Evaluation of Anthropogenic Impacts on the San Diego Coastal Kelp Forest Ecosystem

Biennial Project Report
Spring 2023 – Fall 2025

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EXECUTIVE SUMMARY

The results presented in this biennial report (spring 2023 to fall 2025) of the City of San Diego's evaluation of anthropogenic impacts on kelp forests program show that the giant kelp forests along the San Diego coastline have experienced reduced persistence over the past decade in several historically stable beds. However, for much of the recent reporting period, the kelp forests appear to have generally benefited from extended periods of cooler than average temperatures, sufficient benthic irradiance for photosynthesis, lower wave heights, and reduced urchin densities and recruitment at most sites, indicating ample nutrient and light exposure for reproduction and growth, and reduced wave and herbivory disturbance. Although spatially variable, as a result, the kelp forests of San Diego County have shown episodic kelp recruitment, with increasing abundance and plant size. For example, during this reporting period, some of the monitoring sites showed giant kelp densities of both early and mature life stages, as well as mean plant size, within the top 10% of the time series dating back to 2007. Mean stipe density and maximum plant size were within the top 20%. These results suggest adequate conditions for giant kelp recruitment and growth at many sites.

The region has experienced strong spatial variability in temperatures, with net cool water and associated nutrient exposure being prominent features of the reporting period. Although monthly bottom temperature anomalies across the region varied by both depth and site, they did show cooler anomalies (compared to the monthly average for 2007 to 2025) across many sites in late 2024 and early 2025, and again at some sites, particularly shallow ones, in late 2025. A recent notable pattern of cooler than average temperatures occurred at 8 m depth at the Point Loma Central site, where much of the kelp recovery has been documented, with periods in 2023 and 2025 registering some of the coldest temperatures measured for the entire time series since 2007. Additionally, the monthly average Scripps pier temperatures during the reporting period compared with the monthly average temperatures for the period from 2007 to 2025, show a pattern of negative (cold) monthly anomalies for much of the reporting period, with cooler than average monthly means for some periods exceeding 2 °C cooling. Cooler temperatures in this region are related to higher nutrient concentrations, as they are inversely correlated at temperatures below 15 °C, which is the approximate temperature below which nitrate becomes available in the water column. The monthly average bottom temperatures at many monitoring sites were below this nutrient threshold temperature proxy of 15 °C for consecutive months during the reporting period. The cooler, nutrient replete waters suggested by the temperatures measured

during the reporting period should have provided ample nutrient exposure which is evidenced in giant kelp recruitment and growth.

While giant kelp recovery has been detected at some sites recently, abundance at other study sites remains historically low. The understory macroalgae that compete with giant kelp for bottom space and light have maintained growth, reproduction and stable densities for the reporting period at some of the monitoring sites, which may have limited giant kelp recruitment and growth. Additionally, invertebrate herbivore densities can influence giant kelp survivorship at all life stages. Some sites and seasons did show herbivore presence, with purple sea urchin densities exceeding 10 per 10 m^2, and with red sea urchin densities exceeding 2 per 10 m^2, falling within the upper 10% of the historical time series dating back to 2007. Along with the densities on the transects at the monitoring sites, recruitment of both sea urchin species was also documented very near some of the monitoring sites. Collectively, these factors are known to constrain giant kelp recruitment and survival, even under otherwise favorable oceanographic conditions.

Overall, giant kelp forest recovery occurred during the period from spring 2023 to fall 2025 yet was spatially variable with reduced densities and plant sizes compared to historical patterns at many sites. The measured recovery was most likely related to the cooler than average benthic temperatures indicating nutrient availability, sufficient bottom light, reduced wave action, and lower sea urchin herbivore densities at some of the monitoring sites during this reporting period.

INTRODUCTION

Kelp forests along the San Diego region provide highly valuable socioecological and socioeconomic services, with importance for coastal protection, habitat for biodiverse fauna and flora, fishing, and recreation, as well as a general cultural significance for the community. The health and resilience of kelp forests are shaped by a complex interplay of coastal oceanography, disturbance regimes, and biotic interactions in the context of a large and growing coastal urban region with myriad potential anthropogenic impacts (Dayton & Tegner 1984, Dayton et al. 1999, Parnell 2015, Parnell et al. 2026). The physical setting and environmental dynamics driving kelp communities in the nearshore environment include the availability of rocky substrata at ~5 to 30 m depth, ocean temperatures, water-column stratification, nutrient delivery, light availability, currents, upwelling intensity, internal waves, and wave-driven disturbance. This suite of factors provides a foundation upon which complex population, community, and patch-level processes unfold and vary at seasonal to annual and decadal scales. Complex interactions between the temporally and spatially variable physical environments and biological processes, especially those affecting kelp reproduction, recruitment, growth, and consumption by herbivores, result in strong spatial variability in kelp abundance, persistence, mortality, and recovery from disturbance. Kelp forests are also sensitive to a range of human impacts including direct harvesting of kelp and associated fish and invertebrate resources, surface run-off, pollution, and potential sewage discharge impacts on water quality, sedimentation, and light availability. The socioeconomic importance of kelp forests and the need to distinguish potential anthropogenic impacts from natural environmental dynamics influencing kelp abundance has motivated extensive, long-term research and monitoring including the present effort supported by the City of San Diego in partnership with researchers at Scripps Institution of Oceanography, UC San Diego.

Overall, abundance of the dominant, canopy forming giant kelp *Macrocystis pyrifera* along the San Diego coast has been extremely variable over the ~60-year duration of reliable scientific observations, with apparent sharp declines in many locations over the past decade. The San Diego region is generally characterized by weak and variable upwelling compared with regions further north, with nearshore sub-thermocline nutrient delivery highly sensitive to small changes in thermocline depth, internal wave energy, and horizontal advection. Both the physical environment and the phenology of *M. pyrifera* show predictable variability throughout years. Seasonal storms (e.g. November through March) and wave events are a dominant source of physical disturbance that can open space on benthic rocky surfaces and reduce kelp canopy cover, facilitating greater light penetration. During spring and early summer (e.g. late March through June), increased day length and periods of enhanced episodic upwelling result in generally cold water-column temperatures and exposure to nitrate-rich water along the coast, which are associated with the highest rates of kelp reproduction, recruitment and the appearance of juvenile kelp sporophytes with rapid subsequent kelp growth. Conversely, mid to late summer and fall are typically marked by the highest annual kelp biomass and surface canopies, which reduce bottom light availability and coincide with warmer surface temperatures and increased water-column stratification, and a deepened thermocline and correlated nutracline, leading to limited nutrient supply to shallow waters with resulting decreased kelp growth. Although many of these processes affect the region in a general seasonal fashion, they are also known to vary at much smaller spatial scales.

For example, internal tides and internal bores are important along the San Diego coastal shelf resulting from the interaction of water-column density stratification with tidal forcing along the steep topography of offshore bathymetric features (Jackson & Winant 1983, Leichter et al. 2023). The spatiotemporally variable interactions of stratification and tidal forcing with bathymetry can result in short-term pulses of cold, nutrient-rich water that can temporarily enhance photosynthesis and growth, even during otherwise nutrient-poor periods such as periods of reduced upwelling. This tidally driven mechanism is thought to result in spatial variability in kelp canopy cover responses, which can vary by depth and proximity to the offshore features (Leichter et al. 2023).

Additionally, interannual and decadal climate oscillations further modulate nutrient dynamics in the California Current. For example, during El Niño events, regional warming, strong stratification with deepening thermocline depth, and suppressed upwelling of nutrient enriched waters severely limit nutrient delivery, reducing kelp growth and canopy extent (Dayton et al. 1999). In contrast, La Niña years generally bring enhanced cooling, increased nitrate, and often large kelp canopy expansions. Furthermore, widespread climatic variations such as the Pacific Decadal Oscillation (PDO) and longer term ‘regime shifts’, with generally warmer temperatures and reduced nutrient availability influence the baseline upon which other scales of oceanographic variability occur (Parnell et al. 2010). These oceanographic regimes at varying spatiotemporal scales interact strongly with biological processes such as competition, herbivory, and recruitment, and in conjunction with variable anthropogenic impacts, create temporal mosaics visible in each discrete kelp forest along depth gradients.

Light is also an important variable for kelp forests as kelps depend on photosynthesis to grow and require adequate light thresholds for gametogenesis of microscopic stages on the benthos, essential for subsequent kelp recruitment. Light dynamics contribute to fine-scale patchiness in kelp recruitment and growth and can vary across small spatiotemporal scales. Light attenuation varies significantly in space and time in coastal San Diego waters due to sediment inputs, phytoplankton blooms, storm-driven runoff, and resuspension events. Turbidity reduces benthic light availability, very likely suppressing kelp recruitment. Light attenuation also varies with storm cycles, and summer stratification, and the quantity and quality of benthic light is greatly impacted by the canopies of understory kelps and turf algae, resulting in bottom shading. The spatial extent of where giant kelp can be found is mainly controlled by the availability of hard substrate at depths where light penetration is adequate for gametogenesis, recruitment and growth since the plants recruit and begin their life cycle at the bottom. Light is attenuated in a logarithmic fashion with depth in the ocean, and attenuation is wave length dependent across the photosynthetic spectrum.

The critical process of photosynthesis for kelp metabolism and growth is dependent on light radiation across wavelengths between ~400 and 700 nanometers. Light energy within this bandwidth is generally considered to be of primary importance for photosynthesis and is termed Photosynthetic Active Radiation (PAR). Longer wavelength red light is most rapidly attenuated with depth, while shorter wavelength blue light, most important for gametogenesis, a critical step in recruitment in Laminarian kelps including *M. pyrifera* (Lüning & Dring, 1975), penetrates further into the water column. Light availability limits the deepest depths that giant kelp can exist along the mainland shelf of southern California to ~25 m. The main limiting factor for kelp recruitment at depth, besides hard substrate, is the availability of light for gametogenesis, the lower limit of which has been estimated as a quantum dose of ~0.4 mol of photons $m^{-2} d^{-1}$ (Deysher & Dean, 1984), and ~0.7 mol of photons $m^{-2} d^{-1}$ for early sporophyte growth (Dean & Jacobsen, 1984). Thus, light availability is highly variable, responding to changes across seasons, atmospheric and water column conditions, and shading by kelps and other macroalgae on the seafloor. These factors influencing light availability all likely contribute strongly to variation in kelp abundance, along with disturbance, temperature and nutrient availability.

Wave exposure also exerts both constructive and destructive roles (Parnell et al. 2026). Moderate wave energy enhances nutrient exchange around kelp blades, reduces sediment accumulation, and helps maintain open substrate for recruitment. Extreme winter storm events, however, remove adult kelp plants, create canopy gaps, and trigger successional transitions. These disturbance-driven openings are the foundation of patch dynamics in kelp forests and show complex patterns also resulting in spatiotemporal variability (Dayton et al. 1984, Dayton et al. 1999, Seymour et al. 1989).

The physical drivers described above interact strongly with biological drivers of recruitment and growth, such as herbivory and competition. For example, sea urchins (notably purple urchins, *Strongylocentrotus purpuratus* and red urchins, *Mesocentrotus franciscanus*) are among the most influential herbivores in kelp forest ecosystems in San Diego County (Tegner & Dayton 1977, Parnell et al. 2026). At moderate densities, urchins contribute to the processing of detritus and the transfer of kelp-derived energy to benthic food webs, facilitating resource availability to a suite of detritivores and invertebrates. However, urchin populations can increase rapidly, likely in response to stochastic influences on recruitment and post-settlement mortality, especially when predator control is weakened by overfishing of natural urchin consumers such as sheephead (*Bodianus pulcher*) and spiny lobsters (*Panulirus interruptus*). Urchin populations can proliferate and intensify grazing on kelp stipes and entire holdfasts in urchin feeding fronts. This can transform kelp forests into areas virtually devoid of macroalgae, termed urchin barrens, where macroalgal biomass is markedly depleted and ecosystem productivity declines (Steneck et al. 2002).

Other herbivores in the system such as abalone (*Haliotis spp*.) and snails (such as the wavy turban snail, *Megastrea undosa*) occupy both intertidal and subtidal reef habitats within kelp forests, impacting kelp forests by grazing as well as by occupying space as competitors for other grazers such as sea urchins. Abalone historically supported productive fisheries and competed for space with other herbivores. At historical abundances, abalone foraging likely influenced kelp canopy dynamics and created space for new kelp recruitment, contributing to habitat heterogeneity. However, abalone populations have declined markedly due to overharvesting and disease since the 1970s. Grazing by abalone and other gastropods can reduce epiphytic growth on kelp surfaces and may contribute to recycling of organic matter within kelp forests, although their ecological impact is generally thought to be more subtle than that of more aggressive herbivores such as sea urchins.

