the height of permanently established spikes at replicate locations within each of those forests.



Appendix A.3
Map of the San Diego inner shelf showing locations of the Point Loma, La Jolla, North County, and Imperial Beach kelp forests (indicated by PLKF, LJKF, NCKF, and IBKF, respectively). Permanent study site locations are indicated by blue circles and corresponding study site names. Depth contour units are meters.

Appendix A.4

List of study sites including year of establishment and work conducted at each site. ABT = algal band transects, USF = sea urchin size frequency, Inv = Invertebrate censuses, AR = algal reproduction and growth measurements, and BT = bottom temperature. Frequencies are noted in parenthesis: a = annual, sa = semi-annual, q = quarterly, m = monthly.

Study Site	Depth (m)	Year Established	Work Conducted (frequency)
Card	17	2006	ABT(q), Inv(a), BT(10min), Sed(q)
SB	16	2006	ABT(q), Inv(a), BT(10min), Sed(q)
DM	16	2007	ABT(q), Inv(a), BT(10min), Sed(q)
LJN18	18	2004	ABT(q), Inv(a), USF(sa), BT(10 min)
LJN15	15	2004	ABT(q), USF(sa), Inv(a), BT(10 min)
LJN12	12	2004	ABT(q), USF(sa), Inv(a), BT(10 min)
LJS18	18	2004	ABT(q), USF(sa), Inv(a), BT(10 min)
LJS15	15	1992	ABT(q), USF(sa), Inv(a), BT(10 min)
LJS12	12	2004	ABT(q), USF(sa), Inv(a), BT(10 min)
PLN18	18	1983	ABT(q), USF(sa), Inv(a), BT(10 min)
PLC21	21	1995	ABT(q), USF(sa), Inv(a), AR(m), BT(10 min)
PLC18	18	1983	ABT(q), USF(sa), Inv(a), AR(m), BT(10 min)
PLC15	15	1983	ABT(q), USF(sa), Inv(a), AR(m), BT(10 min)
PLC12	12	1983	ABT(q), USF(sa), Inv(a), AR(m), BT(10 min)
PLC08	8	1997	ABT(q), USF(sa), Inv(a), AR(m), BT(10 min)
PLS18	18	1983	ABT(q), USF(sa), Inv(a), BT(10 min)
PLS15	15	1992	ABT(q), USF(sa), Inv(a), BT(10 min)
PLT12	12	1997	ABT(q), USF(sa), Inv(a), BT(10 min)
PLT15	15	1997	ABT(q), USF(sa), Inv(a), BT(10 min)
PLM18	18	1996	ABT(q), USF(sa), Inv(a), BT(10 min)

Bottom temperature is recorded at 10 min intervals using ONSET Tidbit recorders (accuracy and precision = 0.2˚C and 0.3˚C, respectively. All field work was conducted using SCUBA.

Growth of *Macrocystis pyrifera* is monitored by counting the number of stipes on each tagged plant one meter above the substratum. Reproductive state is represented by the size of the sporophyll bundle (germ tissue) at the base of each plant. Sporophyll volume is calculated as a cylinder based on the height and diameter of each bundle. This is an indirect measure of reproductive effort. Reed (1987) has shown that sporophyll biomass is closely related to zoospore production. Reproductive capacity, a derived parameter that represents the relative reproductive potential among plants by coupling sporophyll volume and reproductive state, is calculated as the product of sporophyll volume and squared reproductive state. Reproductive capacity is then standardized by division of each value by the maximal value observed among all sites. Reproductive state for each plant is ranked according to the ordinal scale in Appendix A.5.

Growth of *Pterygophora californica* is determined by the method of DeWreede (1984). A hole (6 mm) is punched into the midrib of the terminal blade ~30 mm from the base of the blade, and another hole is punched monthly at the same location. The distance between the two holes represents the linear growth of each blade. Reproductive effort for *P. californica* is evaluated by a count of the total number of sporophyll blades on each plant and the number with sori. Sori are the sites of active spore production in ferns, fungi, and algae and consist

Appendix A.5

Ordinal ranking criteria for *Macrocystis pyrifera* reproductive state.

Reproductive Score	Description
0	No sporophylls present
1	Sporophylls present but no sori (sites of active reproduction) development
2	Sporophylls with sori only at the base of sporophylls
3	Sporophylls with sori over most of the sporophylls surface
4	Sporophylls with sori over all of the sporophylls surface
5	Sporophylls with sori over all of the sporophylls surface releasing zoospore

of clusters of spore producing sporangia. Growth of *Laminaria farlowii* is determined in a similar manner to *P. californica*. A 13 mm diameter hole is punched 100 mm from the base of each blade and is repeated each visit. The distance between the two holes represents the linear growth of each blade. The reproductive status of *L. farlowii* is evaluated as the percent of each blade covered by sori.

Sea urchin recruitment is sampled semi-annually (spring and fall) at all Point Loma and La Jolla study sites. Sea urchins are exhaustively collected in haphazardly placed 1 m^2 quadrats in suitable substrate within 50 m of each study site. Suitable substrate includes ledges and rocks which can be fully searched for sea urchins as small as 2 mm. Sea urchins are measured using calipers and then returned to where they were collected.

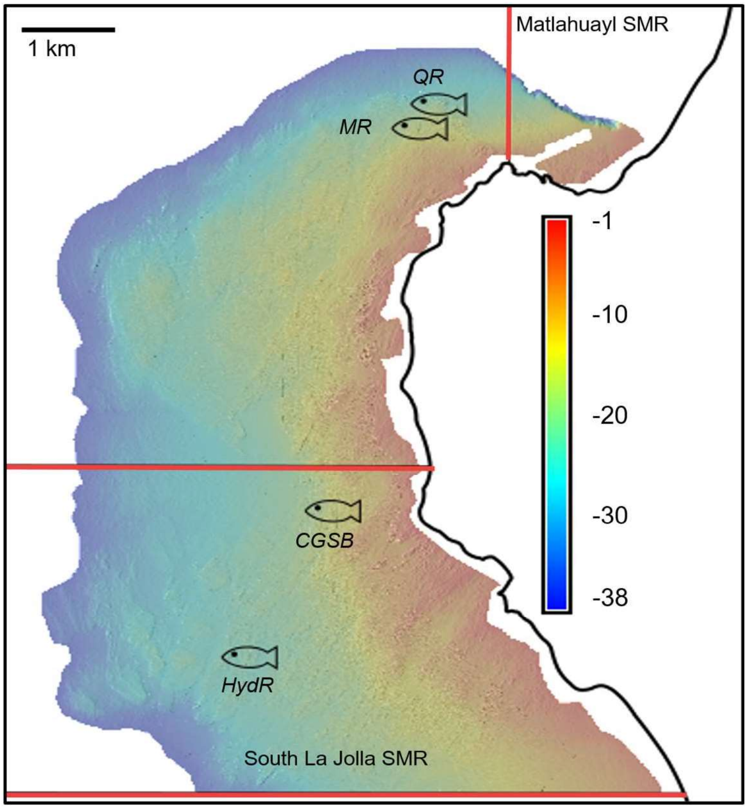
The distribution of algal species among all permanent sites was calculated using factor analysis in R (R Core Team 2018). Factor analysis (Lawley and Maxwell 1971) was used to reduce the multi-dimensional algal data. This technique facilitates the examination of entire algal communities in two or three dimensions that can then be plotted to determine community composition differences among study sites and over time. Thirteen algal groups and derived bare space were analyzed among 20 sites. Relative bare space was derived by ranking the sum of rankings for individual algal groups among sampling units. Sampling units (individual 10 m^2 quadrats) with the least amount of total algae (density or percent cover) were ranked highest for bare space.

Fish surveys were initiated in the fall of 2019 and will continue semi-annually (fall/spring) at four sites within the LJKF (Appendix A.6) and three sites within the PLKF (Appendix A.7). Sites were chosen based on topographic features that fish are known to prefer and are as similar as possible in reef size and rugosity based on previously collected bathymetric data (Parnell 2015). Sites were paired within the LJKF where a large marine protected area (MPA, South La Jolla State Marine Reserve) is located in the southern half (Appendix A.6). The take of all species is prohibited within the MPA which went into effect in 2012. Study sites within the LJKF and PLKF were paired by depth (21 and 15 m) to facilitate comparisons of the fish communities inside and outside the MPA (Appendix A.8). Fish counts are conducted along replicate 30 x 4 m band transects (up to 3 m off the bottom) which include an initial swimming count for conspicuous species followed by a thorough search for cryptic species using a light.

Results and Discussion

Ocean Climate

The ENSO index (ONI – Oceanic Nino Index) (Appendix A.1) is based on equatorial sea surface temperatures in the eastern Pacific Ocean. ENSO warming and cooling of the west coast of the Americas propagates poleward from the tropics, and each El Niño or La Niña event penetrates higher latitudes differently. Therefore, while

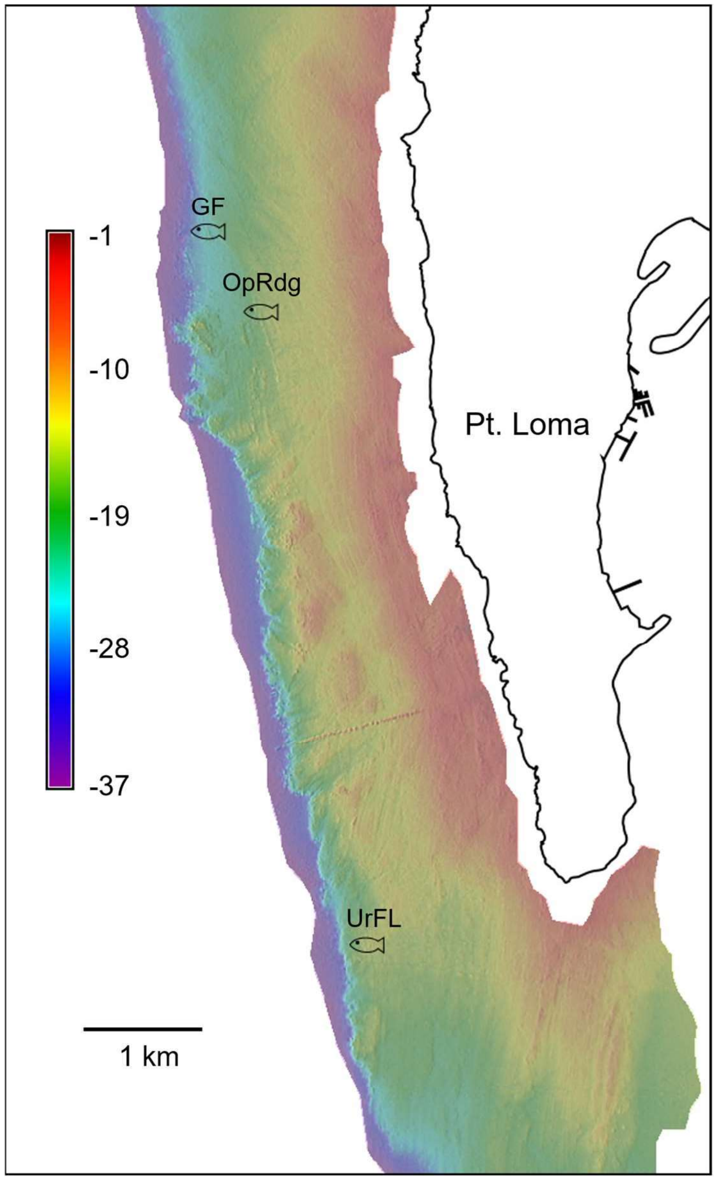


Appendix A.6

Locations of fish survey study sites within the La Jolla kelp forest. Color legend indicates depth in meters. The red lines indicate boundaries of the marine protect areas (SMR = State Marine Reserve).

correlated, the magnitudes of ENSO events at the equator and temperatures along the SCB can be somewhat decoupled.

The bottom temperature record at the central Point Loma study sites extends back to 1983 when the strong 1982/1983 El Niño was ebbing. Since then, the largest temperature signals in the time series include the 1997/98 El Niño and the extended warm period of 2014–2015 that occurred during the present study and was associated with a large scale anomalous NE Pacific warm event (Di Lorenzo and Mantua 2016) termed the BLOB but more recently referred to as a marine heat wave. This was immediately followed by a strong El Niño in 2015/2016 (Appendices A.1, A.9, A.10). The ONI (Appendix A.1) and the Point Loma bottom temperature time series (Appendix A.9) are strongly concordant for the largest ocean climate events including the onset of the coupled BLOB/El Niño warm event beginning in late 2014 which began to ebb by the spring of 2016 immediately followed by cooler La Niña conditions in late 2016 and another cool period between fall 2018 and summer of 2019. The ONI and bottom temperatures off Point Loma indicate rapid cooling both periods separated by a moderate warm event beginning late 2017. An anomalous temperature event occurred during the summer of 2018 in which surface waters (upper 3–5 m) exceeded 27°C and stayed warm through most of the summer. This event was not observed at the bottom at any of the study sites as it was limited to near surface waters, but was evident in the Scripps Pier temperature time series (Appendix A.10) and included the warmest temperatures ever observed in the 103-year time series. This warm event caused significant deterioration of the giant kelp surface canopy which virtually disappeared over the summer. However, most plants were still growing and healthy beneath the warm surface layer at the study sites where recovery from the BLOB/ El Niño warm event had occurred, because bottom temperatures remained relatively cool during the summer of 2018. Bottom and surface



Appendix A.7
Locations of fish survey study sites within the Point Loma kelp forest. Color legend indicates depth in meters.

temperatures cooled in 2019 particularly during the spring and summer upwelling periods when nutrient conditions for giant kelp growth and reproduction improved (see Appendix A.9).

Less pronounced warm periods occurred between the 1997/1998 and 2016/2017 El Niños. Most notable was the 2005/2006 El Niño when much of the giant kelp canopy disappeared at the surface but plants still grew below the thermocline where nutrients were more abundant. Because bottom temperatures decrease with depth, nutrient stress during warming events also decreases with depth. This physical forcing is a fundamental mechanism that controls space competition between understory and canopy kelps. Strong El Niño events, such as the 1997/1998 El Niño and the 2014–2016 marine heat wave, penetrate to the bottom for extended periods even at the offshore edge of the forest stressing all kelps including understory species. By contrast, milder El Niño events do not typically penetrate to the bottom of the forests for extended periods (e.g., > 1 month), and therefore primarily stress the surface canopy kelps (mainly *Macrocystis pyrifera*) more than the understory kelps where temperatures are cooler. Repeated

Appendix A.8

Site details and species richness for fish surveys.

Site	Kelp Forest	Depth (m)	MPA	MPA Pairings	Species Richness
QR	La Jolla	21	No	A	12
HydR	La Jolla	21	Matlahuayl SMR	A	8
MR	La Jolla	15	No	B	12
CGSB	La Jolla	15	Matlahuayl SMR	B	14
UrFL	Pt. Loma	15	No	A	9
OpRdg	Pt. Loma	15	No	A	13
GF	Pt. Loma	21	No	B	14

cycles of mild to moderate El Niño events over many years in the absence of large storm waves can lead to understory domination at the expense of giant kelp canopy cover.