Sea urchins, due to their potential for overgrazing, are linchpins of possible alternate ecosystem states (e.g. kelp forest vs. urchin barrens), while snails and abalone comprise important consumers that influence algal turnover, nutrient cycling, and food web complexity. Understanding the roles of these invertebrates in the kelp forests of San Diego and their population variation, especially in response to anthropogenic impacts, is crucial for ecosystem-based management aimed at maintaining resilient kelp forest ecosystems under changing environmental conditions. Taken together, grazers interact with predators and understory algal competitors for space and light, kelp primary production, patch dynamics and oceanographic conditions to structure kelp forests in the San Diego region.

Additionally, competition for hard substrate and light is central to canopy-forming giant kelp recruitment, resilience and recovery. Understory algal species, including the benthic kelps *Pterygophora californica*, *Eisenia arborea*, and *Laminaria farlowii*, are strong spatial competitors that dominate the benthos when *Macrocystis pyrifera* canopy is reduced by warm temperatures, nutrient deficits, or storms. The stipitate *Pterygophora* kelp produces approximately 1 to 1.5 m stipes with relatively large blades impacting benthic light availability for microscopic kelp gametogenesis, an important step in kelp recruitment, and by out-shading smaller kelp recruits and juveniles (Dayton & Tegner 1984, Dayton et al. 1999). *Eisenia* is also a stipitate kelp which forms longlived and high-temperature tolerant individuals that can monopolize space for years and can out-shade *M. pyrifera* recruits. Stipitate understory kelps such as *Eisenia* and *Pterogophora* may serve as ecosystem engineers providing similar ecosystem services at least at small scales that are provided by canopy-forming giant kelp. *Laminaria*, a foliose kelp with blades up to several meters in length, can thrive in low-light microhabitats once canopy cover declines and prevent new recruitment by both out-shading other algae and by its whiplash effect during wave-exposure with shear impacts on a wide region of the benthos due to their flexible foliose nature. Additionally, other algae including other competitors for space and light such as invasive *Sargassum* species and foliose red macroalgae are also important components of algal assemblages.

Patch dynamics research in southern California shows that kelp forests are mosaics of different aged patches that experience asynchronous disturbance, recovery, and competitive interactions (e.g. Dayton et al. 1984, Parnell 2015, Parnell et al. 2026). Wave-driven disturbance, thermal, light and nutrient impacts on growth and recruitment, and grazing intensity all interact to produce spatially stable patches, transitional patches, and degraded patches of both canopy-forming and understory kelps and other algae, often within meters of each other. Differential patch assemblages can also alter hydrodynamic, light and sediment microhabitats in different manners. For example, understory canopies reduce near-bed flow, trap sediments, and can limit spore settlement and juvenile recruitment. In nutrient-poor years, some benthic algae may expand dramatically and inhibit canopy-forming giant kelp recovery even after oceanographic conditions improve. Thus, competition is not static and is tightly coupled to oceanographic variability and disturbance history (Parnell et al. 2026).

In response to a range of concerns about potential anthropogenic impacts on kelp abundance in the San Diego region, researchers at the Scripps Institution of Oceanography (SIO) have partnered with the City of San Diego Ocean Monitoring Program. The SIO group has conducted regular surveys of the kelp forests off San Diego County since the 1970’s and now regularly surveys the kelp forests off Point Loma, La Jolla and North County (see Figure 1). 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's and 1980's (Dayton & Tegner 1984). Additional study sites have been established more recently in both of those kelp forests as well as 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.

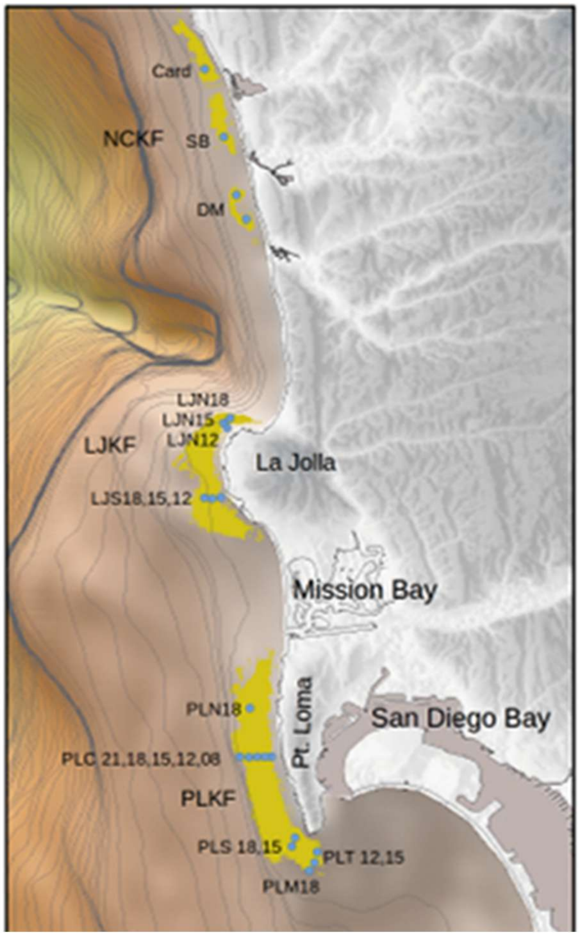


Figure 1: Map of San Diego region kelp forests (contours in meters) with yellow shading showing where surface canopy was observed from 1967-1999 in aerial photographs. NCKF, LJKF, and PLKF refer to the kelp forests off North County, La Jolla, and Point Loma, respectively. Light blue circles show the 20 permanent quarterly monitoring sites (see methods). North County, Card = Cardiff, SB = Solana Beach, DM = Del Mar; La Jolla, LJS = La Jolla South at 12, 15, and 18 m, and LJN = La Jolla North at 12, 15, and 18 m; and Point Loma, PLN = Point Loma North at 18 m, PLC = Point Loma Central (long-term monitoring sites) at 8, 12, 15, 18 and 21 m, PLS = Point Loma South at 15 and 18 m, PLT = Point Loma Tip at 12 and 15 m, and PLM = Point Loma Mouth at 18 m.

METHODS

For this biennial reporting period (spring 2023 to fall 2025), a subset of the most relevant data collected is presented. The full methods of the kelp forest monitoring program are described in a recent paper (Parnell et al. 2026) and in all previous city of San Diego kelp forest monitoring program reports. The most important methods relevant to this report are repeated here for convenience and clarity.

Macroalgae, invertebrates and bottom temperatures are monitored at 20 permanently established study sites (Figure 1). 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 Del Mar study site where two sets of band transects are located ~1300 m apart due to the small size and fragmented shape of the rocky benthic habitat at that kelp forest.

The main components of the kelp forest monitoring program include measuring algal density (and for some species, benthic cover), growth, reproductive condition and recruitment; invertebrate densities; sea urchin demography (size distributions to monitor for episodic recruitment); collection of ocean bottom temperature (a partial proxy of ocean nutrient status); and collection of benthic light data as photosynthetically active radiation.

Algae

Several stages of the giant kelp, *Macrocystis pyrifera*, are enumerated to identify recruitment events and to follow the fate of recruiting cohorts into adulthood. Giant kelp life stages include adults (≥4 stipes), pre-adults (>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 blade stages lacking the initial dichotomous split). Stipe numbers are counted and recorded for each adult plant on each visit.

Conspicuous macroalgal species/groups are enumerated within 5 x 2 m (10 m^2) contiguous quadrats along the band transect lines at all sites.

Reproduction and growth of the giant kelp, *Macrocystis pyrifera*, and the understory kelps, *Pterygophora californica* and *Laminaria farlowii*, are measured on mapped or tagged plants along the central Point Loma study sites. Growth of *M. pyrifera* is monitored by counting the number of stipes on each mapped plant one meter above the substratum. Reproductive state (i.e. spore production by the sporophyte stage) is represented by the size of the sporophyll bundle (germ tissue) at the base of each plant. Reproductive state for each plant is ranked according to the ordinal scale: 0 representing 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 sporophyll surface, 4 sporophylls with sori over all of the sporophyll surface, and 5 sporophylls with sori over all of the sporophyll surface releasing zoospores.

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 active spore production. 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 percentage of each blade covered by sori.

Invertebrates

All conspicuous sessile and mobile invertebrates are enumerated annually in spring within the 10 m^2 quadrats.

Size frequencies of red (*Mesocentrotus franciscanus*) and purple (*Strongylocentrotus purpuratus*) sea urchins are measured semi-annually (spring and fall) for >100 individuals, when possible, for each species located near all the study sites except for the NCKF sites which do not have adequate sea urchin densities. Sea urchins are collected in 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 their place of capture. Sea urchin recruitment is evaluated using the population size frequency data.

Temperature

Sea bottom temperatures are recorded at 10 min intervals using ONSET Tidbit recorders (accuracy and precision = 0.2˚C and 0.3˚C, respectively) at the permanent central Point Loma study sites, and at a range of additional study sites. Recently, we have updated to higher resolution and more reliable oceanographic-quality temperature recorders at all sites for redundancy and accuracy, especially with the goal of characterizing both high-frequency forcing and long-term trends.

Temperature is one of the dominant driving factors in the system and is relatively easy to measure. Temperature has a direct impact on kelp growth and reproduction, and, due to the strong inverse relationship with nutrients in the Southern California Bight region (Ladah 2003, Parnell et al. 2010), serves as a valuable proxy for nutrient availability as well. In this region, cooler temperatures tend to have enriched nitrogenous nutrients especially in the form of nitrate, which is important for kelp metabolism and inversely correlated with temperatures below ~15 °C. The physical environment of the coastal ocean is highly variable with respect to temperature across a range of scales from minutes to hours to seasons, and thus collection of high frequency temperature data is critical to evaluating the dynamics of the system.

Light

Bottom light as Photosynthetically Active Radiation (PAR) is measured at three depths off central Point Loma along a cross-shore transect near the permanent algal study sites but in areas without giant kelp canopy. These areas are dominated by low growing understory algae thus precluding shading by nearby giant kelp canopy. The measurement sites off Point Loma are located at 9, 15, and 24 m depth. Submarine light is also measured off southern La Jolla at a depth of 24 m. PME miniPAR loggers equipped with LICOR LI-192 quantum sensors are used to measure bottom

Photosynthetically Active Radiation (PAR). Sampling is conducted at 1-minute intervals, and the sensors are equipped with external wipers cleaning the sensors at 4-hour intervals to reduce biofouling and maintain sensor accuracy.

RESULTS

Temperature

SIO pier surface and bottom temperature

For much of the reporting period, the temperatures measured at the UCSD-SIO pier at both the surface and the bottom (5-7 m depth) exceeded the regional 15 °C temperature proxy for nitrate, with the primary exceptions occurring during winter and spring of 2023 and 2025 at both depths and, additionally, during winter and spring of 2024 at the bottom (Figure 2a). However, when comparing the monthly average Scripps pier temperatures for the reporting period with the monthly average temperatures for the period from 2007 to 2025, a pattern of negative (cold) monthly anomalies can be seen for most of this reporting period, with monthly averages falling below the zero-anomaly line, except for the periods from November 2023 to March 2024, and in August 2024 and 2025 (Figure 2b). For some periods, the negative monthly anomalies neared or exceeded 2 °C below the mean (cooler than average), for example in June 2023 and from November 2024 to January 2025.

Benthic temperature at the long-term Point Loma Central kelp forest monitoring sites

The time series for the Point Loma Central benthic cross-depth sites from 2007 to 2025 measured at 8, 12, 15, 18 and 21 m depth are shown in Figure 3 (a-e) with the red dotted line marking the approximate temperature below which nitrogenous nutrients, particularly sub-thermocline nitrate, become available in the region (temperature proxy for ~1 μM nitrate is near 15 °C) (Zimmerman & Robertson 1985, Ladah 2003, Parnell et al. 2010, Leichter et al. 2023).