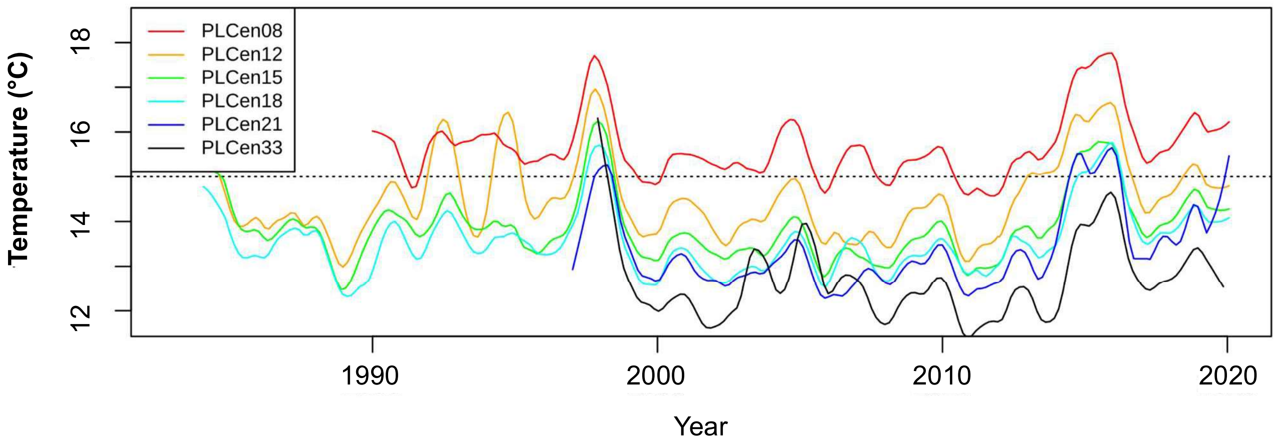
Currently, bottom temperatures have been cool since the spring of 2018 (<15°C at all sites except for the central Point Loma 8-m site) leading to recruitment and growth at many of the study sites. Despite, warming occurring during the fall and winter of 2018/2019, temperatures at the study sites were typically <13°C, due to their depth of >12 m. ENSO neutral conditions have dominated along the equator since June of 2019 and are forecast to persist well into the fall of 2020 (NOAA 2020). The mild El Niño that persisted through the winter and spring along the equator did not appear to have a negative impact on San Diego County kelp forests.

Giant Kelp Status and Reproduction

The primary abundance pattern for *Macrocystis pyrifera* since the 1980s includes rapid declines associated with El Niños followed by step increases in plant and stipe density due to mainly discrete pulses of recruitment leading to varying levels of recovery, or failed recovery if a cohort fails to reach adulthood. In addition to the temporal variation of regional ocean climate, the recruitment, maturation, and establishment of adult giant kelp plants are highly variable in space even within a single kelp forest. Densities of all life stages and stipes are shown in Appendices A.12–A.15. Densities for these life stages at all 18-m deep sites off La Jolla and Point Loma, are plotted in Appendix A.16 for comparisons among the outer kelp forest sites where bottom temperatures are cool relative to shallower sites, and conditions are therefore more persistently conducive for the recruitment and growth of early giant kelp life stages. Presently, mean giant kelp adult and stipe densities for the pooled long-term central Point Loma study sites at 12, 15, and 18 m (1983–2019) are 19% and 47% (respectively) of their all-time highs.

The 2014–2016 warm period caused massive mortality of giant kelp off San Diego County mainly through a combination of nutrient and temperature stress. Giant kelp surface canopy was nearly entirely lost off most of San Diego, Orange, and Los Angeles counties during 2016 (MBC 2017). Densities of adult *Macrocystis pyrifera* plants (Appendix A.11) and stipes (Appendix A.15) decreased dramatically at all study sites off San Diego. *M. pyrifera* has since recruited in some areas of the forests beginning as early as 2016 with subsequent recruitment cohorts observed in 2017 and 2018, with low levels of recruitment continuing into the spring of 2019 (Appendices A.12, A.13). Some of the 2016 site cohorts at least partially matured into pre-adults and adults at a subset of the sites. Presently, sites with the greatest densities of adult and pre-adult giant kelp include the central Point Loma sites at 18 and 21 m (PLC18 and PLC21), the southern La Jolla site at 18 m (LJS18), and the northern Point Loma site at 18 m (PLN18).

No or very few adult giant kelp plants remain at the North County sites even though significant recruitment occurred off Cardiff in late 2017. An



Appendix A.9

Ocean bottom temperature trends along the central Point Loma study sites. Horizontal gray line indicates the temperature (15°C) above which nitrate concentrations are typically limiting for giant kelp growth.

earlier cohort that recruited in 2016 near the end of the El Niño off Solana Beach, has mostly failed to thrive. No giant kelp has been observed off Del Mar since early 2016.

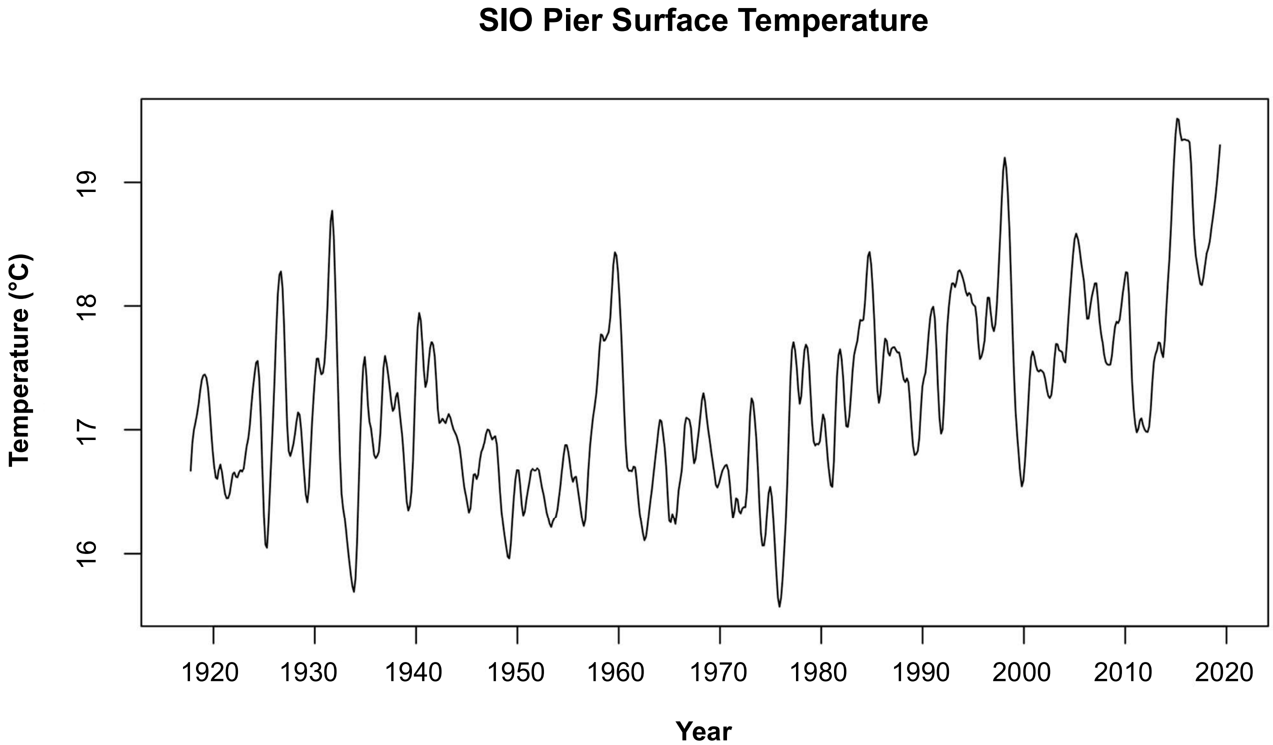
Post warm-event recruitment was observed at the La Jolla study sites including LJN15, and all three of the southern La Jolla sites. Recruitment off southern La Jolla was by far the greatest at the 18-m site. Moderate densities of giant kelp are now present at the LJN15, LJS18, and LJS15 study sites.

Giant kelp recovery at the Point Loma study sites has been highly variable among study sites. Recruitment occurred during the 2015 warm event at PLC12 but that cohort died completely by late 2017. At other sites, where giant kelp adults currently exhibit moderate densities (>0.1 m^{-2}), recruitment occurred beginning as early as 2016 and some sites experienced additional recruitment in 2017 and 2018. These sites include PLC21, PLC8, PLT12, PLS15, and PLS18. Recruitment occurred but did not successfully mature into adult stands at PLC18, PLC15, PLT15, and PLM18. An early-colonizing post-disturbance brown alga, *Desmerestia ligulata*, has dominated the PLT15 and PLM18 study sites until recently, interfering with giant kelp recovery at those sites. Limited recovery at the deeper sites such as PLC18 and PLC21 was limited through 2018 but is now evident. The delayed recovery at the deeper sites may be partly due to decreased light levels reducing rates of kelp germination. However, light penetration data were not available during that period.

The reproductive state of giant kelp along the central Point Loma study sites was greatly diminished by the end of the 2016 El Niño (Appendix A.17). Reproductive capacity was uniformly the lowest among all study sites over the entire time series dating back to before the 1997/1998 El Niño. Sporophyll volumes were greatly reduced by the end of the 2016 El Niño and sporophylls were not reproductive at the PLC8 and PLC21 study sites where adult plants were the most abundant. Diminished reproductive capacity of giant kelp is an indicator of how stressful the warm water events of 2014–2016 were for the species. Additionally, it likely limited the rate at which giant kelp were able to recover since that time given the relationship between reproductive capacity and number of stipes for each individual plant (Appendix A.18). The only study site where reproductive capacity has at least briefly recovered is the central Point Loma site at 15 m.

Understory Kelp Status and Reproduction

Understory kelps and turf algae grow close to the bottom, and unlike the local canopy forming kelps (*Macrocystis pyrifera*, *Egregia menziesii*, and *Pelagophycus porra*), do not have buoyant pneumatocysts to support photosynthetic tissue up in the water column where light is more abundant.



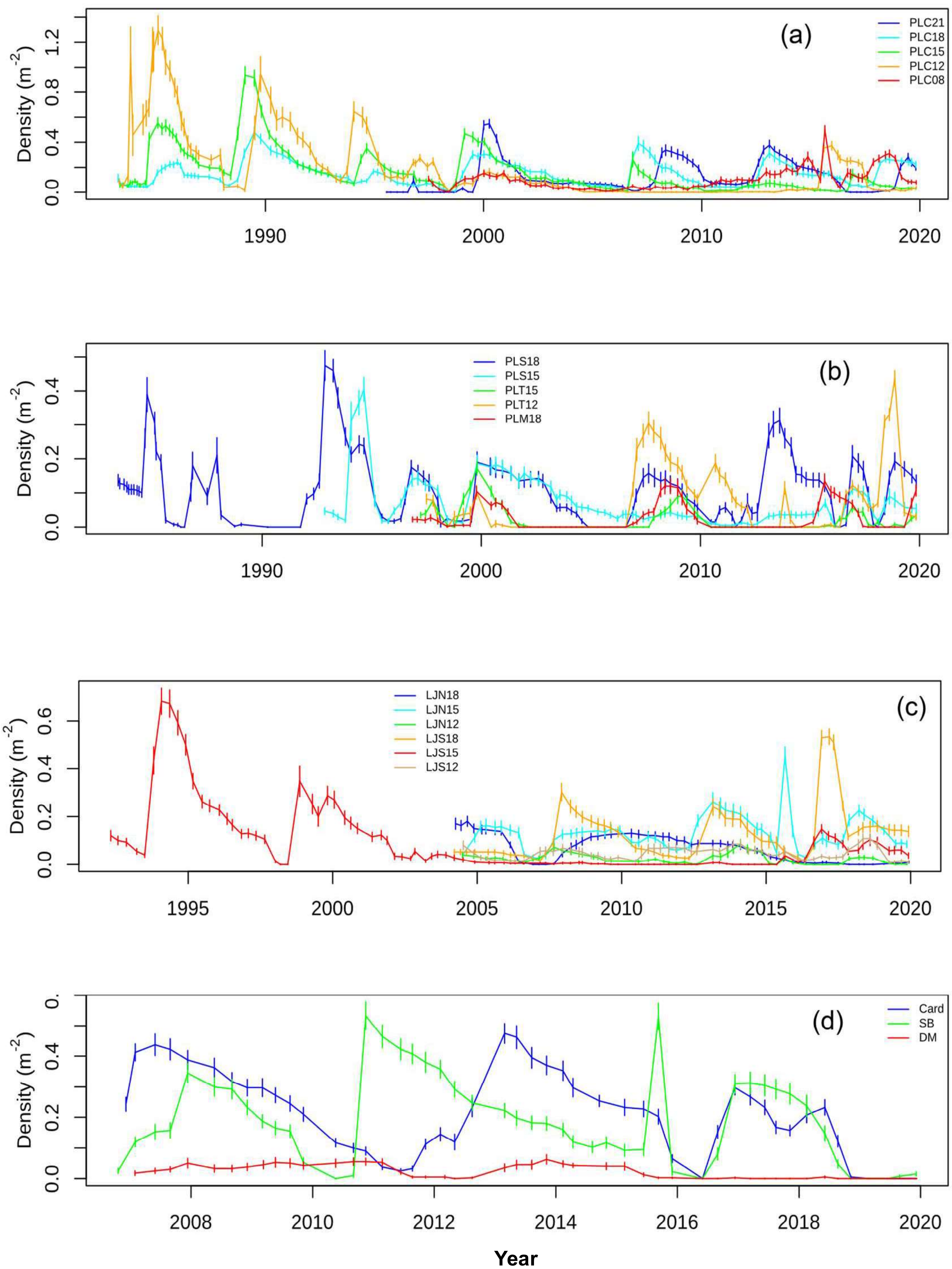
Appendix 10

Trend of surface temperature at the Scripps Institution of Oceanography (SIO) Pier. Data inclusive through Fall 2019.

Therefore, high densities of canopy forming kelps outcompete understory kelps and turf algae. El Niño events modulate this competition between the two types of canopy guilds. Warm and nutrient deplete water is nearest the surface where most of the photosynthetic and nutrient absorbing tissue for giant kelp is distributed. Therefore, giant kelp is disproportionately stressed by El Niño events as giant kelp is stressed by low nutrient and high temperature conditions. By contrast the understory and turf canopy guilds are exposed to cooler and more nutrient replete waters. And as the surface canopy kelps begin to lose tissue and die, the light field for the lower canopy guilds increases leading to rapid growth and reproduction.