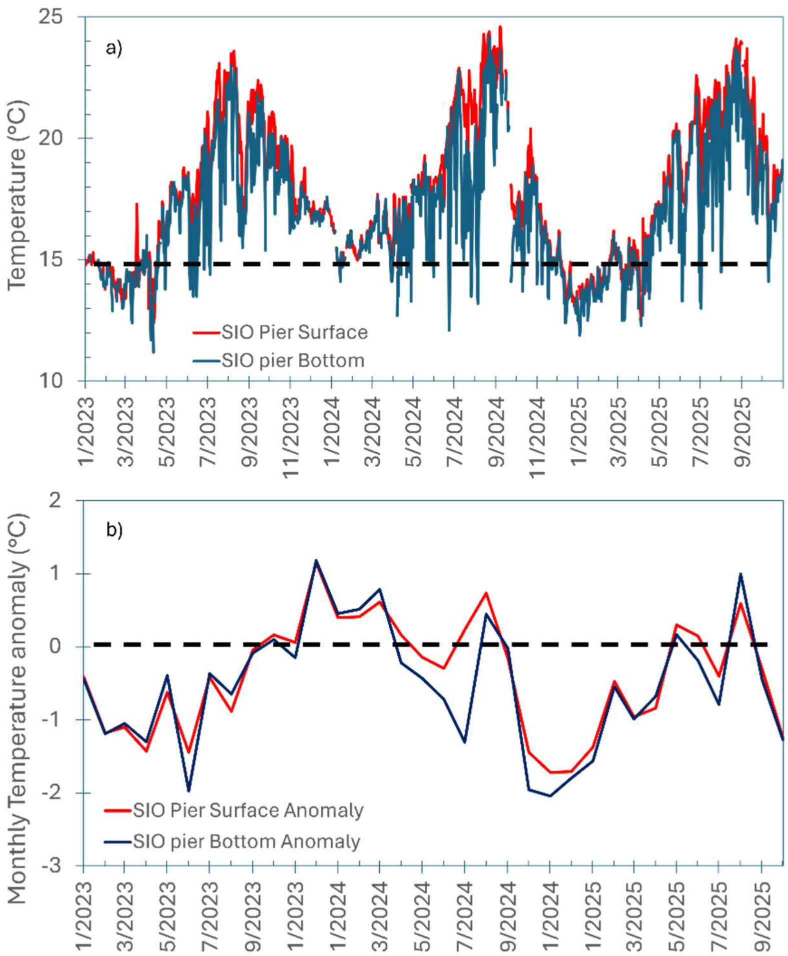


Figure 2: a) Temperature records taken at the surface (red) and bottom (blue) (5-7m depth) of the Scripps pier from January 2023 to December 2025 with the dotted black line showing 15 °C (temperature proxy for nutrients, see methods, with temperatures above this threshold generally being nutrient poor) and b) monthly mean temperature anomaly at the surface and bottom compared to the 2007-2025 monthly means, with the dotted line showing the zero (negative numbers are colder than the long-term mean for that month). See UCSD shore stations for details.

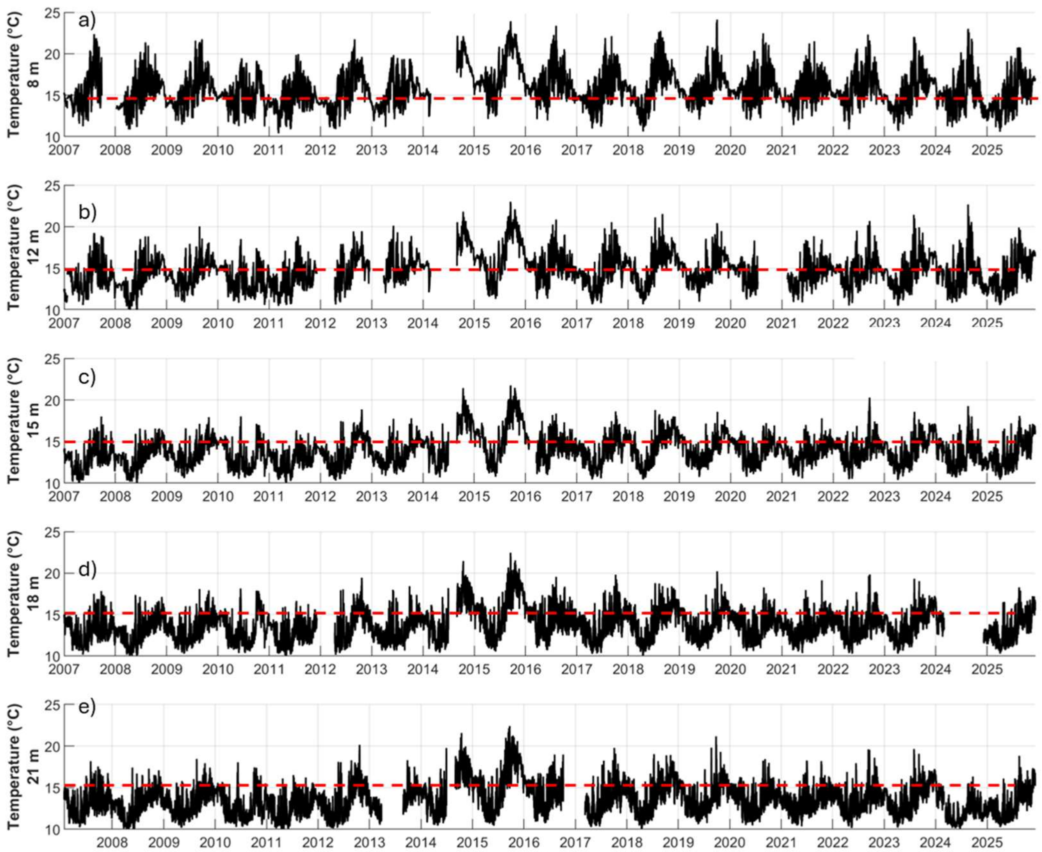


Figure 3: Benthic temperature measured at the cross-depth long-term monitoring sites from 2007 to 2025 at Point Loma Central at: a) 8 m depth, b) 12 m depth, c) 15 m depth, d) 18 m depth, and e) 21 m depth. Red dotted line shows the 15 °C temperature used as a nutrient proxy (see text).

Overall, for the time series back to 2007, the years 2008 and 2011 showed the coldest temperatures measured at all sites, while 2014 and 2015 showed the warmest. Across the sites, there is a clear pattern of increasing nitrate availability (estimated by temperature proxy) with depth, shown by the proportion of the time series below the 15 °C temperature, ranging from 41% at 8 m, 61% at 12 m, 74% at 15 m, 78% at 18 m and 80% at 21 m. In addition, cool temperatures and associated nitrate exposure appear to have been prominent features for the 2023-2025 period. A recent notable pattern of cooler than normal temperatures can be seen particularly at 8 m depth, showing periods in 2023 and 2025 registering some of the coldest temperatures measured for the entire time series since 2007.

Monthly mean benthic temperatures calculated from the data in Figure 3 for the Point Loma Central sites fell below the 15 °C nutrient-threshold proxy for multiple consecutive months at several sites during the 2023-2025 reporting period (Figure 4a). At the 8 m site, monthly mean temperatures remained below this threshold from January to June 2023, January to May 2024, and November 2024 to May 2025. At the 12 m site, monthly mean temperatures were below 15 °C from January to July 2023, January to July 2024, and October 2024 to July 2025. At the 15 m site, temperatures were below the threshold from January to August 2023, January 2024 to July 2025, and again from September to October 2025. At the 18 m site (noting a gap in the record due to a lost temperature logger from March to November 2024), temperatures were below 15 °C from January to August 2023, January to February 2024, and December 2024 to October 2025. At the 21 m site, temperatures were below the threshold from January to August 2023 and throughout the period from January 2024 to October 2025. Late February through early June represents the primary recruitment window for the giant kelp, *Macrocystis pyrifera*, and the cooler, nutrient-replete conditions indicated by these monthly averages during the reporting period would therefore be expected to provide sufficient nutrient exposure to support recruitment and early growth.

Comparing the monthly averages for the current reporting period from 2023 to 2025 (using data from Figure 4a, and using only months with 90% of the data available for that month) to the average monthly temperatures for the entire time series from 2007 to 2025 (data in Figure 3), many of the Point Loma Central benthic sites showed negative monthly anomalies (Figure 4b). For example, the monthly mean temperature at the 21 m site during October–December 2024 was more than 2 °C colder than the long-term average for those months (2007–2025). Similarly, the 8 m, 12 m, and 15 m sites also exhibited cold anomalies exceeding 2 °C below the long-term mean in December 2024. Consecutive months exceeding 1 °C below the long-term average (cold) anomaly for 8 m, 12 m and 15 m depth included the period from November 2024 to February 2025 (through March 2025 for 8 m depth), the months from May 2024 to February 2025 for the 21 m site, and again in September and October 2025 at the 8 m site. At 18 m depth, data for 2024 were limited; however, monthly mean temperatures in January and February 2025 were also more than 1 °C below the long-term average.

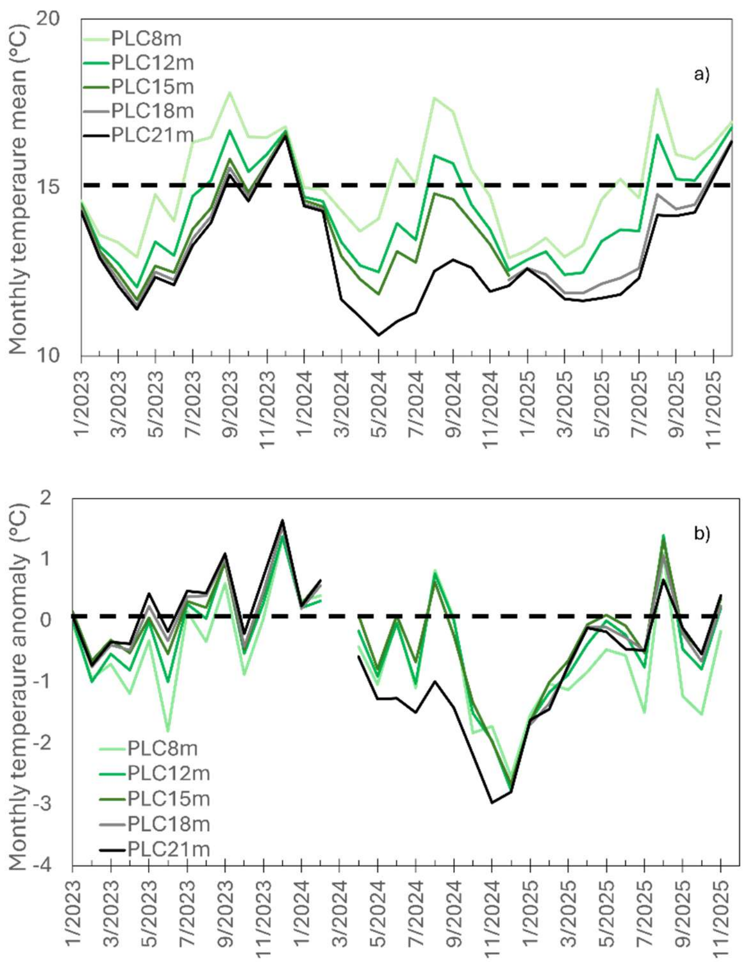


Figure 4: a) Zoom of benthic temperature measured from 2023 to 2025 at Point Loma Central 8 m, 12 m, 15 m, 18 m, and 21 m depth. Black dotted line shows the 15 °C temperature used as a nutrient proxy (see methods); b) Mean monthly temperature anomaly (deviation from the monthly means for the entire time series shown in Figure 3, from 2007 to 2025) at Point Loma Central at 8 m, 12 m, 15 m, 18 m, and 21 m depth. Black dotted line shows the zero-anomaly mark. Above (below) this line, monthly mean temperatures were warmer (colder) than the monthly mean for 2007-2025 period.

Light

Photosynthetically active radiation (PAR) significantly varies with depth in the absence of canopy cover, with the amount reaching deeper waters (24 m in Point Loma and La Jolla) being significantly less than in shallower waters (for example at 9 m depth in Point Loma) (Figure 5). Using the threshold corresponding to 0.7 moles of photons m^{-2} day^{-1} as the requirement for juvenile *Macrocystis* growth (Dean & Jacobsen, 1984), near 75% of the time series for the shallowest site (9 m depth) and near 50% for the 15 m site was above this threshold (Figure 5a,b), whereas for the deeper sites at 24 m depth at both La Jolla and Point Loma (Figure 5c,d), more than 85% of the time series was below this threshold, suggesting light limitation for juvenile growth in deeper waters for most, if not all (for example in 2020 at the 24 m sites), of the year. However, for the reporting period from 2023 to 2025, an increase in peak PAR can be seen particularly at the 15 m and 24 m sites for spring and summer 2023 compared to data available from previous years (Figure 5b-d).

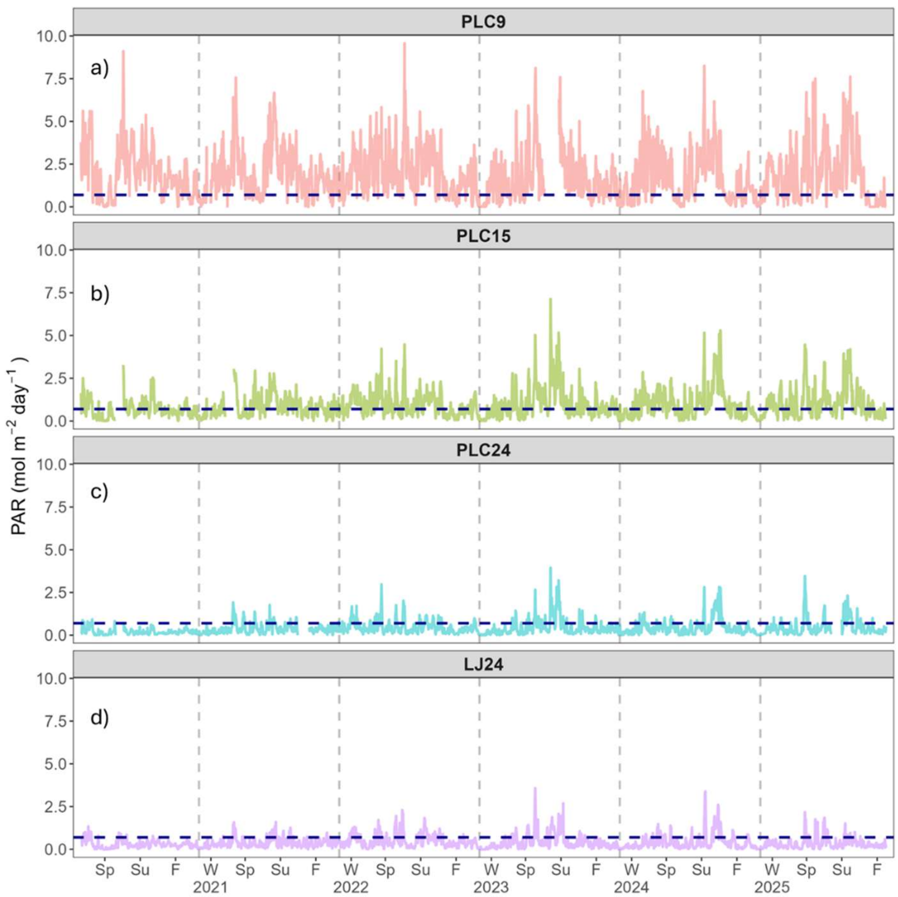


Figure 5: Benthic photosynthetically active radiation (PAR) taken near the kelp monitoring sites at, a) Point Loma Central 9 m depth, b) Point Loma Central 15 m depth, c) Point Loma Central 24 m depth, and d) La Jolla 24 m depth. The dark blue dotted line shows the 0.7 moles of photons m^{-2} day^{-1} threshold, the requirement for juvenile *M. pyrifera* growth (per Dean & Jacobsen, 1984).

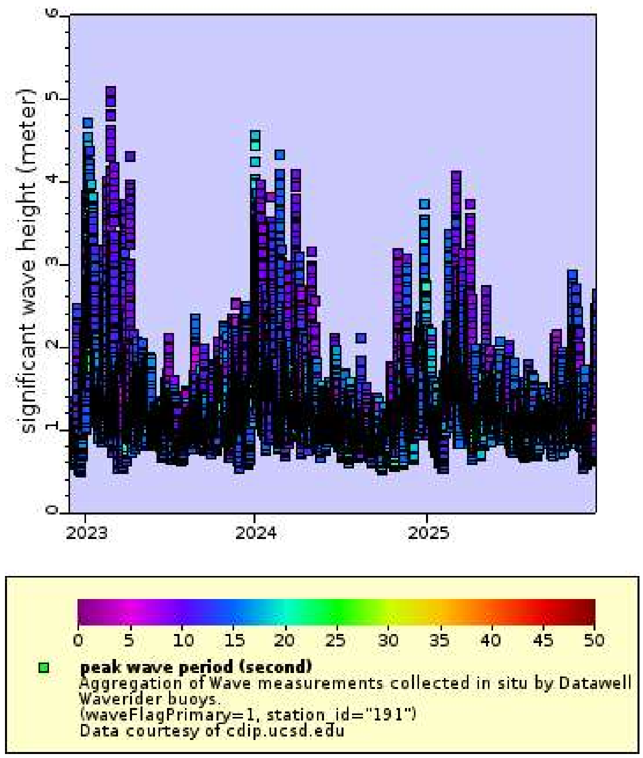
Waves

Using the Point Loma South 191 CDIP buoy station (cdip.ucsd.edu), significant wave height (H_s) and wave period were used to explore wave impacts for the reporting period (Figure 6), as well as historically. Wave height and wave period are important factors influencing kelp dynamics, as larger wave heights and longer-period swells increase the depth of orbital motion and wave speed, enhancing shoaling and allowing wave energy to impact plants in deeper waters. Additionally, because wave energy scales with the square of wave height, a doubling of wave amplitude (wave height) results in a fourfold increase in wave energy (see Seymour et al. 1989).

Looking at the time series back to 2007, some of the highest historically significant wave heights (H_s) occurred on January 6, 2023, and February 22, 2023. The February 22, 2023, event ranks as the eighth highest H_s recorded since January 2017, exceeded only by several events in 2017 and 2021. For example, on January 6, 2023,

H_s exceeded 4.5 m with a long period of 18 s, while on February 22, 2023, H_s exceeded 5 m. Within the reporting period, January 2023 also exhibited the highest monthly mean H_s, at 2.1 m. In contrast, monthly mean H_s during much of 2024 and 2025 were generally at least 0.5 m lower. For example, the monthly mean H_s in January 2025 was nearly half that observed in January 2023.

Figure 6: Aggregation of Wave measurements collected *in situ* by the Datawell Waverider buoy at station 191 Pt Loma. The CDIP Station 191 is a buoy maintained by the Coastal Data Information Program (CDIP) at Scripps Institution of Oceanography. It continuously measures swell height, wave period, direction, and marine weather conditions. The figure shows wave period in colors and significant wave height on the figure in meters. See cdip.ucsd.edu for details.



Macrocystis pyrifera (giant kelp)

Recruitment

Since 2007, the density of pre-bifurcate (or blade stage plants, Figure 7) and bifurcate plants (small juveniles, Figure 8) have shown a pattern of episodic recruitment, with recent recruitment pulses detected during the reporting period (Figure 9,10). For example, for the pre-bifurcate stage, the spring and summer seasons of the years 2007, 2010-2016, 2019 and 2024 show mean densities greater than 10 individuals per 10 m^2 with La Jolla South 18 m showing a relatively large recruitment event in spring 2024, reaching a mean of 36 individuals per 10 m^2. For the bifurcate stage or small juvenile plant recruitment, the spring and summer seasons of the years 2010-2012, and 2015-

2016 show the highest densities exceeding a mean of 10 individuals per 10 m^2, in particular at the La Jolla North 15 m and La Jolla South 18 m, Point Loma Central 18 m and 21 m, and Solana Beach sites.

For this reporting period (Figure 9,10), the spring season of 2024 at the La Jolla South 12 m, 15 m, and 18 m, and at Point Loma South 18 m sites, were among the top 10% pre-bifurcate densities for the entire series dating back to 2007, along with spring 2025 at the Point Loma Central 18 m site. For the bifurcate stage, the summer of 2023 and the spring and summer of 2024 were also among the top 10% of mean bifurcate densities at the La Jolla South 18 m site. The most recent patterns suggest an increase in recruitment after a period of recruitment failure.

Pre-adults

Since 2007, the density of pre-adults (Figure 11) reached its peak in summer 2010 and spring 2015 in the Solana Beach site near a mean of 20 individuals per 10 m^2, followed by summer 2016 at the La Jolla South 18 m site.

For this reporting period (Figure 12), the summer and fall seasons of 2023 (at the La Jolla South 18 m and Point Loma South 18 m sites), the summer and winter season of 2024 (at the La Jolla South 18 m site), the spring season of 2025 (at the La Jolla South 18 m site), and the summer and fall season of 2025 (at the Point Loma Central 18 m site) were within the top 10% mean densities of pre-adults, suggesting adequate conditions for growth of recruits to reach the pre-adult stage.

Adults

Since 2007, the highest density of adult plants (Figure 13) occurred in fall 2010 and summer 2015 in Solana Beach, and in fall 2016 and winter and spring of 2017 at the La Jolla South 18 m site, exceeding a mean of 5 adult individuals per 10 m^2.

For this reporting period (Figure 14), the mean adult density per 10 m^2 at the La Jolla South 18 m site was within the top 10% of the entire time series dating back to 2007, with mean densities of adults in spring, summer and fall of 2025, exceeding a mean of 2 adults per 10 m^2, also suggesting adequate conditions for continued adult survivorship and growth.

Stipe density

Since 2007, the highest mean stipe density (Figure 15), an indicator of the biomass carrying capacity of the system, occurred at the Cardiff (fall 2013 and winter 2014) and Point Loma 21 m (spring 2013) sites, exceeding 80 stipes per 10 m^2.

For this reporting period (Figure 16), the mean stipe density at the La Jolla South 18 m site, at 34 stipes per 10 m^2 for fall 2025 falls within the top 20% of the time series dating back to 2007, suggesting that although stipe density is currently somewhat lower than in previous years, conditions remain adequate to maintain critical giant kelp biomass.

Adult plant size (as stipe counts)

Since 2007, the largest mean plant size (using stipe counts per individual) (Figure 17) was detected in spring and summer of 2022 at the Point Loma Central 15 m site, exceeding a mean of 74 stipes per plant. The Point Loma Central 15 m site dominated the series showing the largest mean plant size exceeding 50 stipes per plant for spring and summer 2010, and fall 2021 through fall 2022, as well as the Solana Beach site with 54 stipes per plant in fall 2025.

For this reporting period (Figure 18), the Point Loma Central 15 m site in winter 2023, the La Jolla South 15 m site from summer 2023 to spring 2024, the Point Loma Mouth 18 m site in spring and summer 2025, and the Solana Beach site in summer and fall 2025 were among the top 10% of the time series dating back to 2007 in mean plant size, all above a mean of 35 stipes per plant, again suggesting that conditions were adequate to maintain somewhat larger plants.

Since 2007, historically the largest plants (maximum stipe counts per plant) (Figure 19) were found at the La Jolla South 18 m site with a maximum of 130 stipes per plant in summer 2014 and in Cardiff in summer and fall 2010 with maxima of 117 and 128 stipes per plant, respectively. The periods and sites with the maximum plant size reaching 100 stipes or greater included Cardiff in summer and fall 2013; La Jolla North 15 m in summer and fall 2014; La Jolla North 18 m in summer 2009, 2010 and 2012; La Jolla South 12 m in fall 2013; La Jolla South 18 m in spring and summer 2014; Point Loma Central 8 m in fall 2011 and summer 2013; Point Loma Central 12 m in summer 2022, Point Loma Central 15 m in summer and fall 2011, Point Loma Central 18 m in summer 2010, spring and summer 2013; Point Loma Central 21 m in summer 2010; and Solana Beach in summer and fall 2013, and spring, summer and fall 2014.

During the reporting period (Figure 20), the largest plants, falling within the top 20% of observed sizes, occurred at the Point Loma Central 8 m site in summer 2023 and the Point Loma Mouth 18 m site in summer 2025, with maxima exceeding 70 stipes per plant. The recent documentation of larger plants at various sites does indicate that although they are not as large as in previous decades or prior to the marine heat wave of 2024-2015, larger plants do still exist in the system suggesting adequate conditions to maintain mature plant biomass.