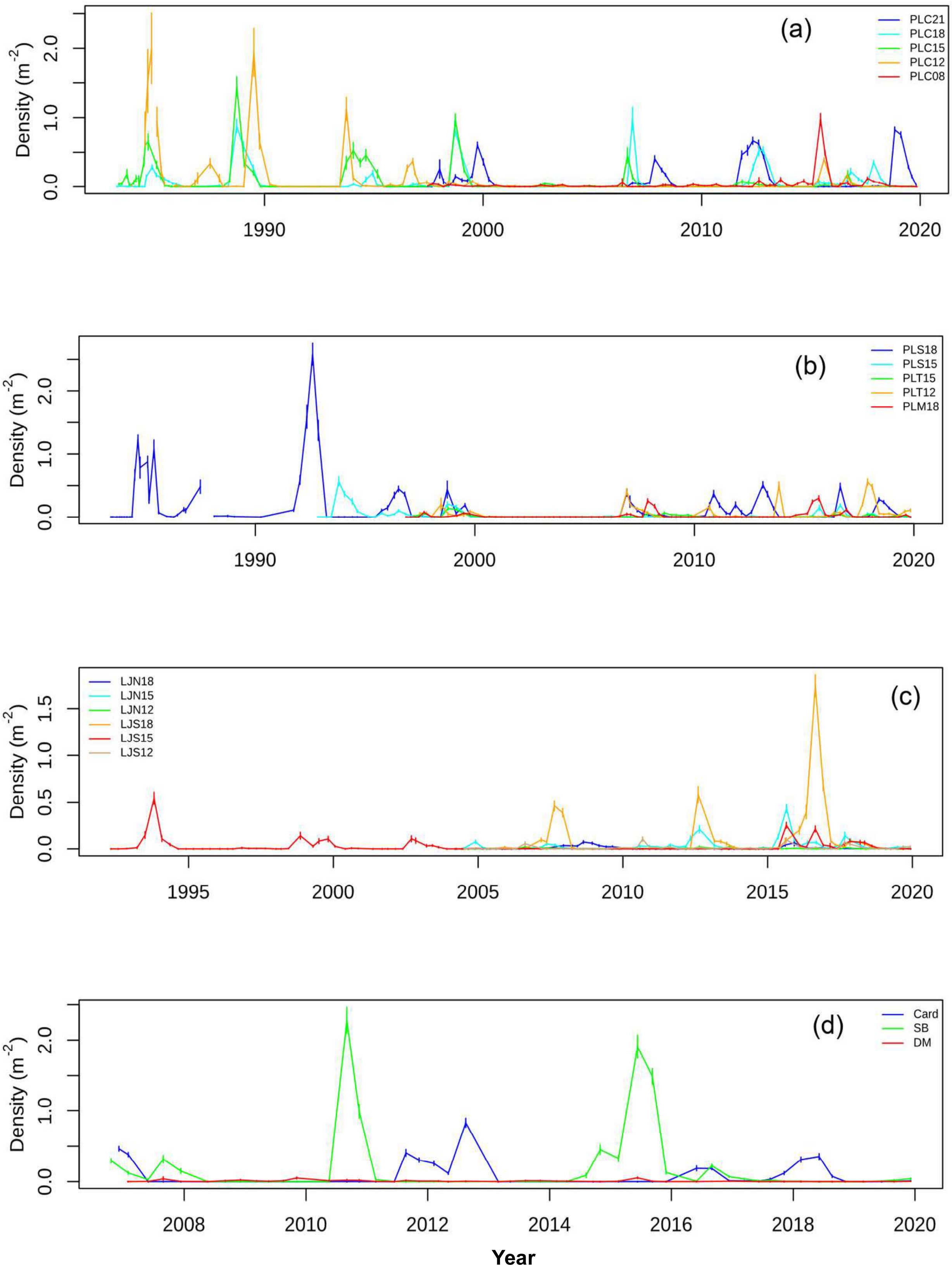
Pterygophora californica, a stipitate understory kelp has a central woody stipe that supports photosynthetic blades from below. Stipes can grow up to 2 m in height off the bottom and individuals can persist for decades. The growth form consists of a ribbed terminal blade that grows outward from the end of the stipe. Sporophyll blades grow horizontally outward from the narrowed margins of the stipe. Soral (reproductive) tissue develops on these side branching sporophyll blades. *Laminaria farlowii*, a prostrate understory kelp grows as a long blade along the bottom where it is attached by a small woody stipe and holdfast. Soral tissue develops along the length of the blade. Reproduction and growth is seasonally offset in both species with growth occurring during late spring and summer while reproductive tissue development peaks in winter.

Pterygophora californica and *Laminaria farlowii*, were affected differently by the consecutive warm periods. The main effects of the warm periods on *P. californica* were exemplified by two groups of sites (Appendix A.19). The first group included sites where densities decreased dramatically with the BLOB and remained low during and after the 2016 El Niño (PLC21, PLC18, PLC12, PLC08, LJN15, LJN12, LJS12). Densities of *P. californica* at the second set of sites decreased during the BLOB then increased rapidly through the 2016 El Niño (PLC15, LJS18, LJS15). Densities of *P. californica* at the North County sites have been persistently



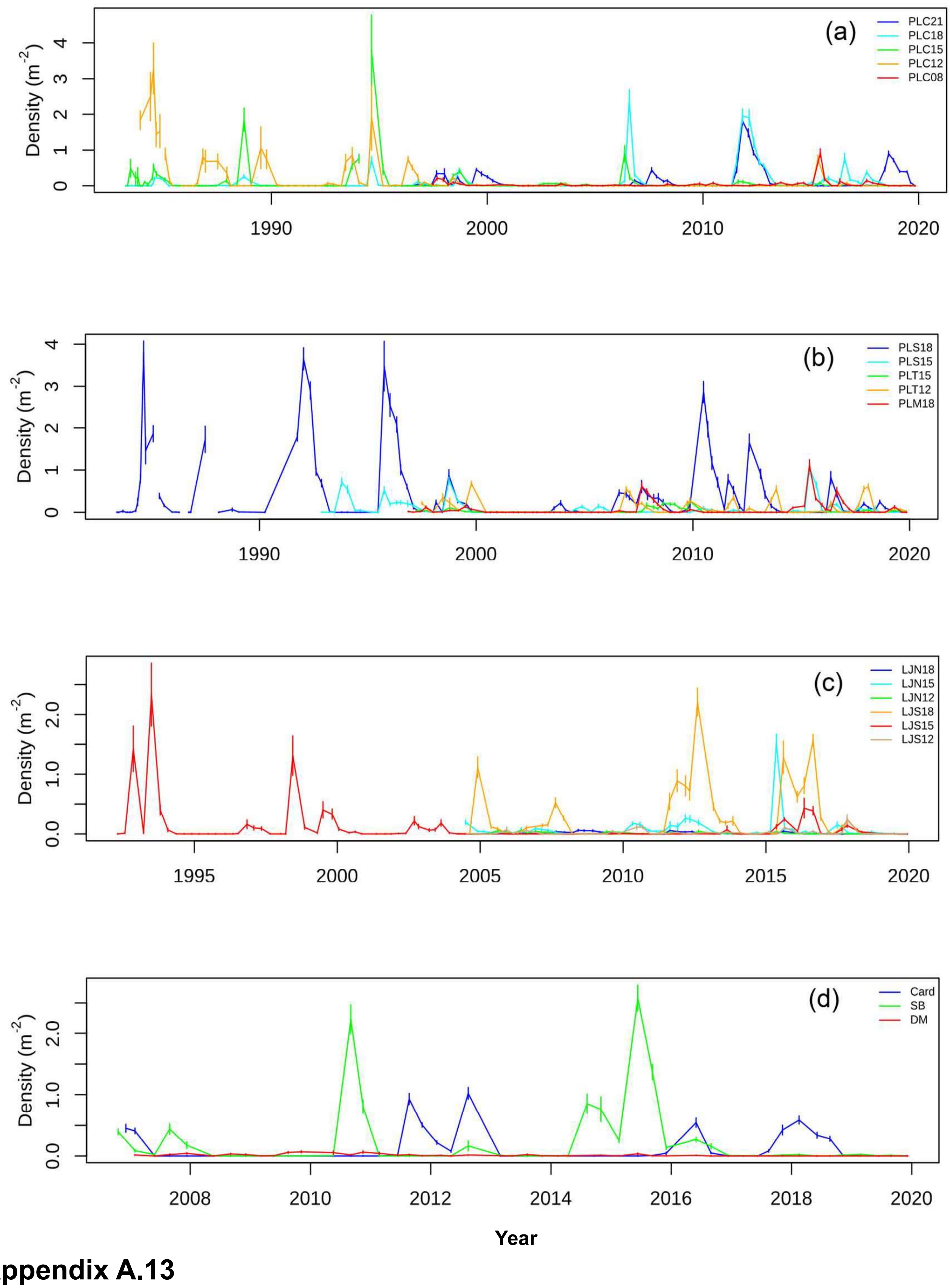
Appendix A.11

Mean densities of adult *Macrocystis pyrifera* among study site groups: (a) central Point Loma, (b) south Point Loma, (c) La Jolla, and (d) North County. Error bars indicate standard errors.



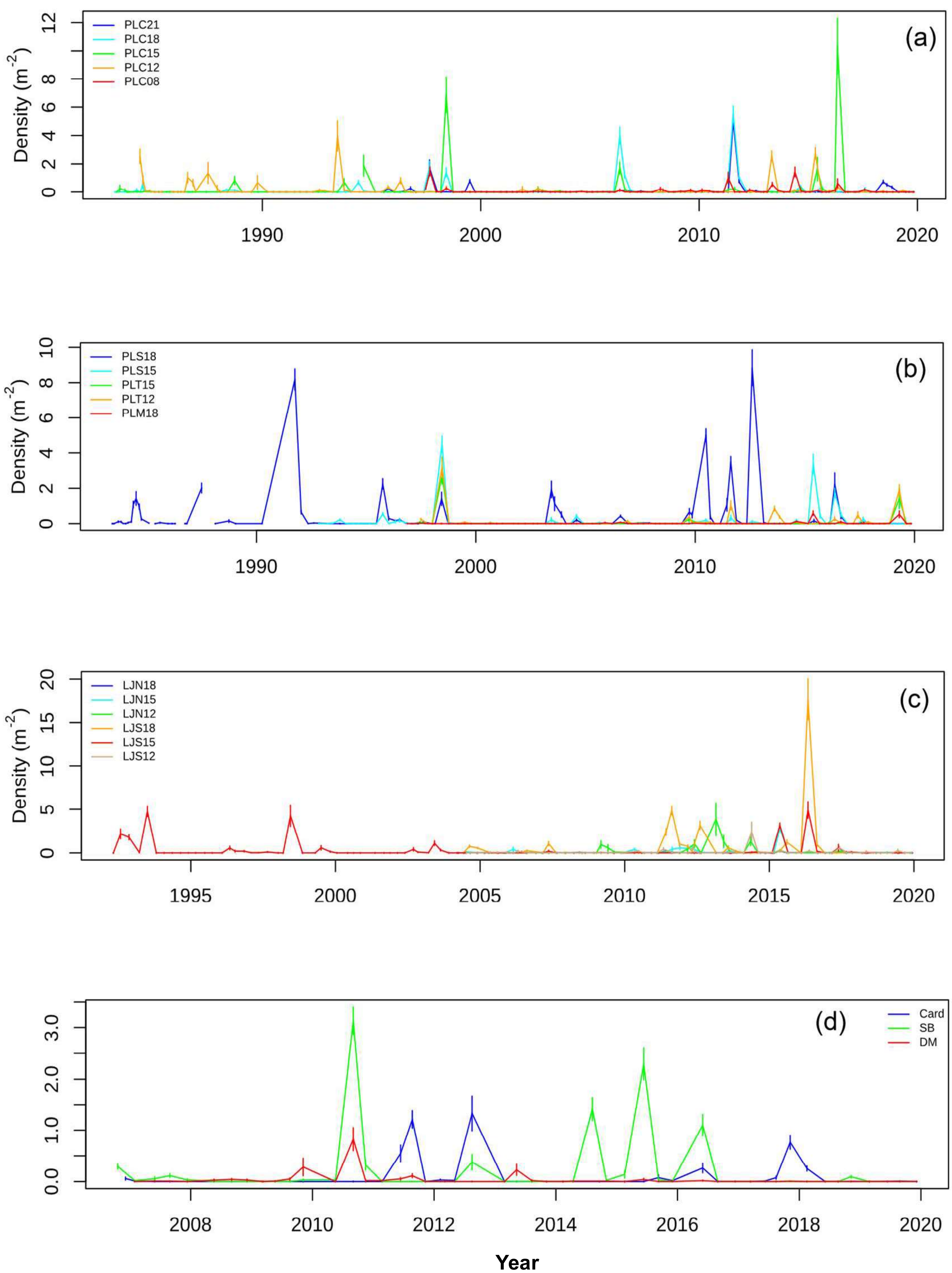
Appendix A.12

Mean densities of *Macrocystis pyrifera* pre-adults (≤4 stipes): (a) central Point Loma, (b) south Point Loma, (c) La Jolla, and (d) North County study sites. Error bars indicate standard errors.



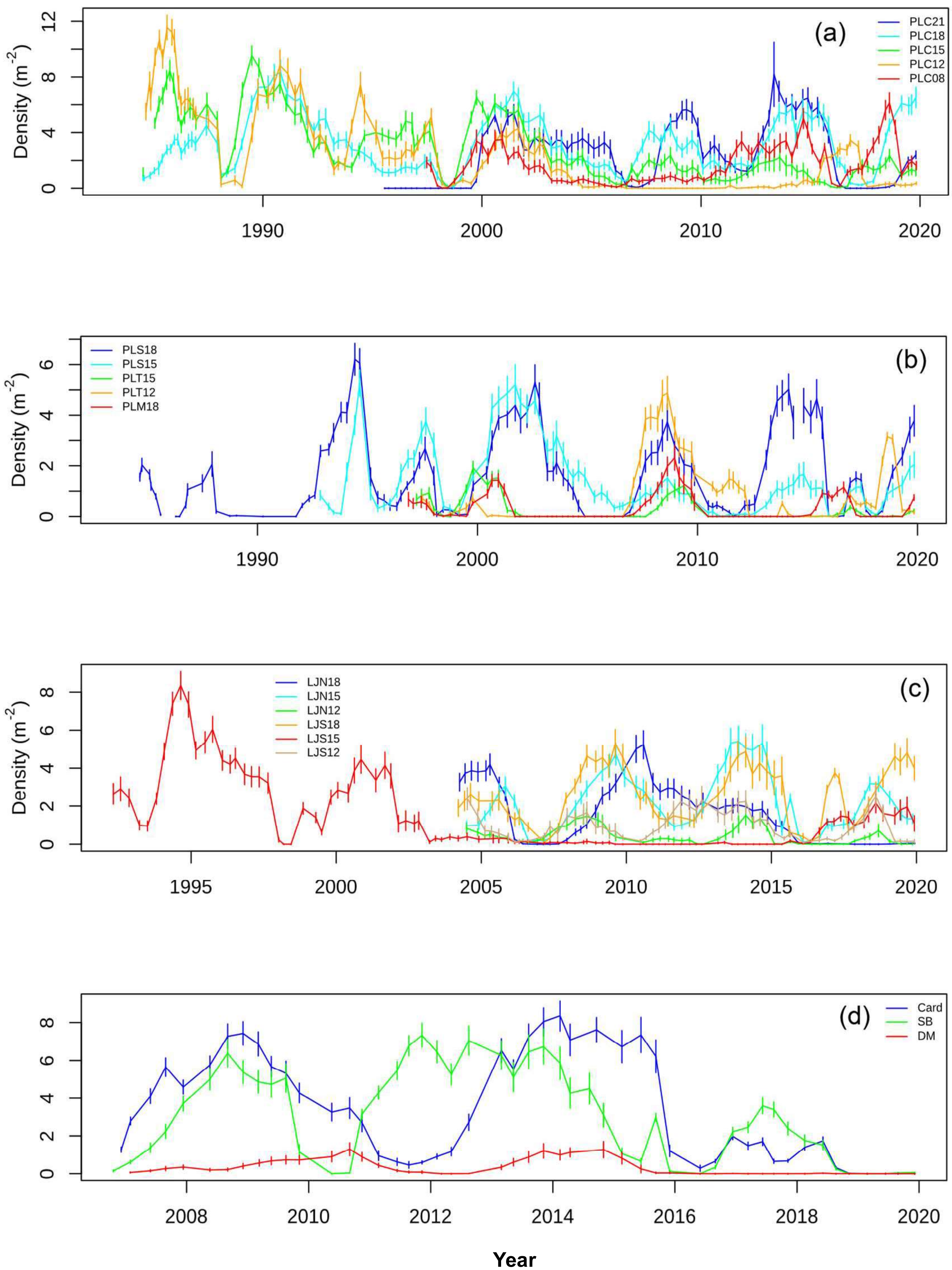
Appendix A.13

Mean densities of *Macrocystis pyrifera* bifurcates: (a) central Point Loma, (b) south Point Loma, (c) La Jolla, and (d) North County study sites. Error bars indicate standard errors.



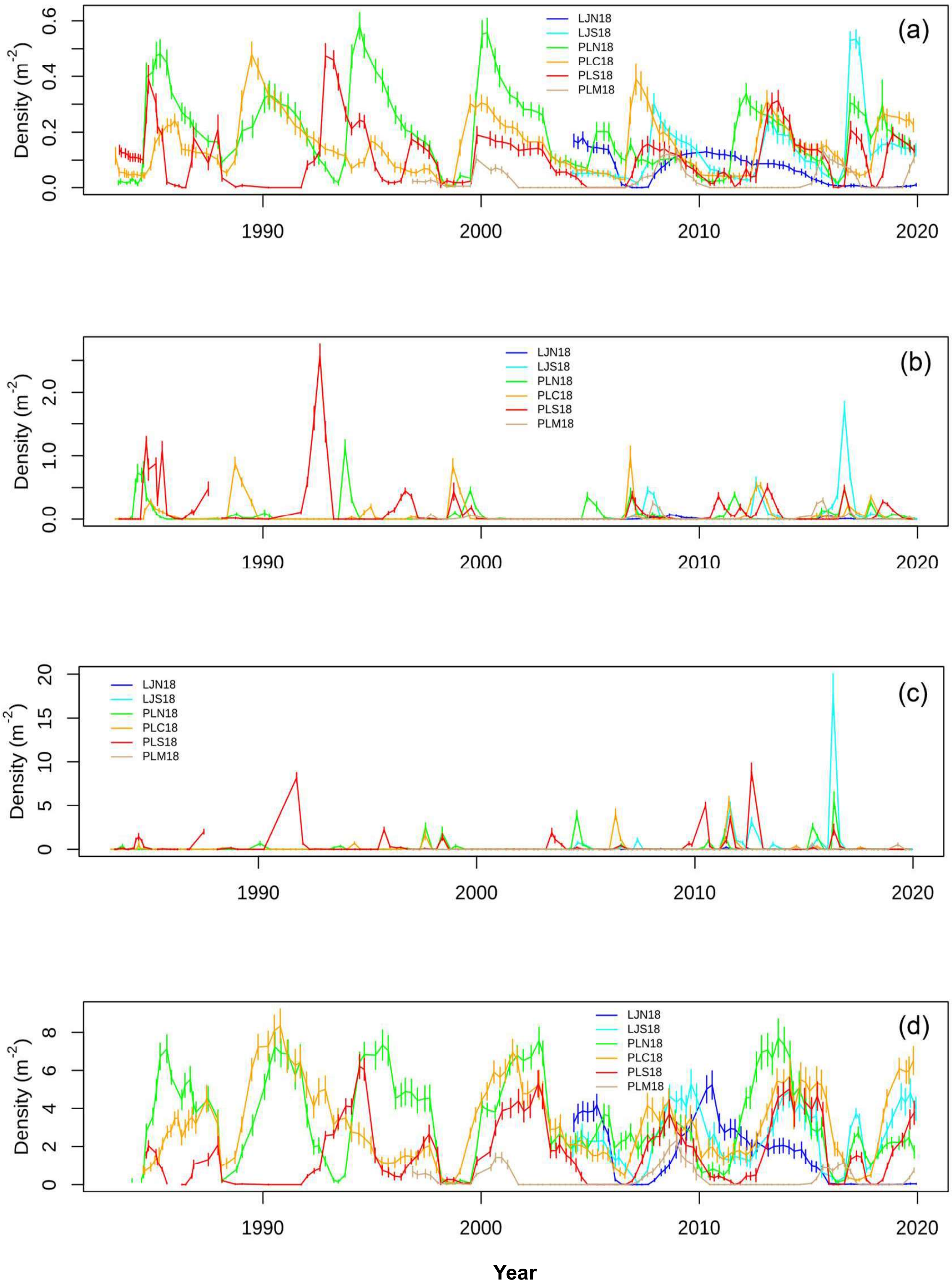
Appendix A.14

Mean densities of *Macrocystis pyrifera* pre-bifurcates: (a) central Point Loma, (b) south Point Loma, (c) La Jolla, and (d) North County study sites. Error bars indicate standard errors.



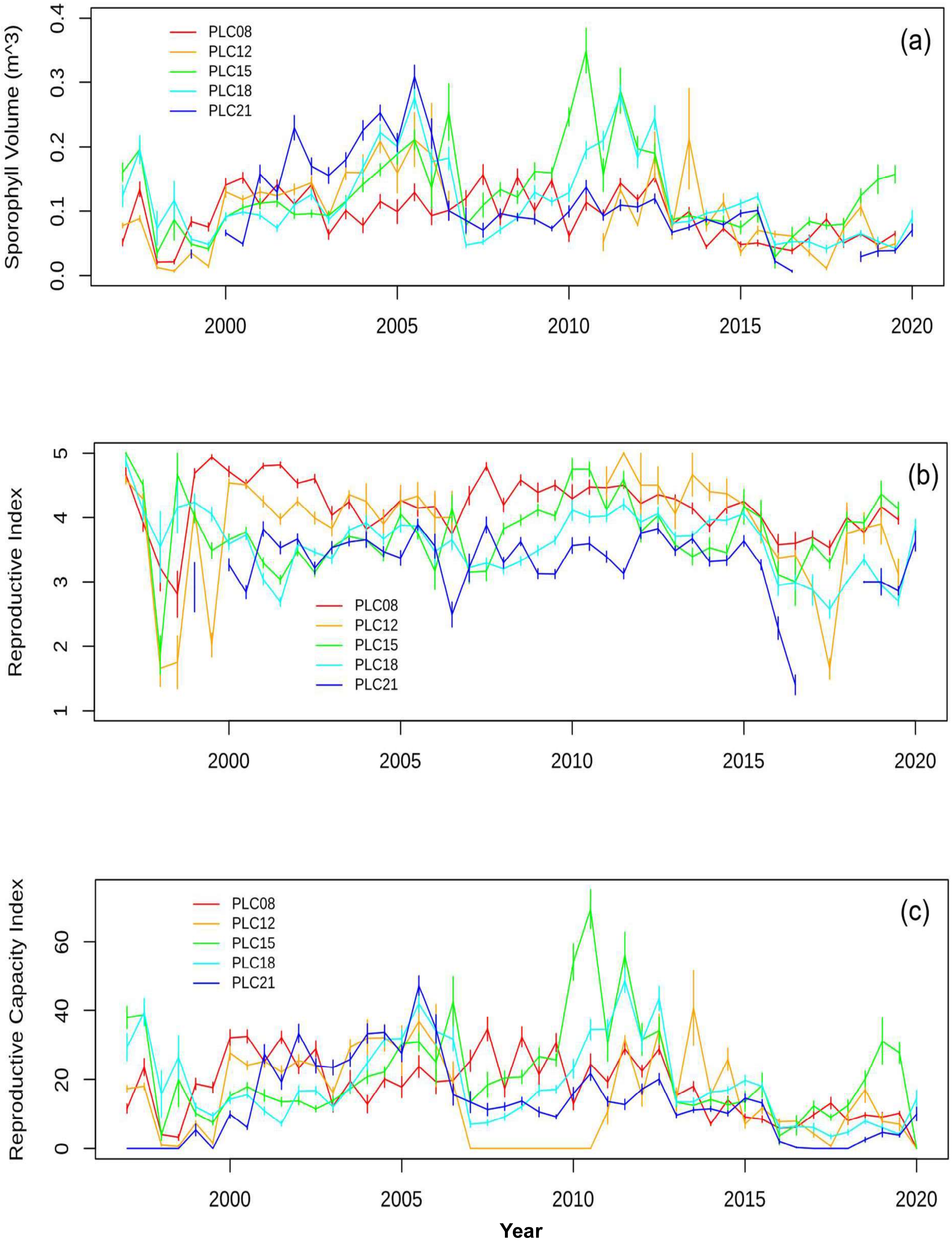
Appendix A.15

Mean densities of *Macrocystis pyrifera* stipes: (a) central Point Loma, (b) south Point Loma, (c) La Jolla, and (d) North County study sites. Error bars indicate standard errors.



Appendix A.16

Mean densities of *Macrocystis pyrifera* (a) adults, (b) pre-adults, (c) pre-bifurcates, and (d) stipes along the 18-m sites off La Jolla and Point Loma. Error bars indicate standard errors.



Appendix A.17

Reproductive states of *Macrocystis pyrifera* at the central Point Loma study sites: (a) sporophyll volume, (b) reproductive index (see Appendix A.5), and (c) reproductive capacity (derived index of relative among-site reproductive potential - see Methods). Means are plotted and error bars indicate standard errors.

low and remain low at present with the exception of a 2017 cohort that died by late 2018. Presently, *P. californica* is present in at least moderate density (>1 m^{-2}) at the LJS18, LJS15, PLC15, PLT12 study sites. The 2016 cohort is presently still thriving at the sites where post El Niño recruitment was greatest (PLC15, LJS18, LJS15).

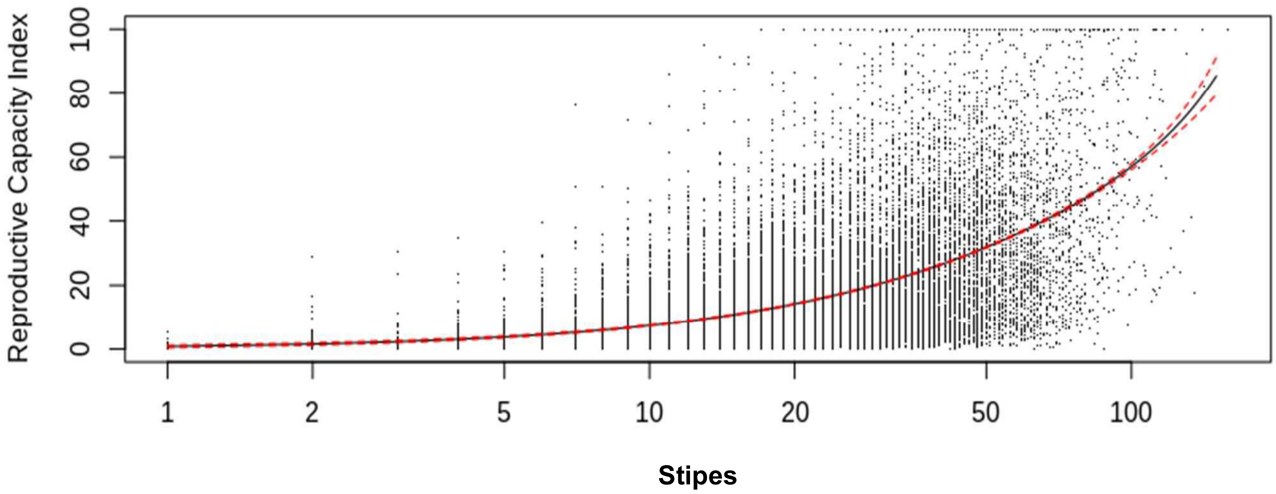
The response of *Laminaria farlowii* to the recent consecutive warm periods was more variable among study sites (Appendix A.20). Three types of responses were observed. First, previously high densities at many sites quickly decreased during the BLOB with subsequent increases during the 2016 El Niño (e.g., PLC15, LJS18, LJS15). Relatively high cover at other sites decreased due to the BLOB and remained reduced through the 2016 El Niño. These mainly include the sites off La Jolla and Del Mar. The third response occurred at PLS15 where cover was increasing prior to the BLOB, which caused a notable decrease, followed by a rapid increase during and after the 2016 El Niño. Currently, *L. farlowii* is present at densities of at least 1 m^{-2} at all of the central and south Point Loma study sites with the exception of PLM18 and PLT15, and all of the La Jolla study sites. *L. farlowii* densities continue to be very low in North County but have recently begun to increase, albeit at much lower densities than most other study areas.

The complex trajectories of understory kelps during and after the consecutive warm periods appear to have switched states. These states can be defined by three canopy/understory modes and are forced by the shading effects of *Macrocystis pyrifera* surface canopy. The three states include (1) lush to moderate surface canopy with low understory, (2) lush understory with low surface canopy, and (3) lush to moderate canopy with low fractional cover of understory. A fourth ephemeral mode was also observed during the consecutive warm periods with sparse canopy and understory forced by the unprecedented duration of nutrient stress during the combined warm periods. In contrast to previous warming events when the shading effect of giant kelp on understory decreases due to thinning of the surface canopy, warm temperatures during the BLOB penetrated to the bottom for an extended period of time (Appendix A.9). This resulted in long periods of nutrient stress for these lower canopy species, and effectively limited their recovery even when light limitation decreased during periods of low surface canopy.

Growth and reproductive states of both *Pterygophora californica* (Appendices A.21, A.22) and *Laminaria farlowii* (Appendices A.23, A.24) were reduced during the BLOB but increased afterward. Both growth and reproduction of *P. californica* remained depressed at the deeper central Point Loma sites until 2017. Decreased reproductive output by both species can delay understory recovery after El Niño disturbances (Dayton et al. 1984), and may contribute to the persistence of switched canopy/understory modes. Such forcing can result in long term dominance over giant kelp than can persist for several years until the occurrence of a new major disturbance. For both species, growth, and reproduction, to a more limited extent, have recovered at all the study sites off central Point Loma. Growth and reproduction of *P. californica* was clearly more affected than *L. farlowii* by the marine heat wave of 2014–2016 and has been somewhat slower to recover.

Algal Community Analysis

Algal community composition among all of the study sites for the last two years is shown in Appendices A.25 and A.26. These plots result from the factor analyses of all algal species and derived bare space. When plotted against one another, the first two factors graphically depict the community-wide state of algae at each site. Together, these factors account for ~31% of the overall variance in the dataset and therefore provide a good representation of the algal communities over time. Factor 1 indicates a continuum of understory algal guild composition ranging (from positive to negative) from fleshy red and articulated coralline algae to the stipitate brown algal species, *Eisenia arborea*, and *Pterygophora californica*, the prostrate brown alga *Laminaria farlowii*, to the post-disturbance pioneer brown alga *Desmerestia ligulata*, to bare



Appendix A.18

Reproductive capacity of *Macrocystis pyrifera* as a function of the number of stipes. Fit is a second order polynomial fit and dashed red curves indicate 95% confidence intervals. Data are inclusive between 1997–2019.

space. This factor encompasses a depth gradient effect from shallow to deep (positive to negative). Factor 2 indicates the condition of *Macrocystis pyrifera*, whether sites are dominated by adults and abundant stipes (positive values) or young recruits and pre-adults (values near zero). The largest changes between 2018 and 2019 reflect the increases in kelp cover at PLC18 and decrease in understory including turf algae, and loss of kelp at the expense of turf species at PLC08. The southern Point Loma sites, with the exception of PLS18, remained dominated by a combination of bare space and *D. ligulata* and low giant kelp density. A major grouping of sites having low giant kelp densities with high turf and understory cover include LJN18, PLC12, LJN12, LJS12.