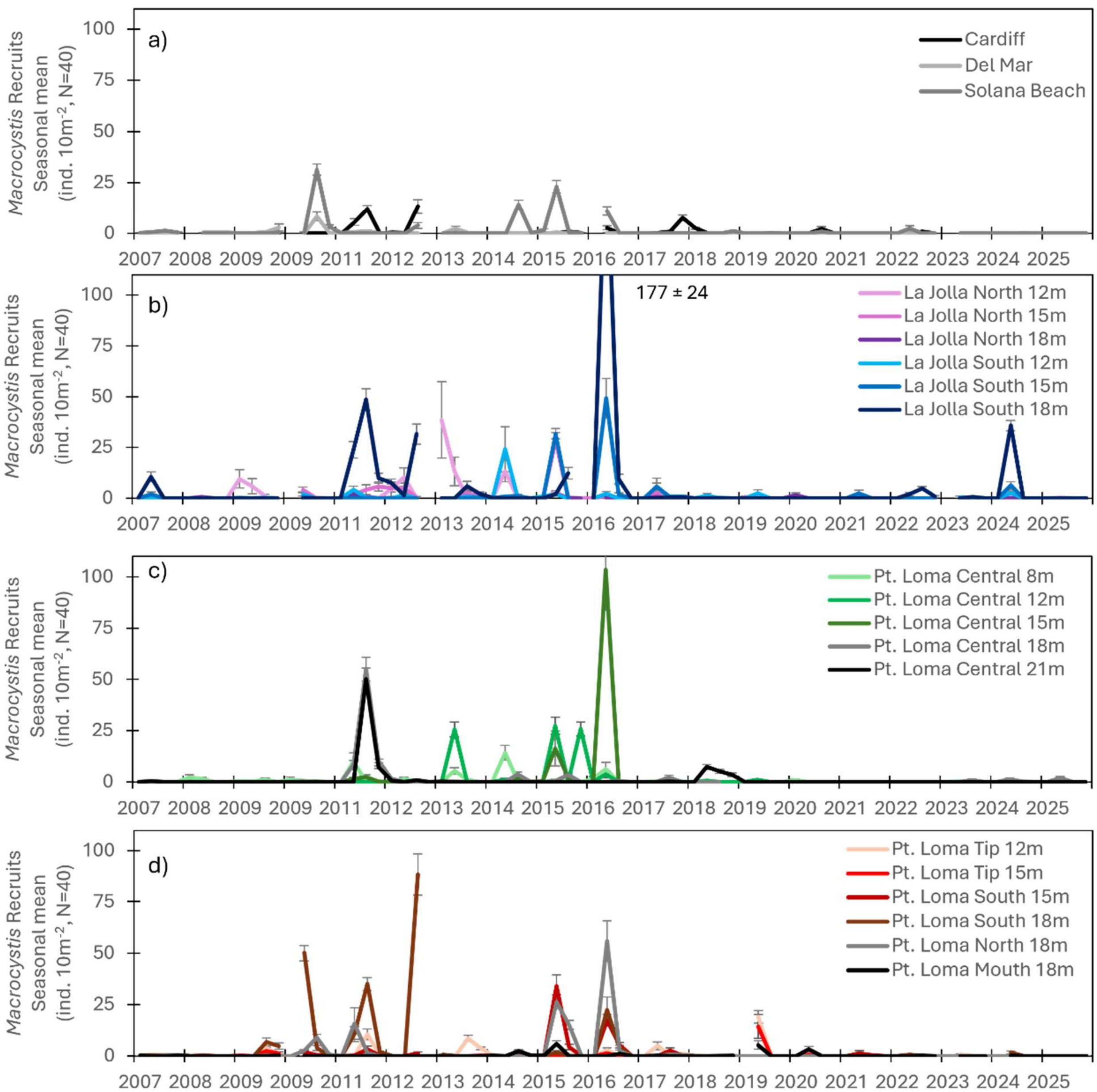


Figure 7: Density of *Macrocystis pyrifera* recruits (number of individual pre-bifurcate or blade stage individuals, shorter than 1 m); seasonal means (Winter 2007 to Fall 2025) from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

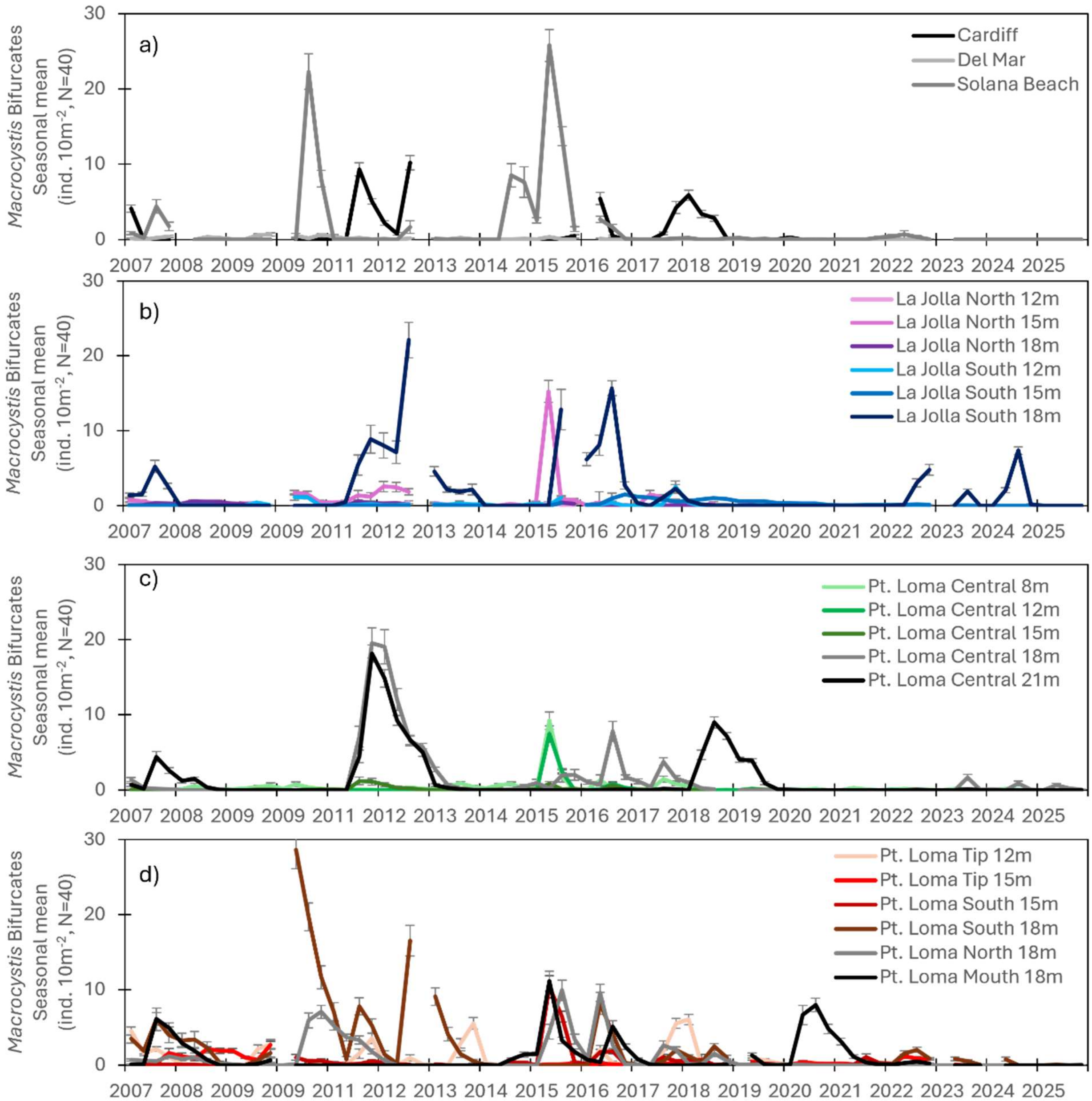


Figure 8: Density of *Macrocystis pyrifera* small juveniles (number of bifurcated individuals shorter than 1 m); seasonal means (Winter 2007 to Fall 2025) from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

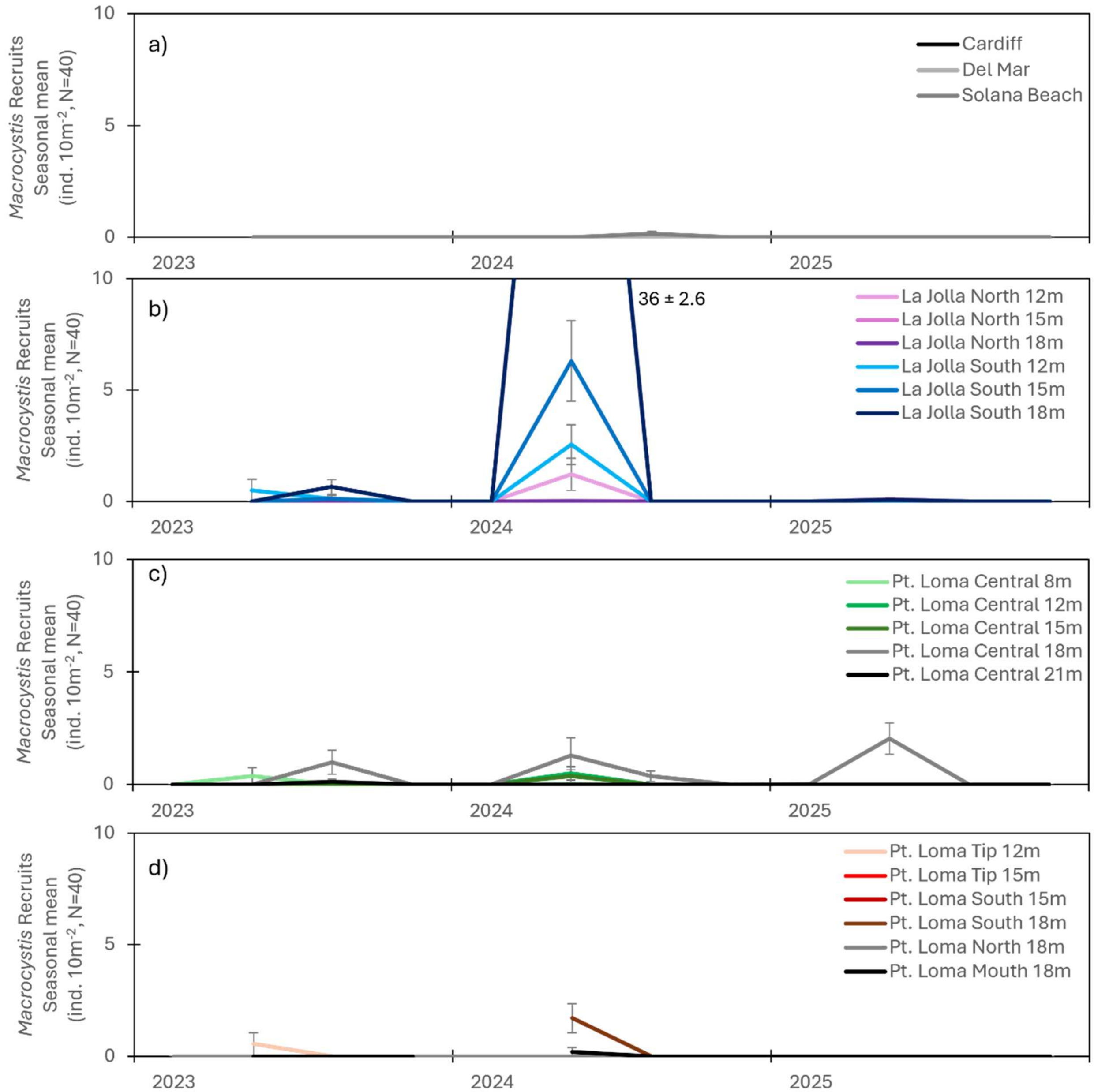


Figure 9: Zoom for reporting period (2023-2025) (note change of scale) of density of *Macrocystis pyrifera* recruits (number of individual pre-bifurcate or blade stage individuals, shorter than 1 m); seasonal means from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

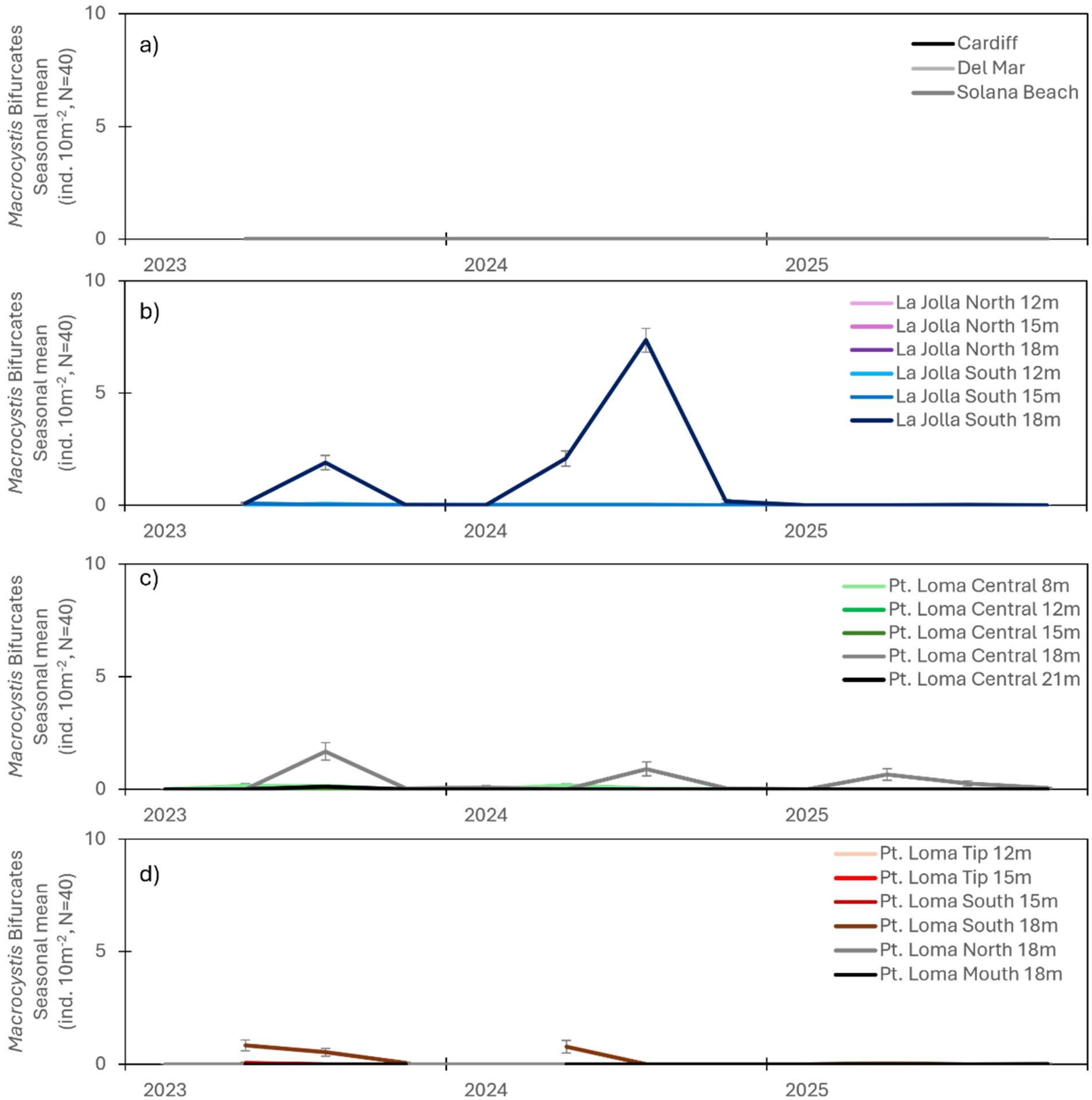


Figure 10: Zoom for reporting period (2023-2025) (note change of scale) of density of Mac*rocystis pyrifera* small juveniles (number of individual bifurcated individuals, shorter than 1 m); seasonal means from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