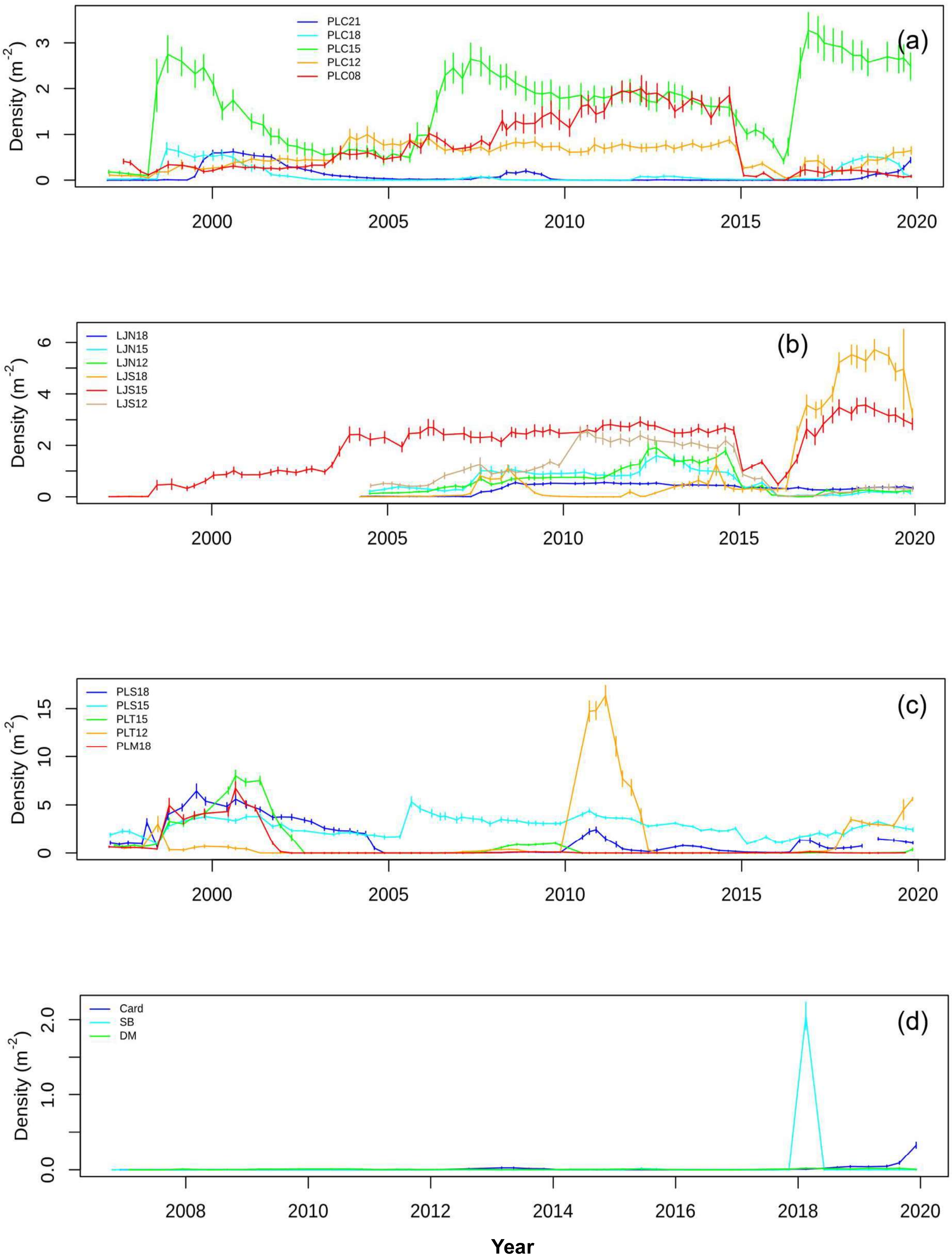
Invasive Algal Species

Sargassum horneri is an invasive alga that invaded southern California in 2006 when it was reported from Long Beach Harbor (Miller et al. 2007). Since that time, it has gradually spread along the coast and was observed in Mission Bay by 2008. *S. horneri* dominates some areas formerly dominated by *Macrocystis pyrifera* including areas off Santa Catalina Island and the Northern Channel Islands off Santa Barbara. *S. horneri* was first observed in the kelp forests off San Diego at the beginning of the study period in 2014 and spread to 13 of our study sites. Initially, it was only observed near some of the study sites, but has subsequently become established within the permanent band transects at several sites. Appendix A.28 lists first sightings within the actual band transects and Appendix A.27 shows relative abundances and frequency among the study sites pooled over time. The greatest percent cover observed thus far was at LJN18 in the fall of 2017 when mean percent cover exceeded 3%. This was followed by increases approaching 2.5% at LJN18. However, while *S. horneri* invaded an increasing number of sites up to 2018, no new sites were invaded in 2019 and there does not appear to be an upward trend for this invasive species (Appendix A.29).

Clearly, *Sargassum horneri* poses a risk to *Macrocystis pyrifera* and other algal species due to its potential seasonal growth rates. It is not implausible for it to take over some areas of the San Diego kelp forests especially after a future major disturbance that reduces the densities and cover of native algal species. Presently, it is too sparsely distributed to be significantly affecting giant kelp with the exception of the LJN18 study site and the deeper portions of the northern La Jolla kelp forest.

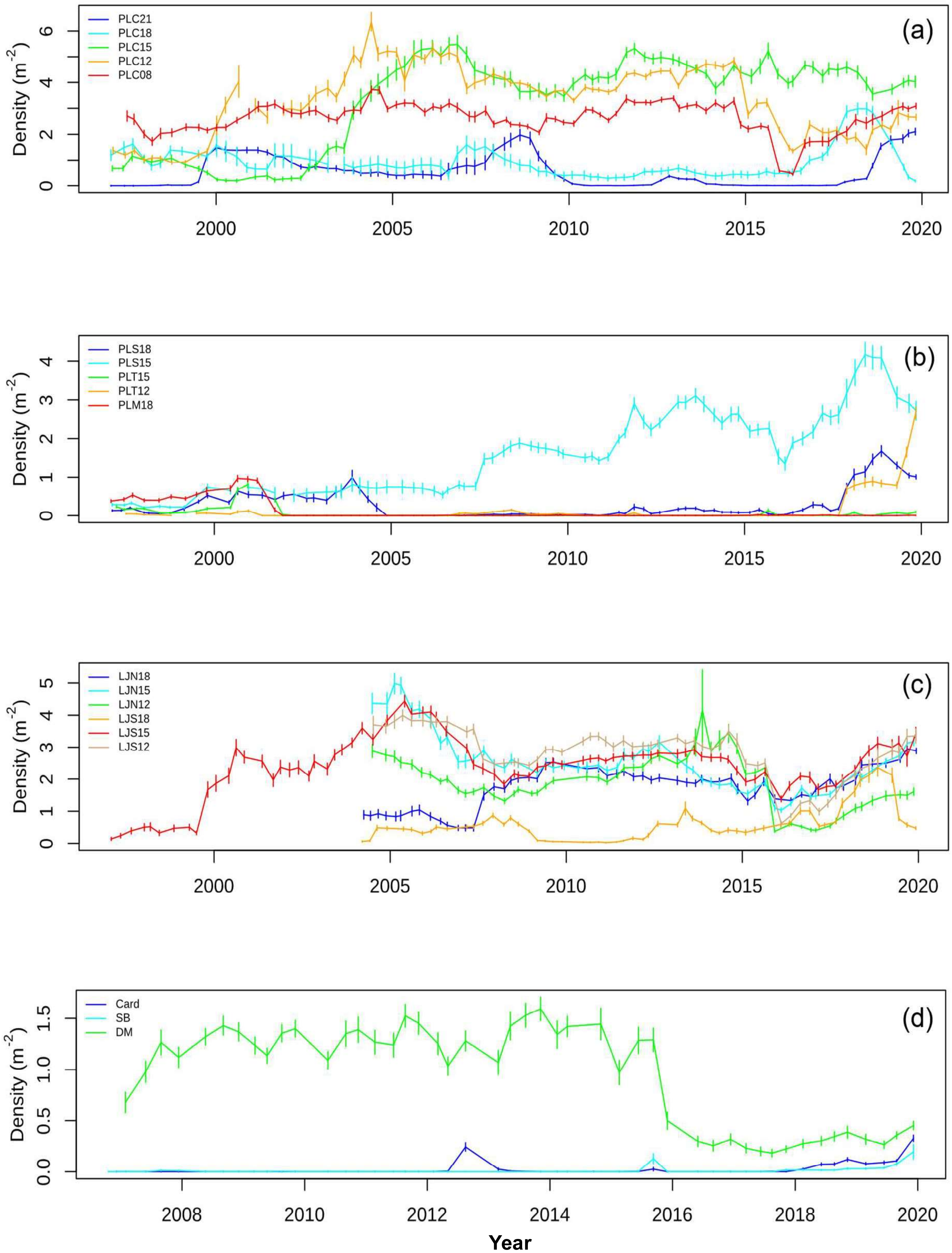
Invertebrates

Many species of invertebrates were also stressed by the 2014–2016 warm event. Sea urchins (Echinoids)



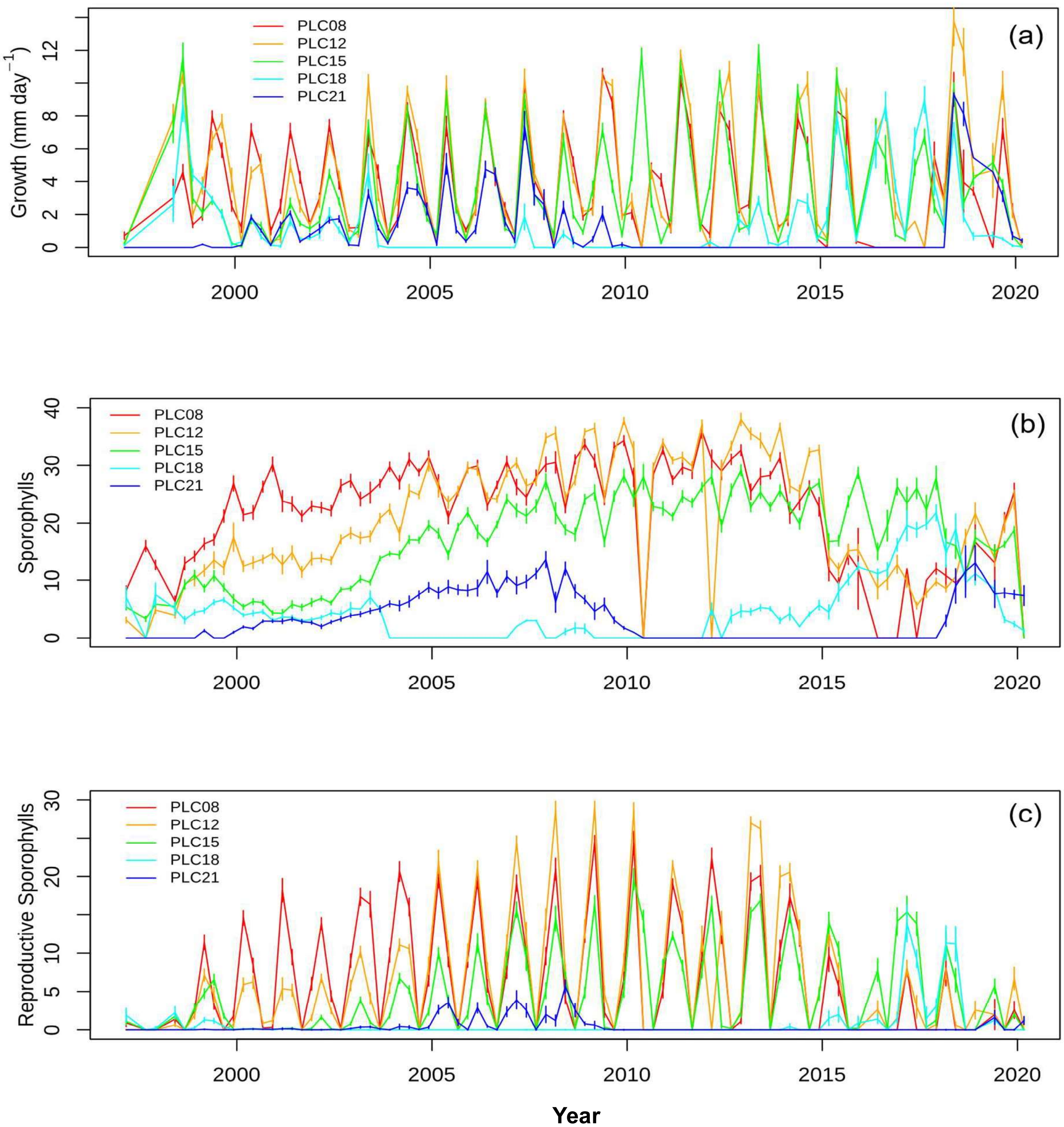
Appendix A.19

Mean densities of the understory kelp *Pterygophora californica*: (a) central Point Loma, (b) south Point Loma, (c) La Jolla, and (d) North County study sites. Error bars indicate standard errors.



Appendix A.20

Mean densities of the understory kelp *Laminaria farlowii*: (a) central Point Loma, (b) south Point Loma, (c) La Jolla, and (d) North County study sites. Error bars indicate standard errors.

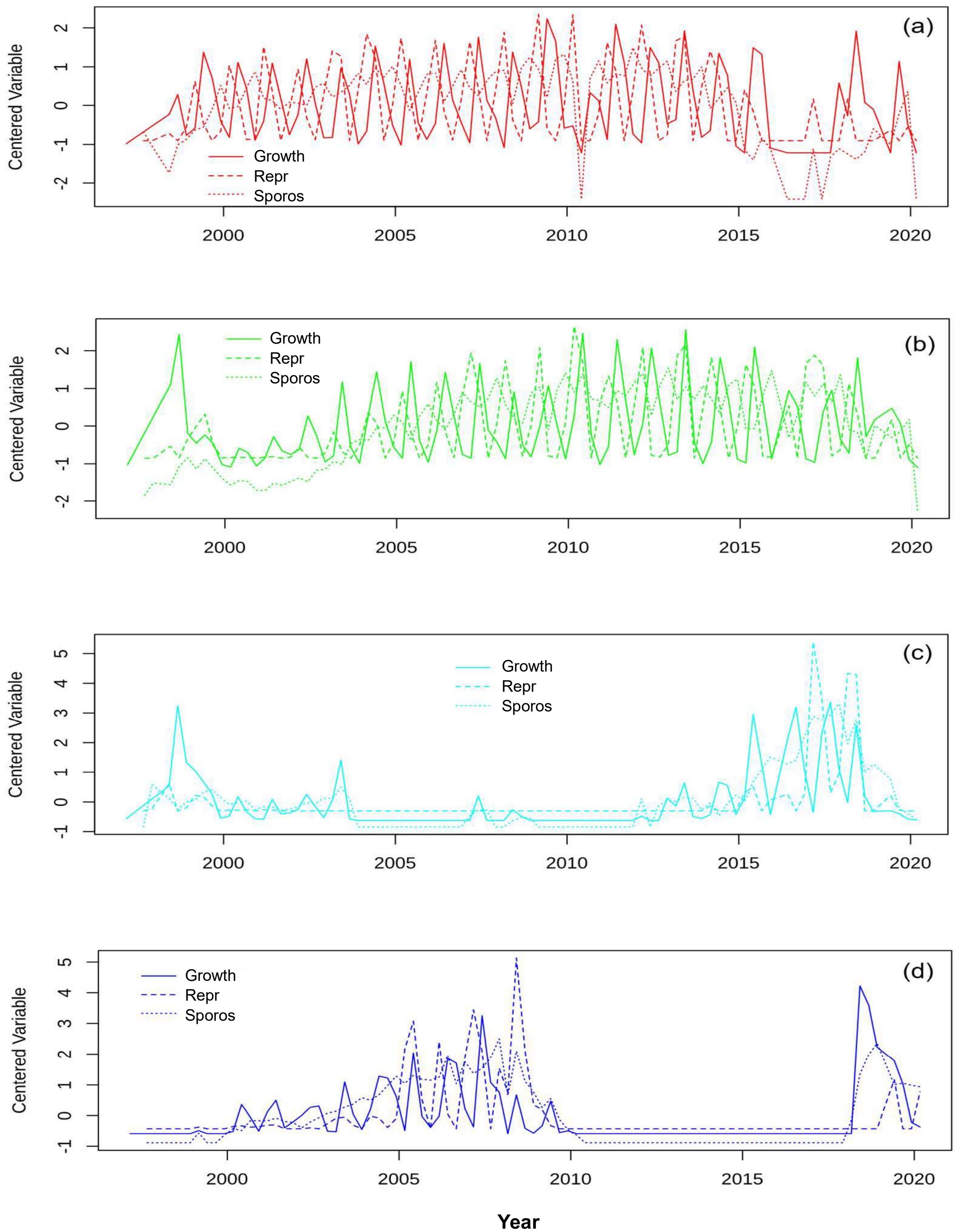


Appendix A.21

Growth and reproduction of the understory kelp *Pterygophora californica* at the central Point Loma study sites: (a) growth, (b) # sporophylls, and (c) # reproductive sporophylls. Means are plotted and error bars indicate standard errors.