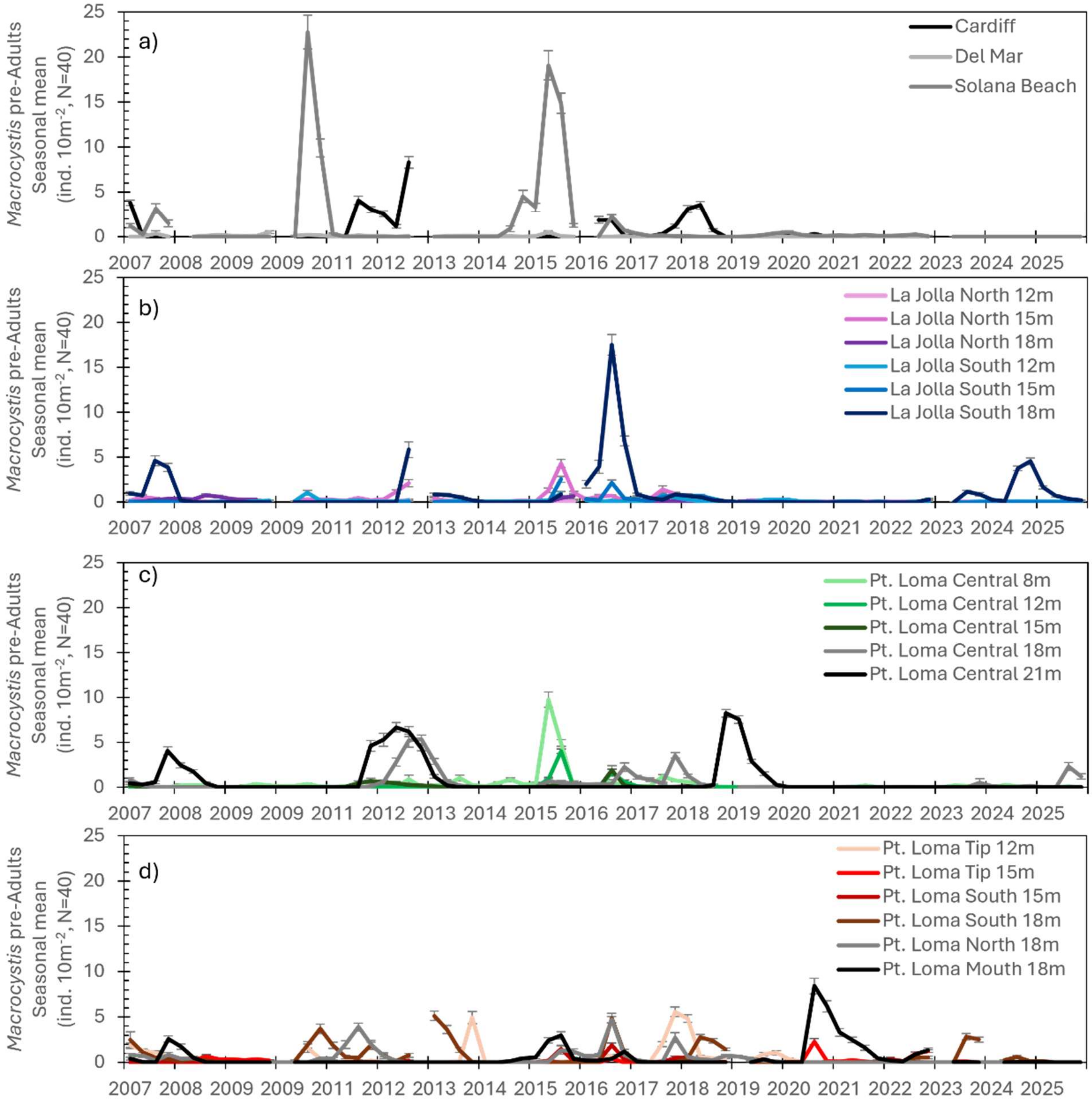


Figure 11: Density of *Macrocystis pyrifera* pre-adults (number of individuals with ≥ 2 and < 4 stipes longer than 1m); seasonal means (Winter 2007 to Fall 2025) from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

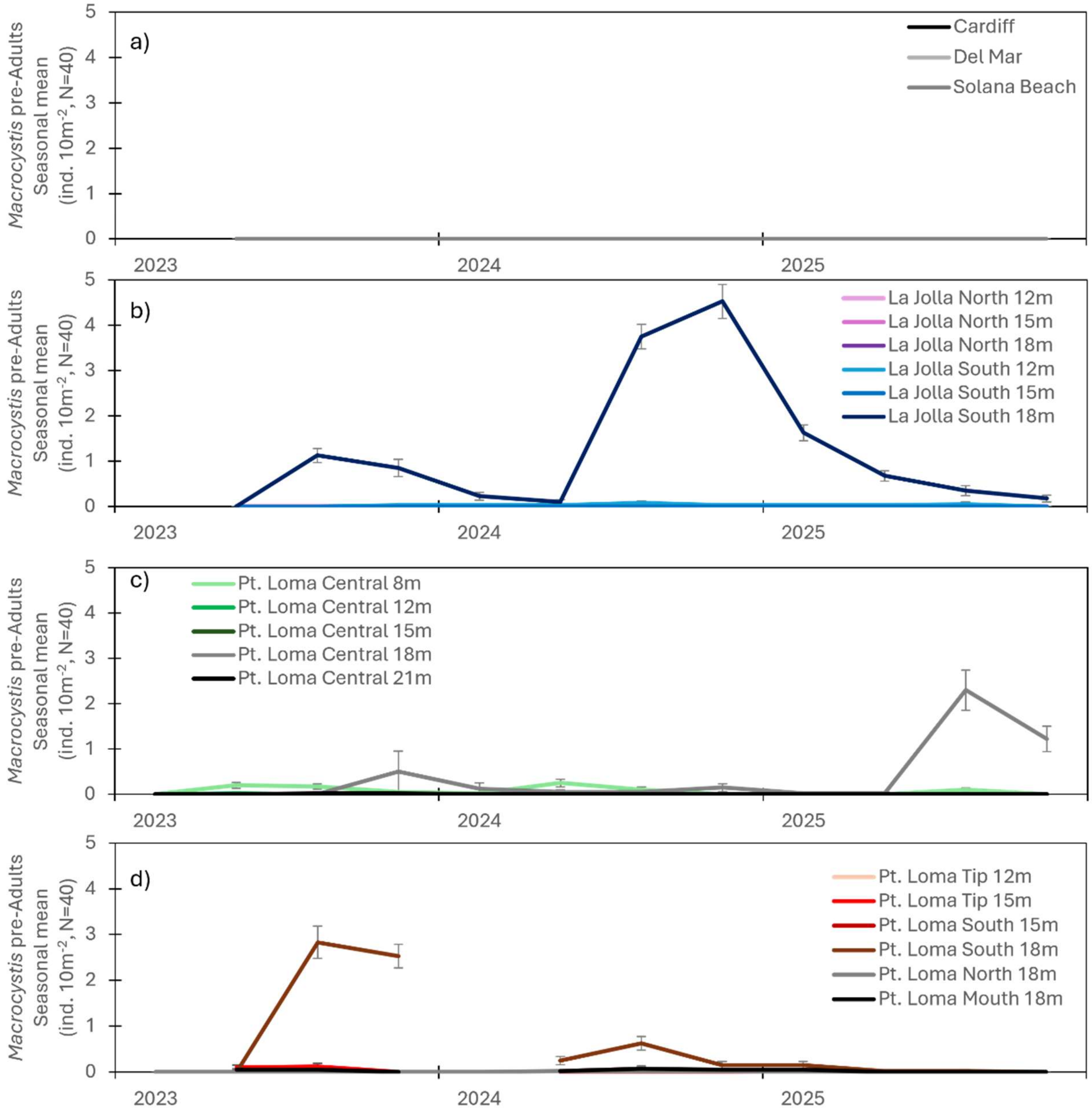


Figure 12: Zoom for reporting period (2023-2025) (note change of scale) of density of *Macrocystis pyrifera* pre-adults (number of individuals with ≥ 2 and < 4 stipes longer than 1m);); seasonal means from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

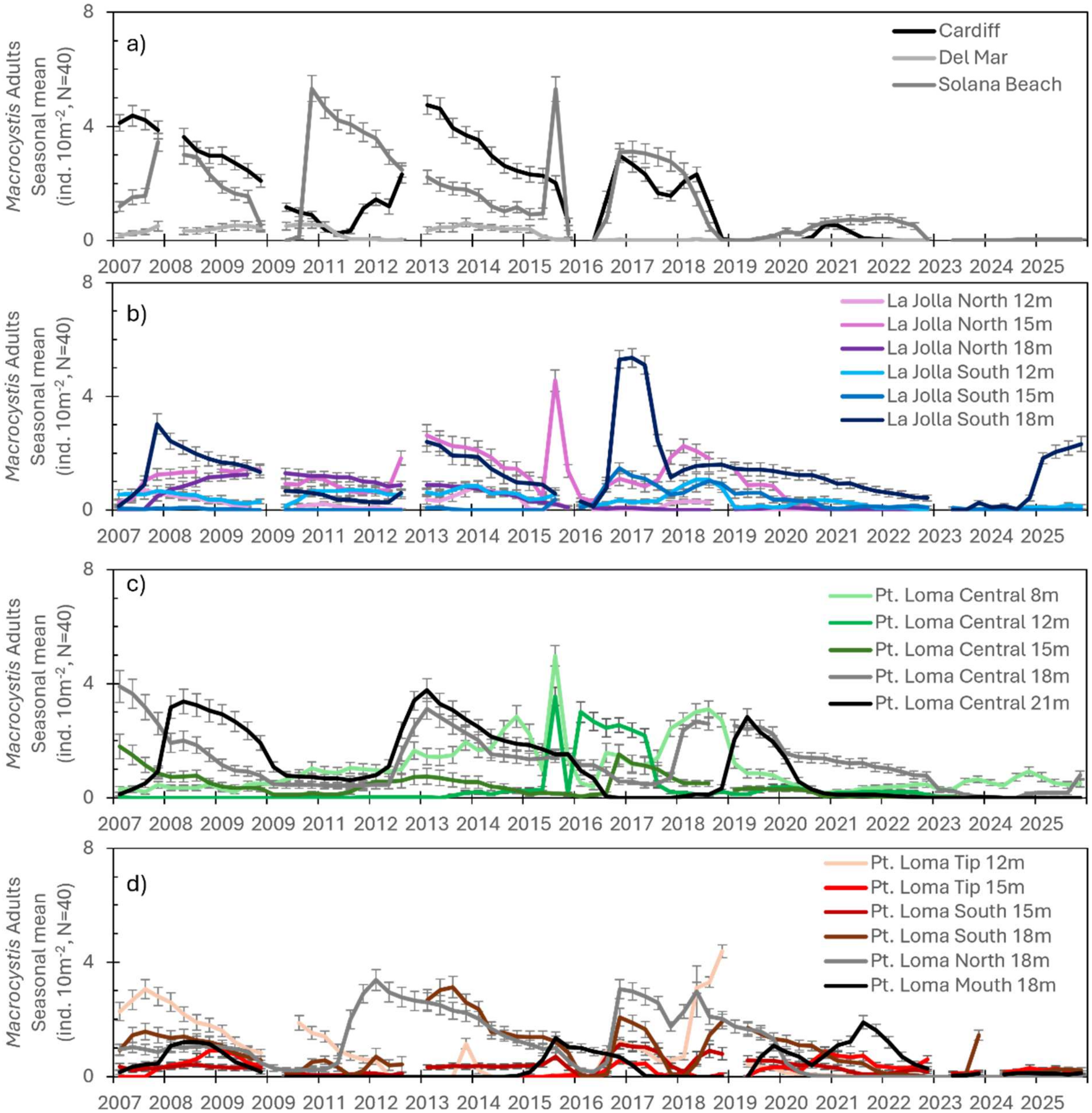


Figure 13: Density of *Macrocystis pyrifera* adults (number of individuals with ≥ 4 stipes longer than 1m); seasonal means (Winter 2007 to Fall 2025) from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