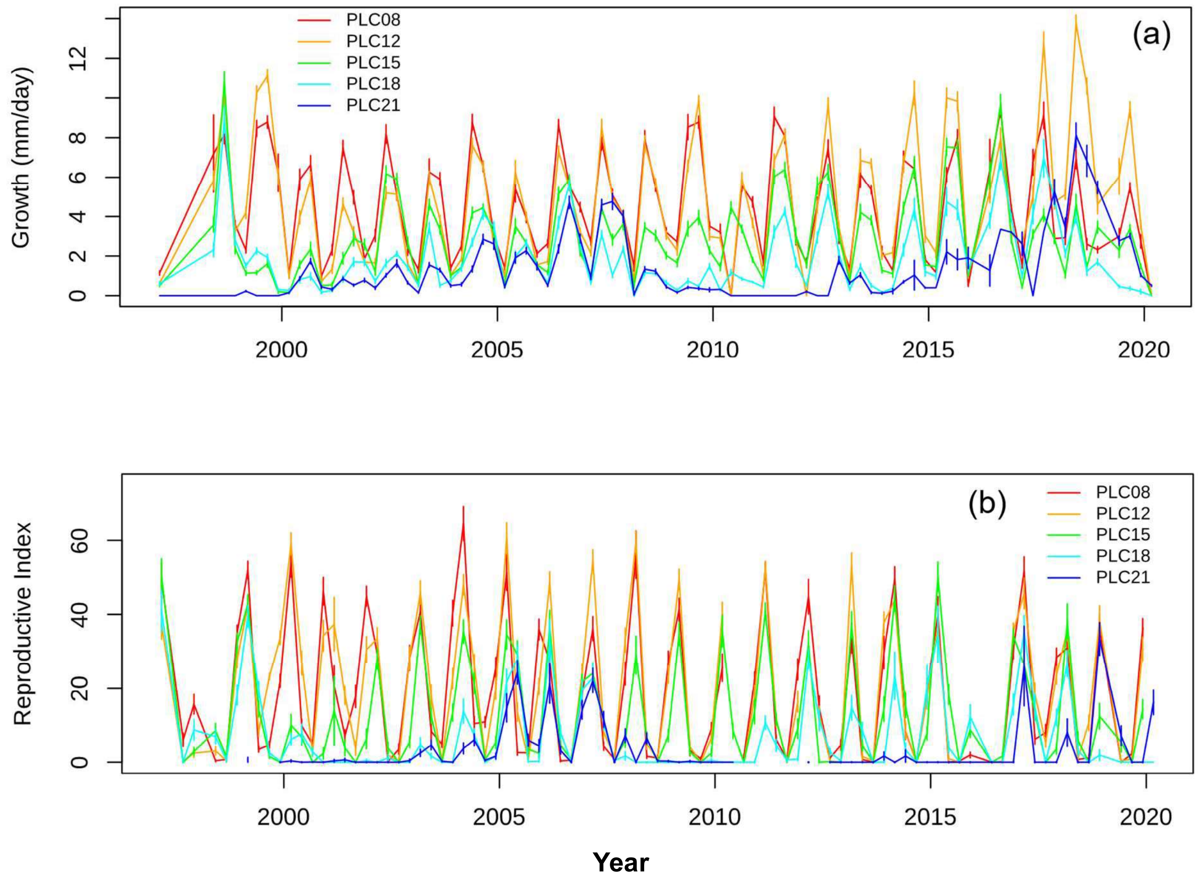
and seastars (Asteroids) were most affected. Both groups have important functions within kelp forests. Sea urchins are major grazers of algae and can overgraze kelp forests if they become too numerous and mobile. Seastars are important benthic predators. Both groups suffered heavy mortality off San Diego during the warm event and remain depressed.

Densities of both red (*Mesocentrotus franciscanus*) and purple (*Strongylocentrotus purpuratus*) sea urchins (RSU and PSU, respectively) either crashed in response to the consecutive warm periods or were already experiencing disease mortality. Sea urchin densities are shown in Appendices A.30–A.33 for the sites where these species were most abundant



Appendix A.22

Centered means of *Pterygophora californica* growth rates, sporophylls, and number of reproductive sporophylls for (a) PLC08, (b) PLC15, (c) PLC18, and (d) PLC21 study sites.



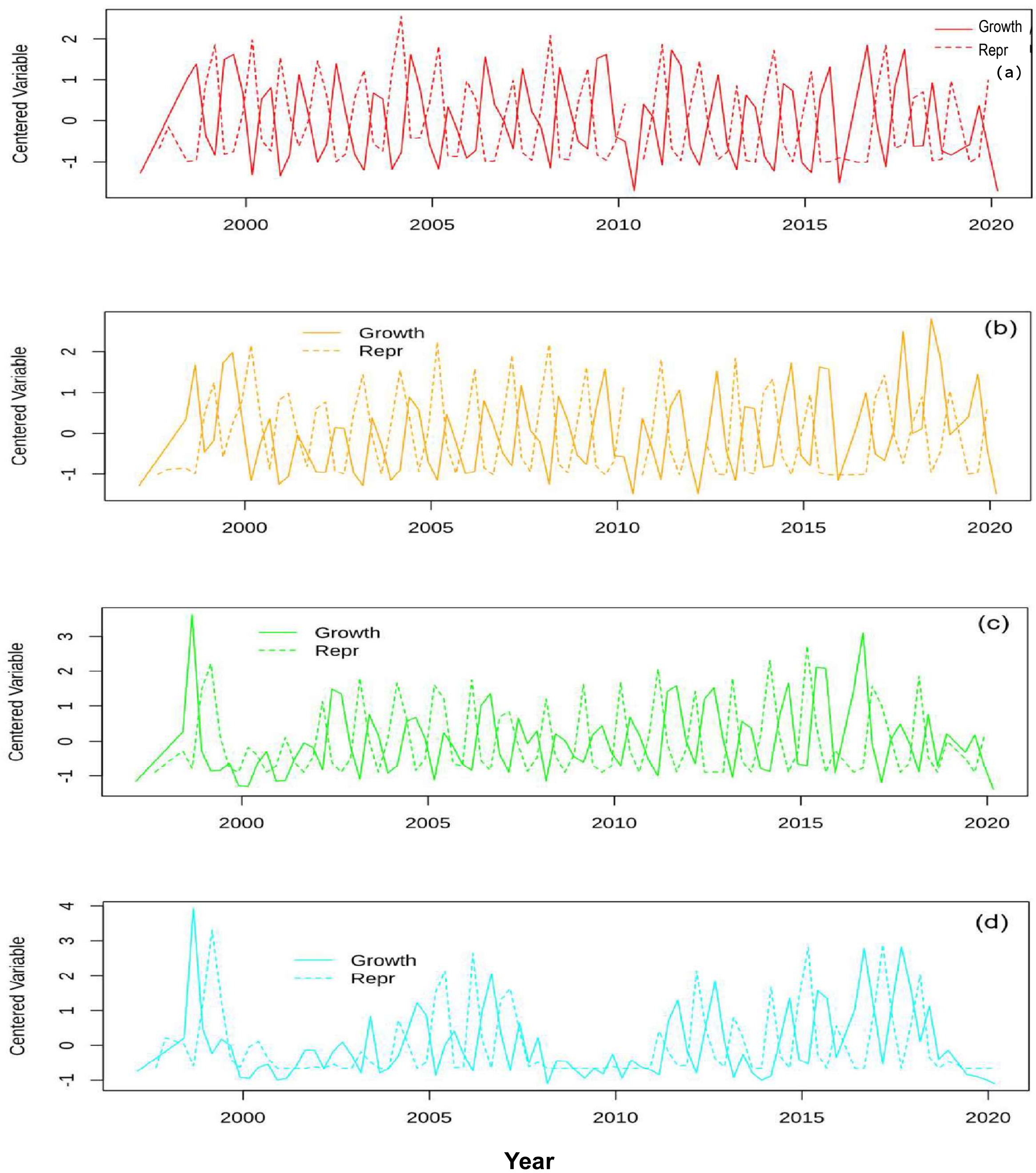
Appendix A.23

Growth and reproduction of the understory kelp *Laminaria farlowii* at the central Point Loma study sites: (a) growth, and (b) % of blade that is sorus (reproductive), Means are plotted and error bars indicate standard errors.

prior to 2014. Decimation of sea urchin populations off San Diego was a direct result of disease mortality and included the 'dark-blotch' disease. Disease epidemics commonly occur in echinoids (sea urchins - Lafferty, 2004) and asteroids ('sea star wasting disease' - Eckert et al. 2000) during periods of warm water stress. Presently, there are few sea urchins of either species at any of the study sites, even off south Point Loma where sea urchin overgrazing has been historically resilient (Parnell 2015). However, red sea urchin densities at the PLC21 and PLC18 sites have remained fairly stable though at low density (Appendix A.31). Additionally, sea urchin recruitment was absent or extremely limited at all sites until the fall of 2017 (based on semi-annual size frequency sampling). Sea urchin recruitment (percent in the first-year age class at a site) for both species has since increased at several sites (Appendix A.34). The largest increases were observed mainly at the southern Point Loma sites, and all sites off La Jolla. Recruitment of RSU was robust at the outer central Point Loma stations (PLC18 and PLC21).

Sea urchins are nonetheless not likely to have any immediate effects on kelp recovery due to their reduced abundance and delayed recruitment. However, the fall 2017 and 2018 sea urchin recruitment cohorts may eventually lead to overgrazing at some sites as the sea urchins mature and migrate away from sheltering juvenile habitat and begin to actively seek forage. Thus, sea urchin overgrazing may occur at some sites by late 2020 as the fall 2017–2018 cohort matures.

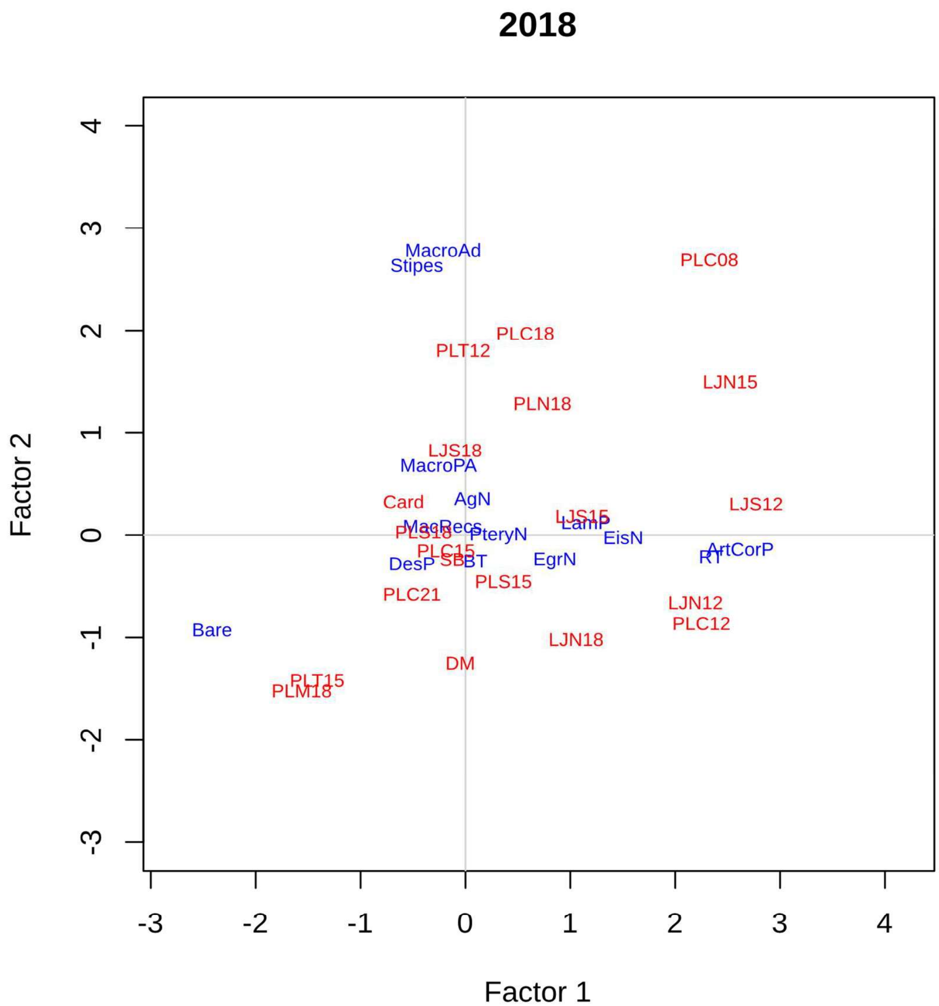
Diseases affecting echinoderms also caused mass mortality of several asteroid species throughout the Southern California Bight during the consecutive warm periods (Hewson et al. 2014). Species that suffered the greatest mortality at our study sites



Appendix A.24

Centered mean growth and reproduction of the understory kelp *Laminaria farlowii* at the central Point Loma study sites (a) PLC08, (b) PLC12, (c) PLC15, and (d) PLC18.

included *Pisaster giganteus* (Appendix A.35) and *P. brevispinus* where densities were reduced to zero for both species, even at sites where they were previously abundant. Disease induced mass mortality events of asteroids and echinoids are commonly followed by recovery at differing rates. Juvenile *P. giganteus* were observed recruiting onto giant kelp fronds off Point Loma beginning in 2017 and continuing into 2018, thus heralding their recovery. However, disease has also decimated *Pycnopodia helianthoides*, an important sea urchin predator (Moitoza and Phillips 1979). This species has not been observed anywhere off Point Loma since 2014 even in areas where they were once common. *P. helianthodes* was in decline even prior to the BLOB event.



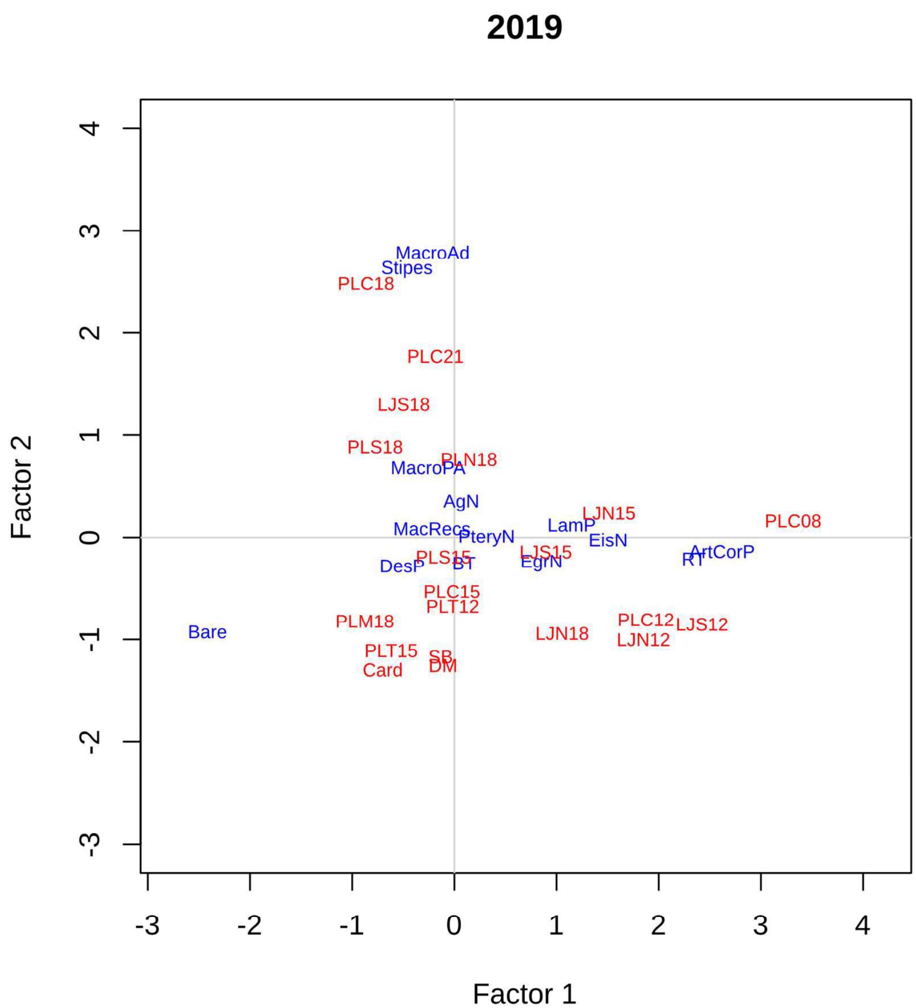
Appendix A.25

Plot of first two factors resulting from the factor analysis of algal groups among the 20 permanent study sites in 2018. Algal group definitions: Bare = derived bare space, MacRecs = *Macrocystis pyrifera* recruit stage (pre-bifurcates + bifurcates), MacroAd = *M. pyrifera* adult density, Stipes = *M. pyrifera* stipe density, MarcroPA = *M. pyrifera* pre-adults (<4 stipes), PteryN = *Pteryogophora californica* density, LamP = *Laminaria farlowii* percent cover, EisN = *Eisenia arborea* density, EgrN = *Egregia menziesii* density, AgN = *Agarum fimbriatum* density, DesP = *Desmerestia ligulata* percent cover, ArtCorP = *articulated coralline* algae percent cover, RT = foliose red algal percent cover, BT = brown algal turf percent cover.