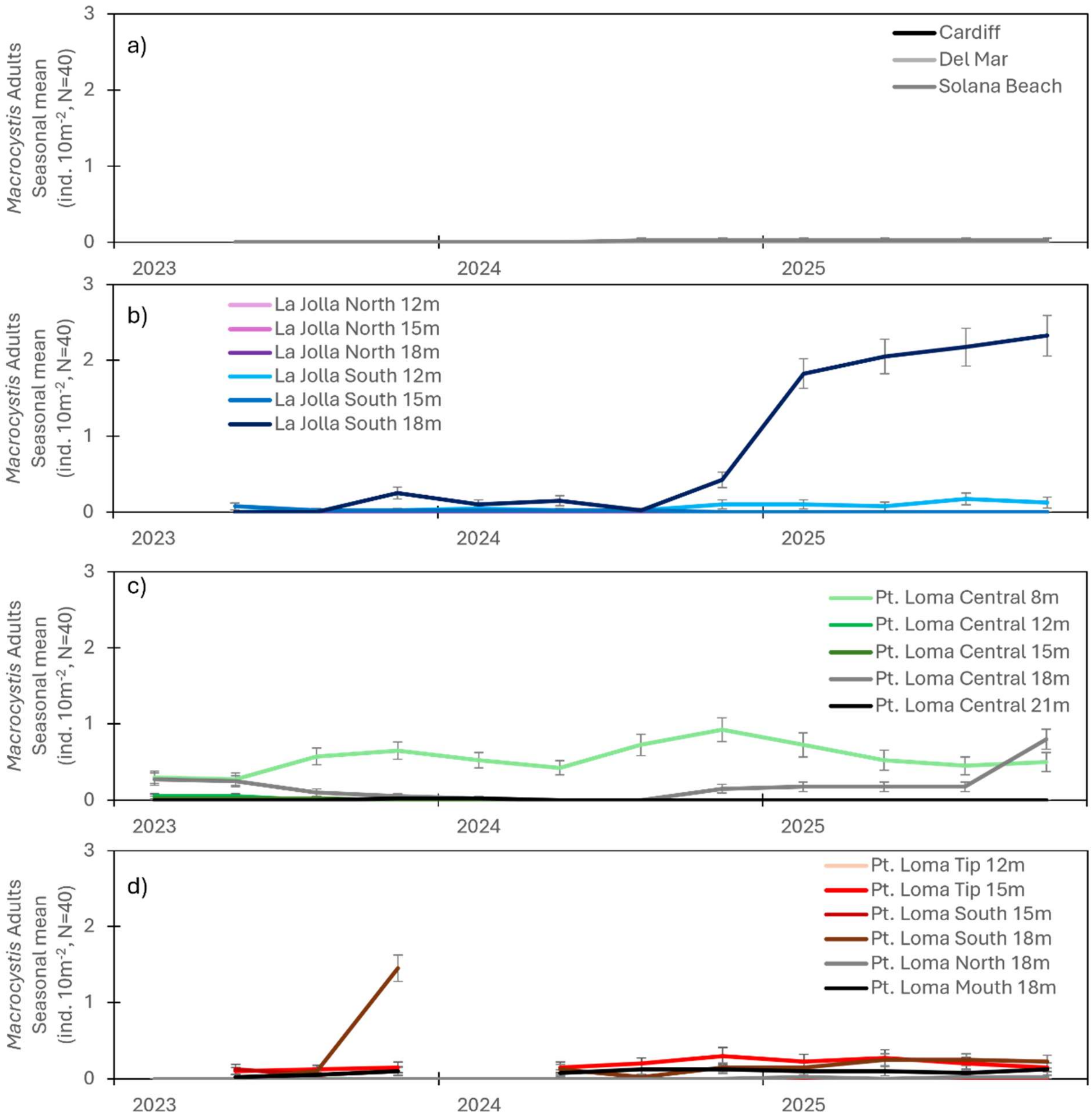


Figure 14: Zoom for reporting period (2023-2025) (note change of scale) of density of *Macrocystis pyrifera* adults (number of individuals with ≥ 4 stipes longer than 1m); seasonal means from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

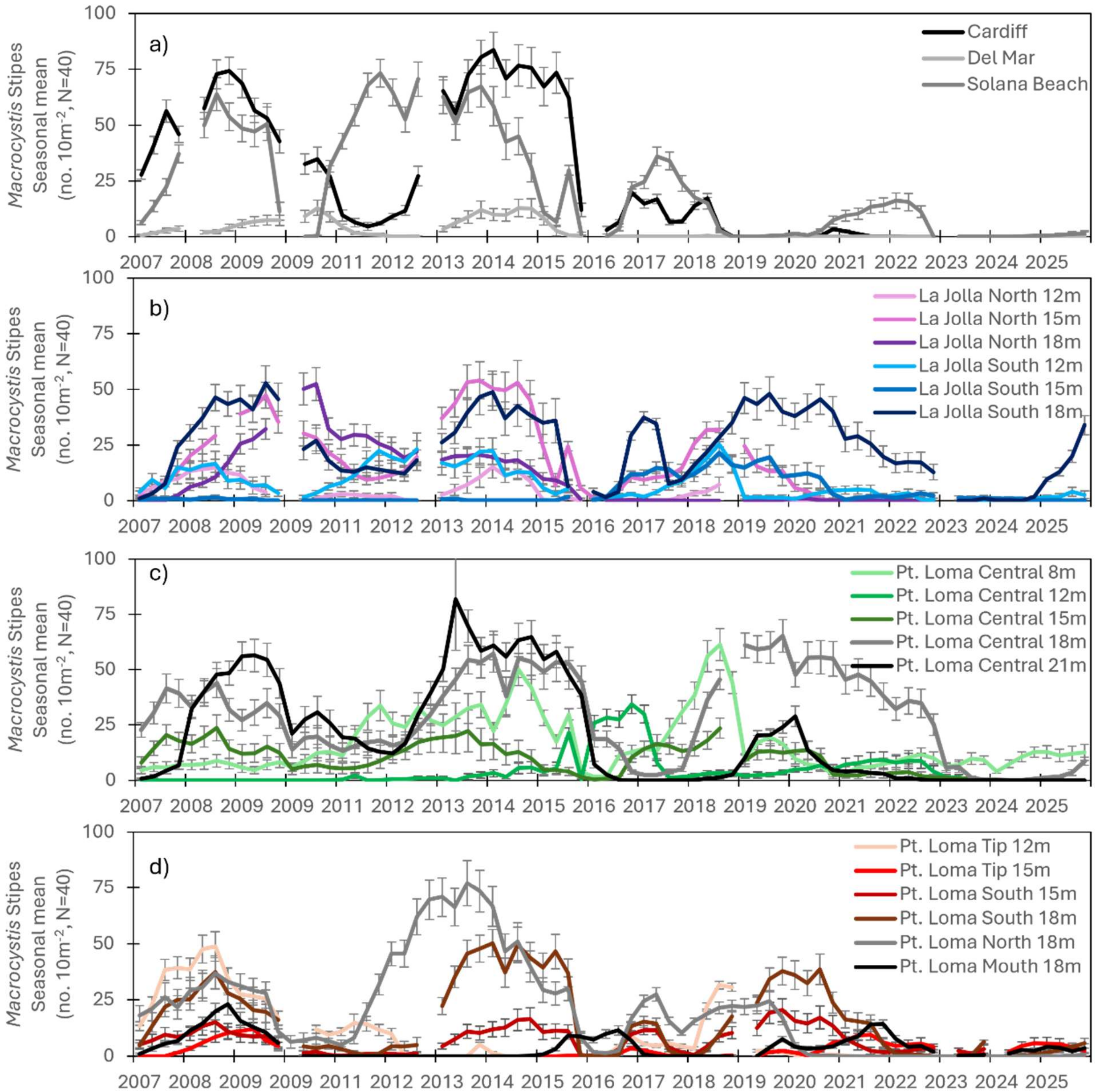


Figure 15: Density of *Macrocystis pyrifera* stipes (number of stipes longer than 1m); seasonal means (Winter 2007 to Fall 2025) from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

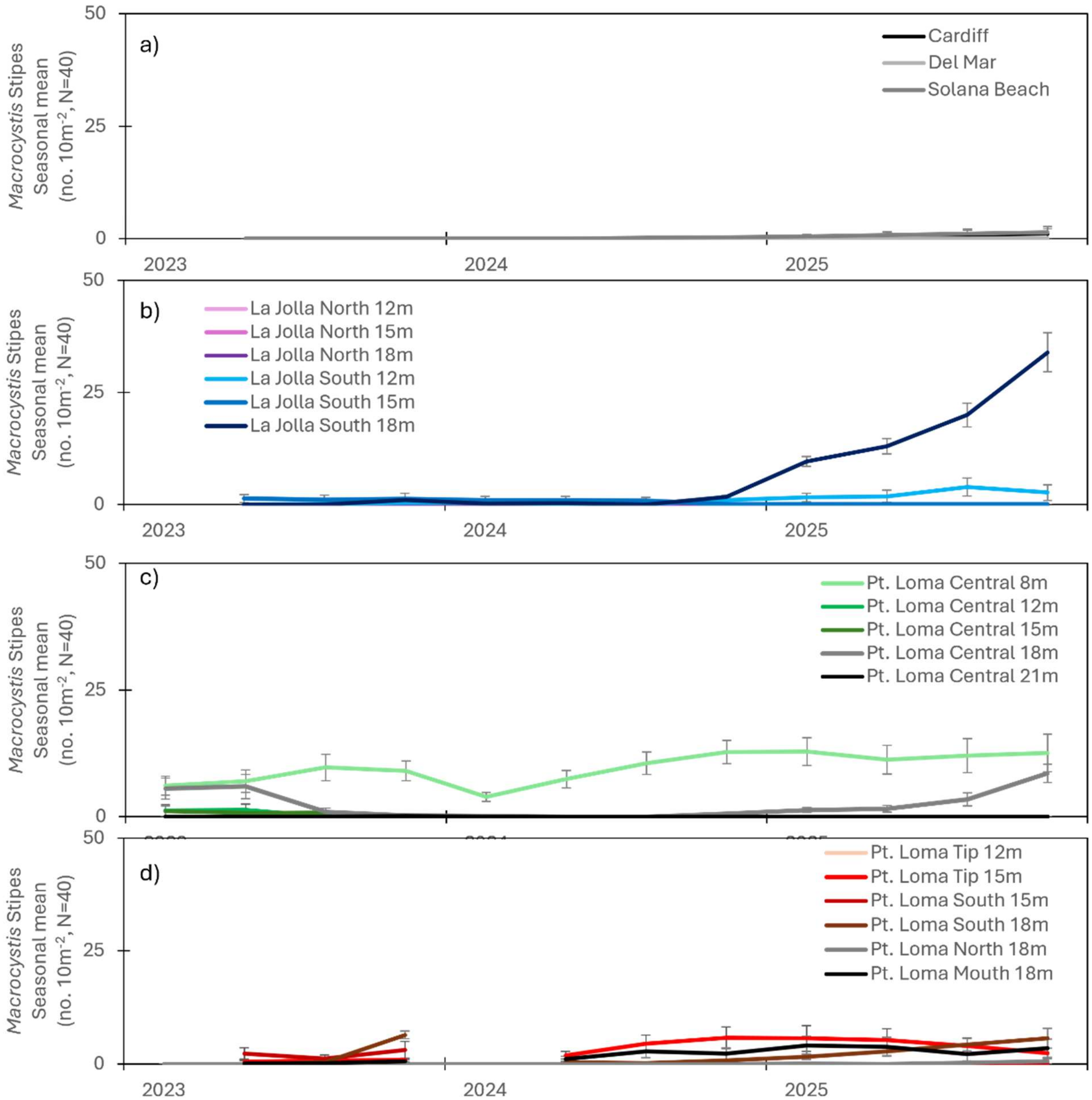


Figure 16: Zoom for reporting period (2023-2025) (note change of scale) of density of *Macrocystis pyrifera* stipes (number of stipes longer than 1m); seasonal means from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