Abalones are marine mollusks that once supported an economically important commercial fishery throughout California until the 1980s. Their primary food in southern California is giant kelp. Therefore, when kelp populations are reduced, abalones become stressed both by the lack of food as well as diseases associated with warm water events (Vilchis et al. 2005). Historically, seven species of abalone have been common off San Diego. Two species, *Haliotis cracherodii* and *H. sorenseni*, are now on the federal endangered species list. Another species, *H. rufescens* has been in decline off southern California since the 1970s, and populations off Point Loma crashed in the 1980's (Tegner and Dayton 1987). However, *H. rufescens* persisted in low numbers near PLS18 and LJS18. Those few were lost during the recent prolonged warm periods. At the same time, densities of pink abalone (*H. corrugata*) have been steadily increasing at PLC8 since 2012 (Appendix A.36), exhibiting steady population increases throughout the warm period.

North County Sedimentation

Sediments at the NCKF sites have been relatively stable since 2008. Sediment horizons have varied



Appendix A.26

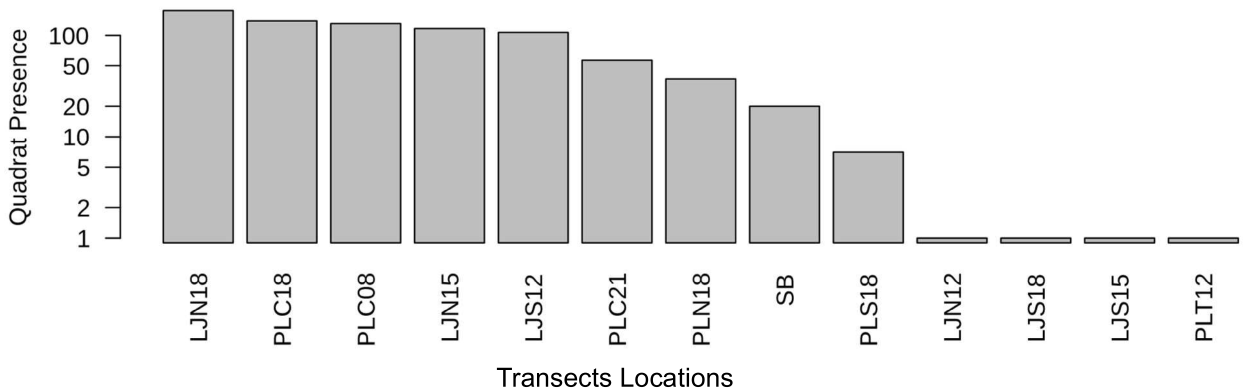
Plot of first two factors resulting from the factor analysis of algal groups among the 20 permanent study sites in 2019. See Appendix A.25 for description of plot.

less than 10 cm since 2008 when the sediment time series began. This period included the significant replenishment of beaches inshore of the study sites in 2012. North County beaches have recently been replenished as part of a project that is slated to last four years. The grain size of sediments used for beach replenishment is an important determinant of beach stability. The 2012 replenishment event utilized coarser sediments than previous replenishment efforts, and therefore erosion of those beaches did not appear to affect NCKF reefs. The source of sediments for the present beach replenishment effort is San Elijo Lagoon, as part of an effort to restore the estuary to more marine conditions. The grain size composition of these sediments is not clearly defined and therefore the potential impact of this most recent replenishment project on North County reefs is presently uncertain.

Summary of Findings

(1) The kelp forests of southern California, including those off San Diego, were decimated by the marine heat wave of 2014–2016. Cooler and more nutritive conditions for kelps returned by the spring of 2017 when many of the kelp forests off San Diego began their recovery. This recovery has included the recruitment and growth of at least two giant kelp cohorts and their subsequent successful reproductive recovery. Reproduction and growth of the understory kelps have also resumed.

(2) The recovery of San Diego kelp forests has varied both among and within the forests. The La Jolla and Point Loma kelp forests have recovered



Appendix A.27

Presence of the invasive alga, *Sargassum horneri*, among the study sites where it has been observed within the permanent band transects. Quadrat presence indicates the total number of 5 x 2 m quadrats along the transects where it has been observed over time since first sighting at each individual site.

the most and are presently at ~47% of their all-time historic highs in terms of giant kelp stipe density. There was limited recruitment of giant kelps off Del Mar, Solana Beach, and Cardiff, but that initial recovery has been unsuccessful and there is little kelp in those areas due to space competition with understory species and likely limited light levels due to turbidity.

(3) Ocean climate conditions forecast for the upcoming year are conducive for the further recovery of the kelp forests off La Jolla and Point Loma.

(4) The distribution and density of the invasive alga *Sargassum horneri* appear to have stabilized indicating it may not be as great a threat to the open coastal kelp forests off San Diego as initially thought.

(5) Sea urchins, which are major herbivores of giant kelp, were decimated by a combination of disease and lack of their giant kelp food source during the marine heat wave. Since the heat wave has dissipated, sea urchin recruitment has been strong at many of the study sites and these new cohorts of sea urchins may pose overgrazing risks to some areas of the kelp forests off San Diego, particularly the southern portion of the Point Loma kelp forest where resilient sea urchin barrens have been observed over ~200 hectares for at least 80 years.

(6) Associated with the marine heat wave and just prior to it, several species of seastars were nearly extirpated off San Diego due to wasting disease. There has been limited recruitment of some species, but even these species are presently in very low abundances. Some of these species are important predators of sea urchins including the seastar *Pycnopodia helianthoides*, which has not been observed anywhere off San Diego since the onset of the marine heat wave.

(7) Abalone densities remain low or at zero at most study sites with the exception of the shallowest study sites off central Point Loma where densities of pink abalones, *Haliotis corrugata*, have been recently increasing.

(8) There is no evidence that discharge of wastewater through the Point Loma ocean outfall has negatively affected the nearby kelp forest.

Literature Cited

Clendenning, K.A. and North, W.J. (1960). Effects of wastes on the giant kelp, *Macrocystis pyrifera*. In Proceedings of the First International Conference on Waste Disposal in the Marine Environment University of California, Berkeley, July 22–25, 1959 (p. 82). Pergamon.

Appendix 28

List of study sites and date of first observation of the invasive alga, *Sargassum horneri*, within band transects.

Study Site	Date 1st Observed
SB	Sep. 9, 2105
PLC18	Oct. 10, 2015
PLN18	Dec. 2, 2015
LJN15	Dec. 3, 2015
LJS12	Feb. 8, 2016
PLC08	Mar. 31, 2016
LJS18	May 03, 2016
LJS15	May 03, 2016
PLT12	May 11, 2016
LJN18	May 19, 2016
PLC21	Apr. 18, 2017
LJN12	Jun. 30, 2017
PLS18	May 30, 2018

Dayton, P. K., and Tegner, M. J. (1984). Catastrophic storms, El Niño, and patch stability in a southern California kelp community. Science, 224(4646), 283–285.

Dayton, P. K., Currie, V., Gerrodette, T., Keller, B. D., Rosenthal, R., and Tresca, D. V. (1984). Patch dynamics and stability of some California kelp communities. Ecological Monographs, 54(3), 253–289.

DeWreede, R. E. (1984). “Growth and age class distribution of *Pterygophora californica* (Phaeophyta).” Marine Ecology Progress Series 19: 93–100.

Di Lorenzo, E., and Mantua, N. (2016). Multi-year persistence of the 2014/15 North Pacific marine heatwave. Nature Climate Change, 6(11), 1042–1047.

Eckert, G. L., Engle, J. M., and Kushner, D. J. (2000). Sea star disease and population declines at the Channel Islands. In Proceedings of the fifth California Islands symposium (pp. 390–393).

Grigg, R. W. (1978). Long-term changes in rocky bottom communities off Palos Verdes. Coastal Water Research Project, annual report for the year, 157–184.

Hewson, I., Button, J. B., Gudenkauf, B. M., Miner, B., Newton, A. L., Gaydos, J. K., and Fradkin, S. (2014). Densovirus associated with sea-star wasting disease and mass mortality. Proceedings of the National Academy of Sciences, 111(48), 17278–17283.

Lafferty, K. D. (2004). Fishing for lobsters indirectly increases epidemics in sea urchins. Ecological Applications, 14(5), 1566–1573.

Lawley, D. N. and Maxwell, A. E. (1971). Factor Analysis as a Statistical Method. Second edition. Butterworths.

Leighton, D. L., Jones, L. G., and North, W. J. (1966). Ecological relationships between giant kelp and sea urchins in southern California. In Proceedings of the Fifth International Seaweed Symposium, Halifax, August 25–28, 1965 (pp. 141–153).

MBC Applied Environmental Science (2017). Status of the Kelp Beds, 2017: Ventura, Los Angeles, Orange, and San Diego Counties. Technical Report (97 p.).

Miller, K. A., Engle, J. M., Uwai, S., and Kawai, H. (2007). First report of the Asian seaweed Sargassum filicinum Harvey (Fucales) in California, USA. Biological Invasions, 9(5), 609.

Miller, K. A., Aguilar-Rosas, L. E., and Pedroche, F. F. (2011). A review of non-native seaweeds from California, USA and Baja California, Mexico. Hidrobiológica, 21(3).

Moitoza, D. J., and Phillips, D. W. (1979). Prey defense, predator preference, and nonrandom diet: the interactions between *Pycnopodia helianthoides* and two species of sea urchins. Marine Biology, 53(4), 299–304.

NOAA (2020). ENSO: Recent Evolution, Current Status and Predictions. Update prepared by: Climate Prediction Center/ NCEP, 22 April 2019. Retrieved from NOAA website: https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/lanina/enso_evolution-status-fcsts-web.pdf

Parnell, P., Miller, E. F., Cody, C. E. L., Dayton, P. K., Carter, M. L., and Stebbins, 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.

Parnell, P. E. (2015). The effects of seascape pattern on algal patch structure, sea urchin barrens, and ecological processes. Journal of experimental marine biology and ecology, 465, 64–76.

R Core Team (2018). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Reed, D. C. (1987). "Factors affecting the production of sporophylls in the giant kelp *Macrocystis pyrifera*." Journal of Experimental Marine Biology and Ecology 113: 61–69.

Roberts, P. J. (1991). Ocean outfalls. Critical Reviews in Environmental Science and Technology, 20(5-6), 311–339.

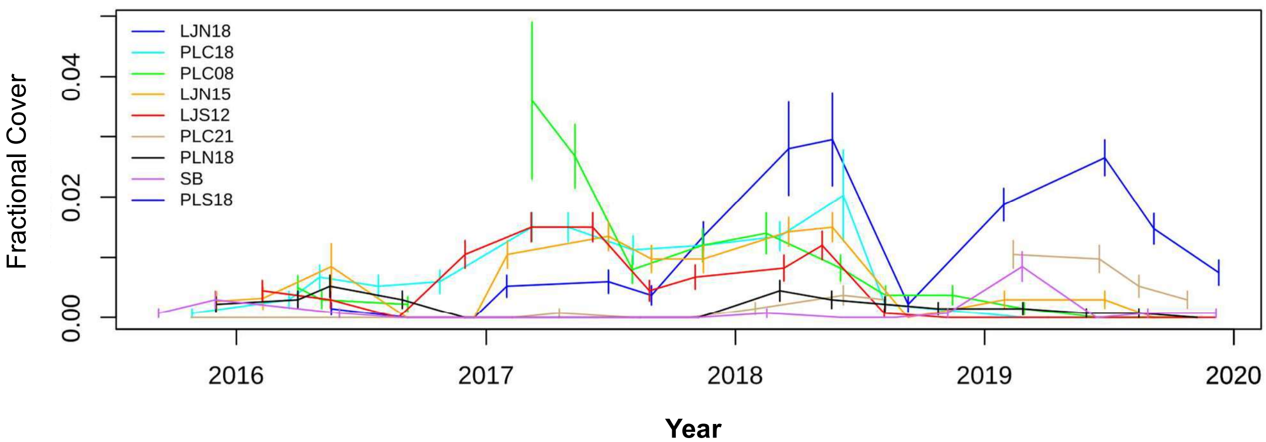
Seymour, R. J., Tegner, M. J., Dayton, P. K., and Parnell, P. E. (1989). Storm wave induced mortality of giant kelp, *Macrocystis pyrifer*a, in southern California. Estuarine, Coastal and Shelf Science, 28(3), 277–292.

Steneck, R. S., Graham, M. H., Bourque, B. J., Corbett, D., Erlandson, J. M., Estes, J. A., and Tegner, M. J. (2002). Kelp forest ecosystems: biodiversity, stability, resilience and future. Environmental conservation, 29(4), 436–459.

Tegner, M. J., and Dayton, P. K. (1987). El Niño effects on southern California kelp forest communities. In Advances in Ecological Research (Vol. 17, pp. 243–279). Academic Press.

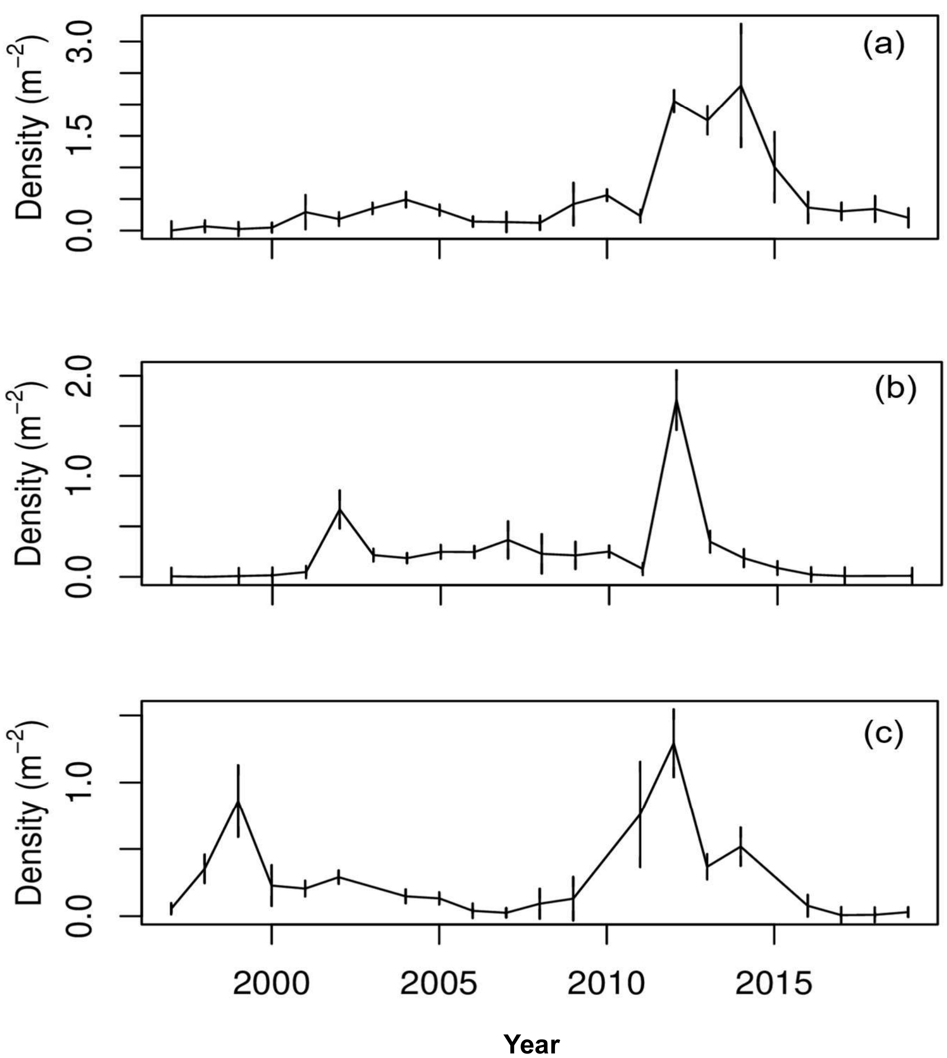
Towle, D. W., and Pearse, J. S. (1973). Production of the giant kelp, *Macrocystis*, estimated by in situ incorporation of 14C in polyethylene bags. Limnology and Oceanography, 18(1), 155–159.

Vilchis, L. I., Tegner, M. J., Moore, J. D., Friedman, C. S., Riser, K. L., Robbins, T. T., and Dayton, P. K. (2005). Ocean warming effects on growth, reproduction, and survivorship of southern California abalone. Ecological Applications, 15(2), 469–480.



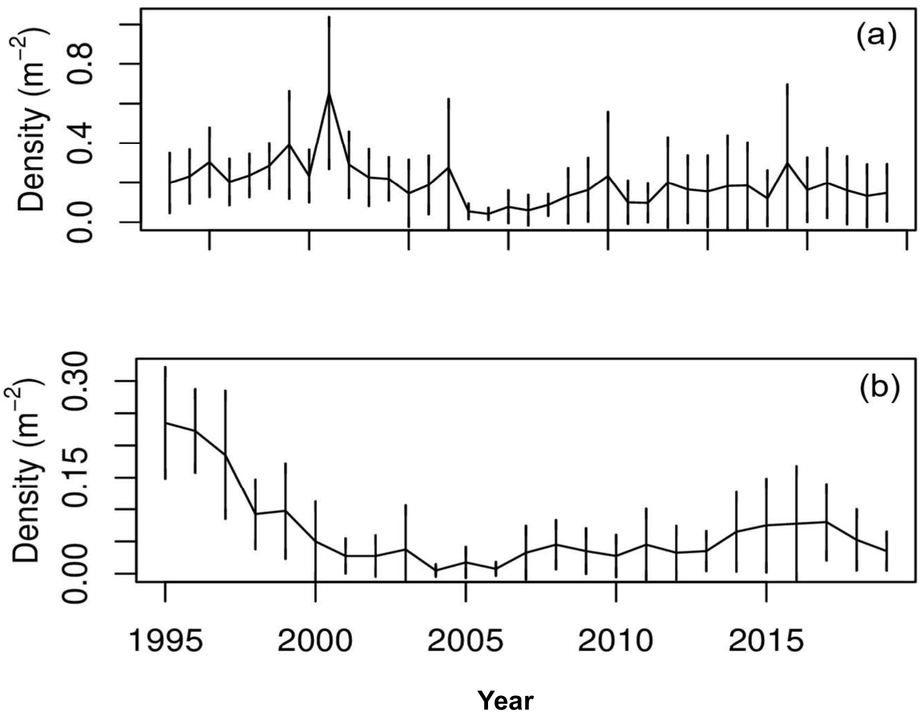
Appendix A.29

Fractional cover of the invasive alga *Sargassum horneri* over time beginning when it was first observed in the kelp forests off San Diego (see Appendix A.28).



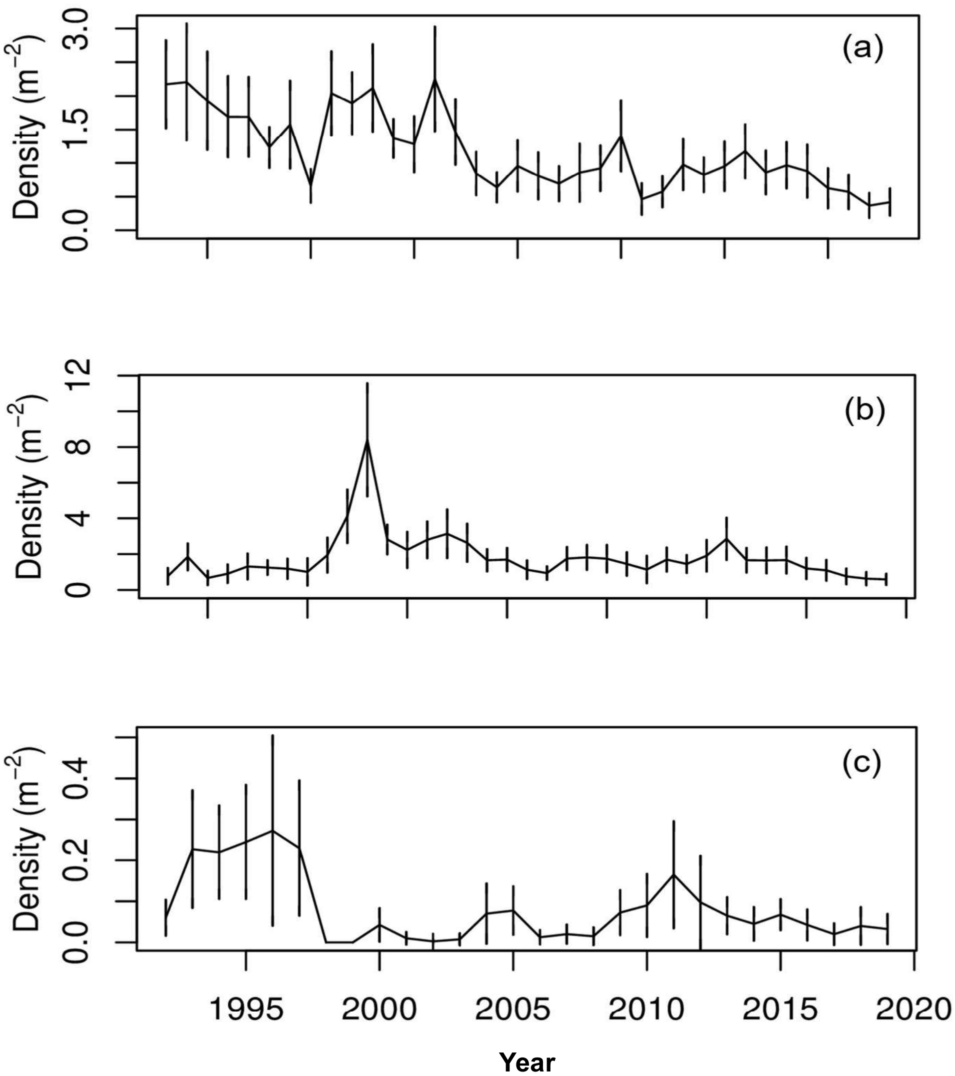
Appendix A.30

Time series of the red sea urchin (*Mesocentrotus franciscanus*) mean densities at the (a) PLM18, (b) PLT15, and (c) PLT12 study sites. Error bars are standard errors.



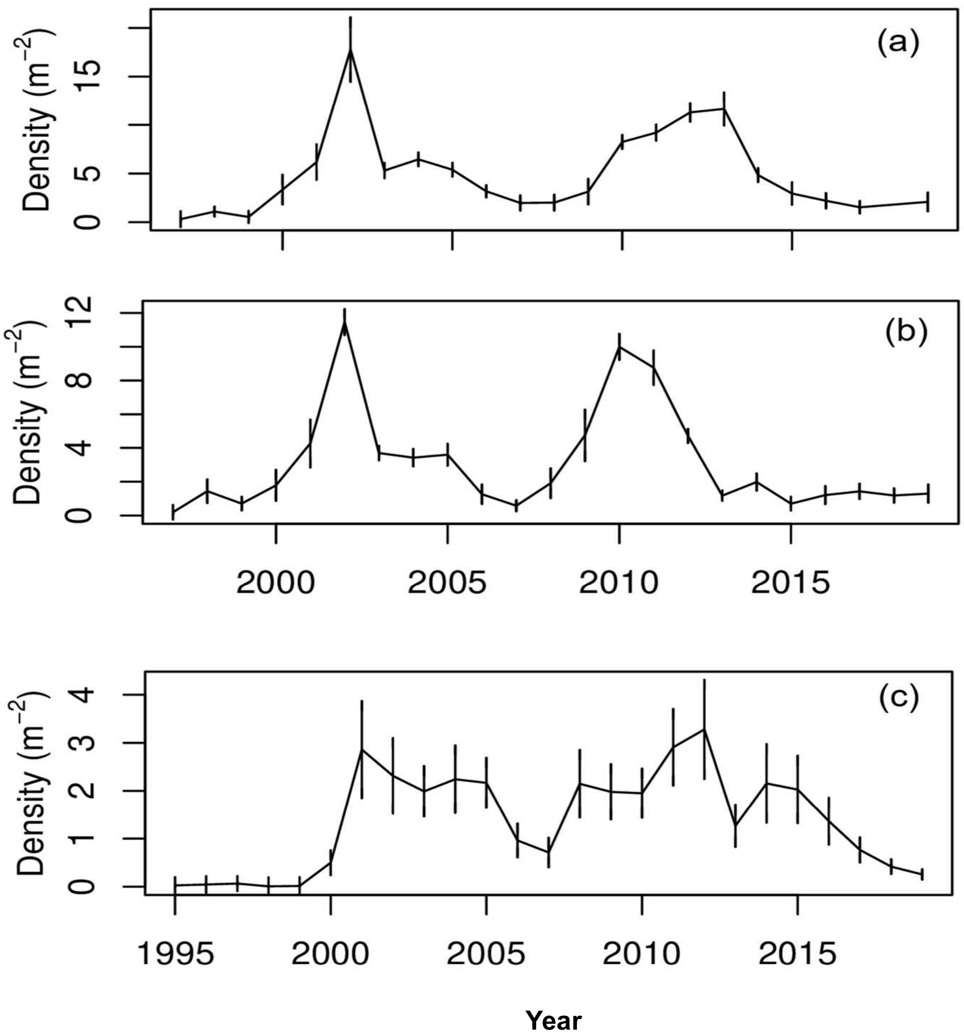
Appendix A.31

Time series of the red sea urchin *(Mesocentrotus franciscanus*) mean densities at the (a) PLC18, and (b) PLC21 study sites. Error bars are standard errors.



Appendix A.32

Time series of purple sea urchin (S*trongylocentrotus purpuratus*) mean densities at the (a) PLC15, (b) PLN18, and (c) LJS15 study sites. Error bars are standard errors.



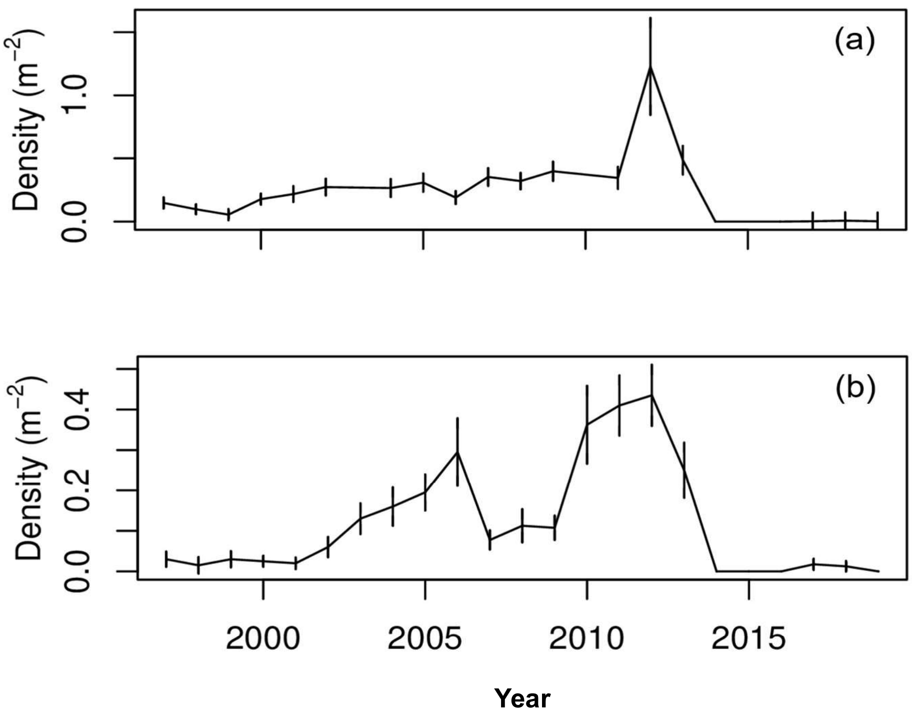
Appendix A.33

Time series of purple sea urchin (*Strongylocentrotus purpuratus*) mean densities at the (a) PLT15 (b) PLM18, and (c) PLC21 study sites. Error bars are standard errors.

Appendix A.34

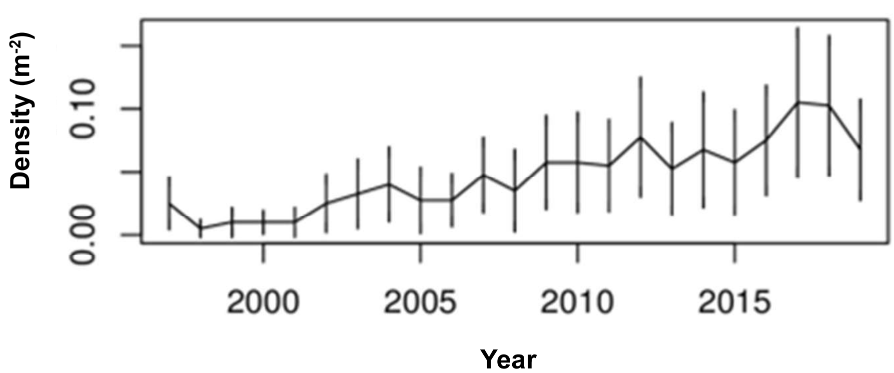
Recruitment rates for red and purple sea urchins (*Mesocentrotus franciscanus* and *Strongylocentrotus purpuratus*, respectively) during the spring and fall of 2019. Recruitment percent is the fraction of ~1 year old individuals sampled within quadrats. Size thresholds for RSU and PSU recruits are <35 and <25 mm, respectively. "*" refers to sites where too few sea urchins were available for measurement (n<30).

	Mesocentrotus franciscanus		*Strongylocentrotus purpuratus*	
Site	**Spring**	**Fall**	**Spring**	**Fall**
LJNorth12	0.38	0.54	0.30	0.30
LJNorth15	0.48	0.19	0.24	0.06
LJNorth18	0.15	0.16	0.16	0.11
LJSouth12	0.33	0.18	0.11	0.17
LJSouth15	0.33	0.25	0.27	0.28
LJSouth18	0.64	0.13	0.24	0.16
PLCen12	*	*	0.11	0.02
PLCen15	0.16	0.00	0.08	0.04
PLCen18	0.21	0.13	0.25	0.13
PLCen21	0.56	0.51	0.49	0.12
PLCen8	*	*	0.27	0.09
PLCenW18	0.31	0.06	0.22	0.17
PLMouth18	0.33	0.28	0.56	0.15
PLNorth18	0.19	0.03	0.06	0.04
PLSouth15	0.36	0.11	0.13	0.03
PLSouth18	0.33	0.38	0.33	0.10
PLSouthW18	0.00	0.08	0.01	0.39
PLTip12	0.41	0.25	0.29	0.14
PLTip15	0.54	0.91	0.88	0.20



Appendix A.35

Time series of the seastar *Pisaster giganteus* mean densities at the (a) PLT12 and (b) PLM18 study sites. Error bars are standard errors



Appendix A.36

Time series of pink abalone (*Haliotis corrugata)* mean densities at the PLC8 study site. Error bars are standard errors.