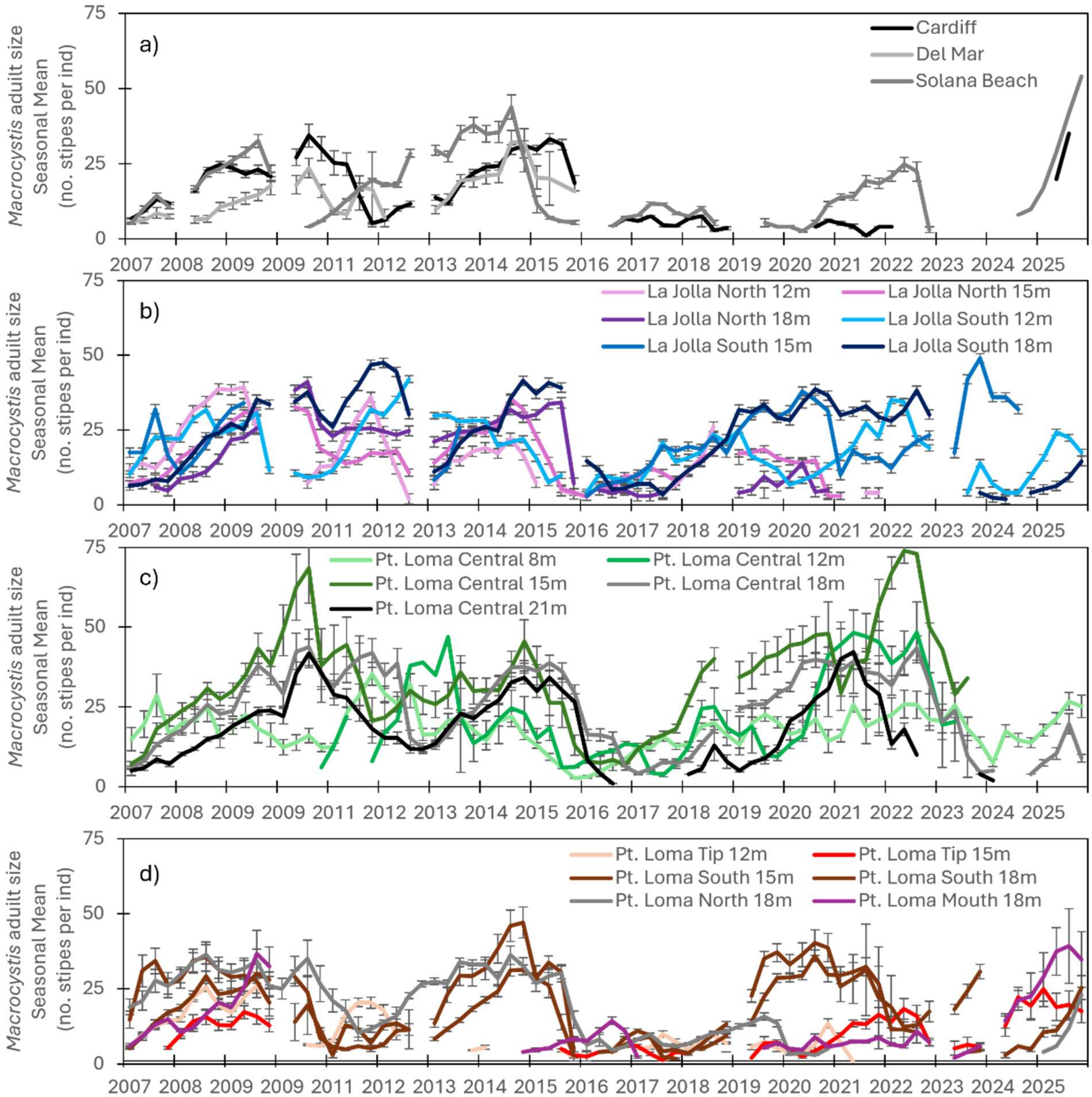


Figure 17: Size of *Macrocystis pyrifera* adults (number of stipes per adult individual longer than 1m); seasonal means from quarterly monitoring of 400 m^2 (Winter 2007 to Fall 2025); in a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

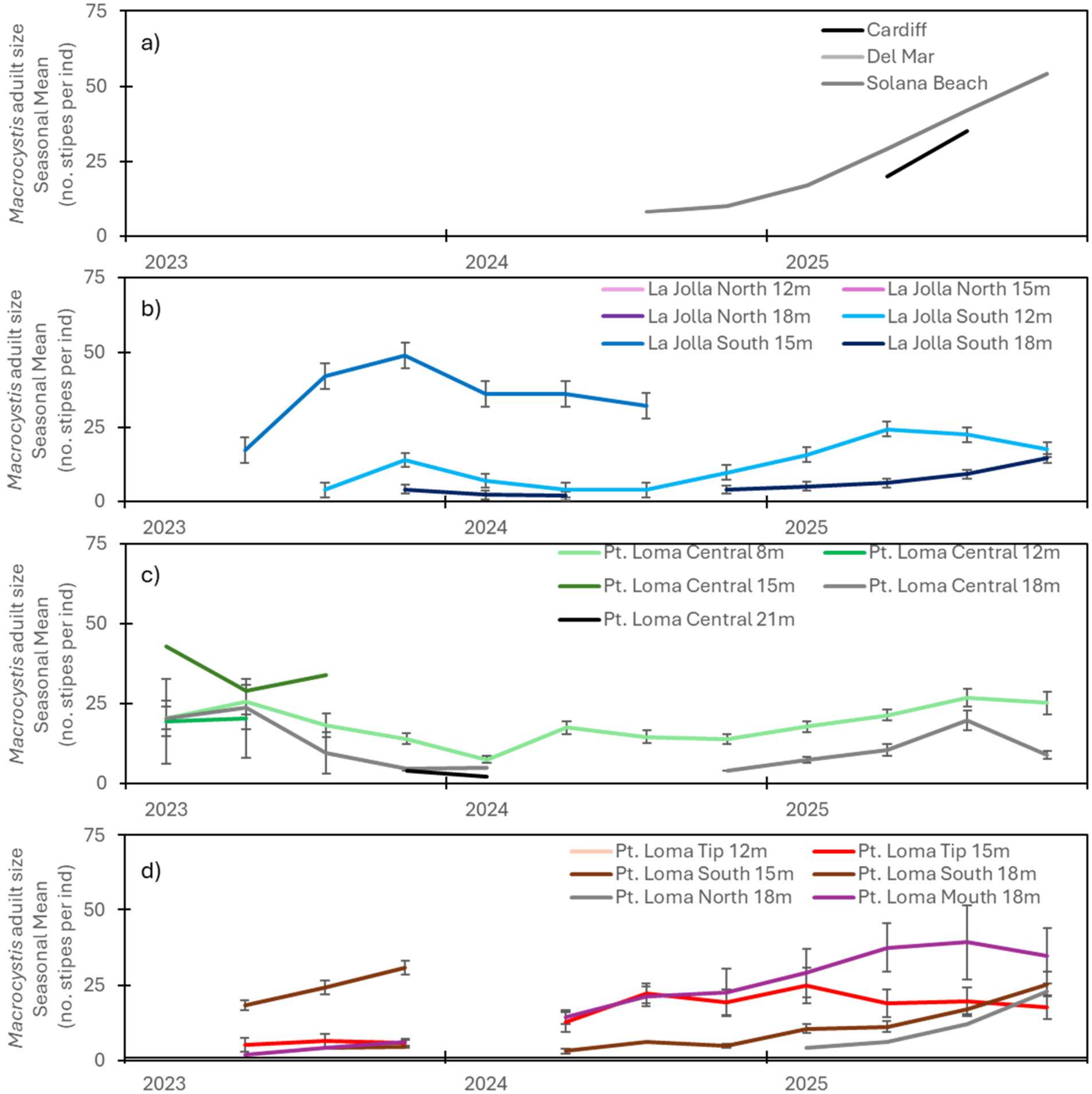


Figure 18: Zoom for reporting period (2023-2025) (no change of scale) of size of Ma*crocystis pyrifera* adults (number of stipes per adult individual longer than 1m); seasonal means from quarterly monitoring of 400 m^2 in a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

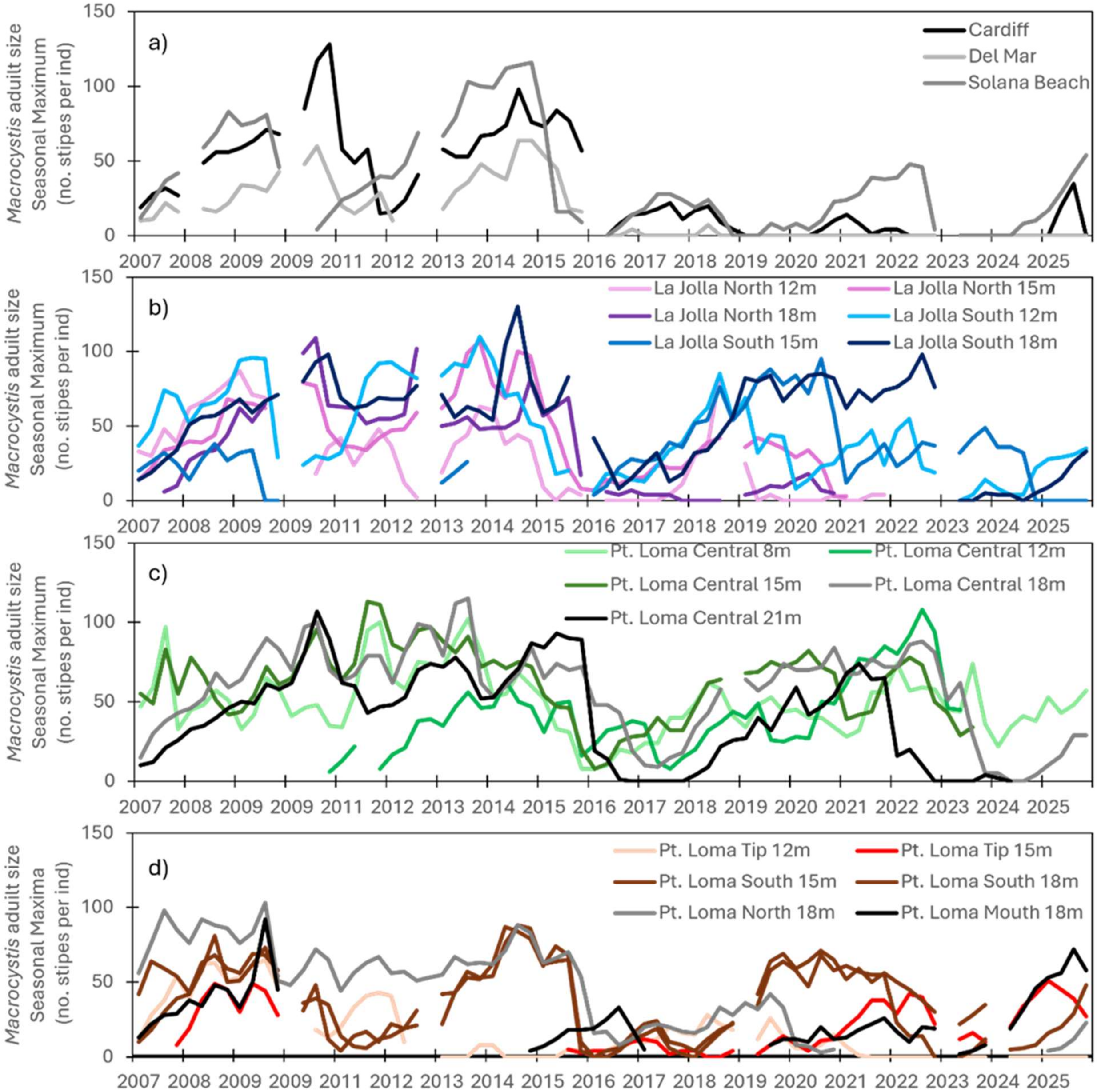


Figure 19: Size of *Macrocystis pyrifera* adults (number of stipes per adult individual longer than 1m); seasonal maxima from quarterly monitoring of 400 m^2 (Winter 2007 to Fall 2025); in a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites.

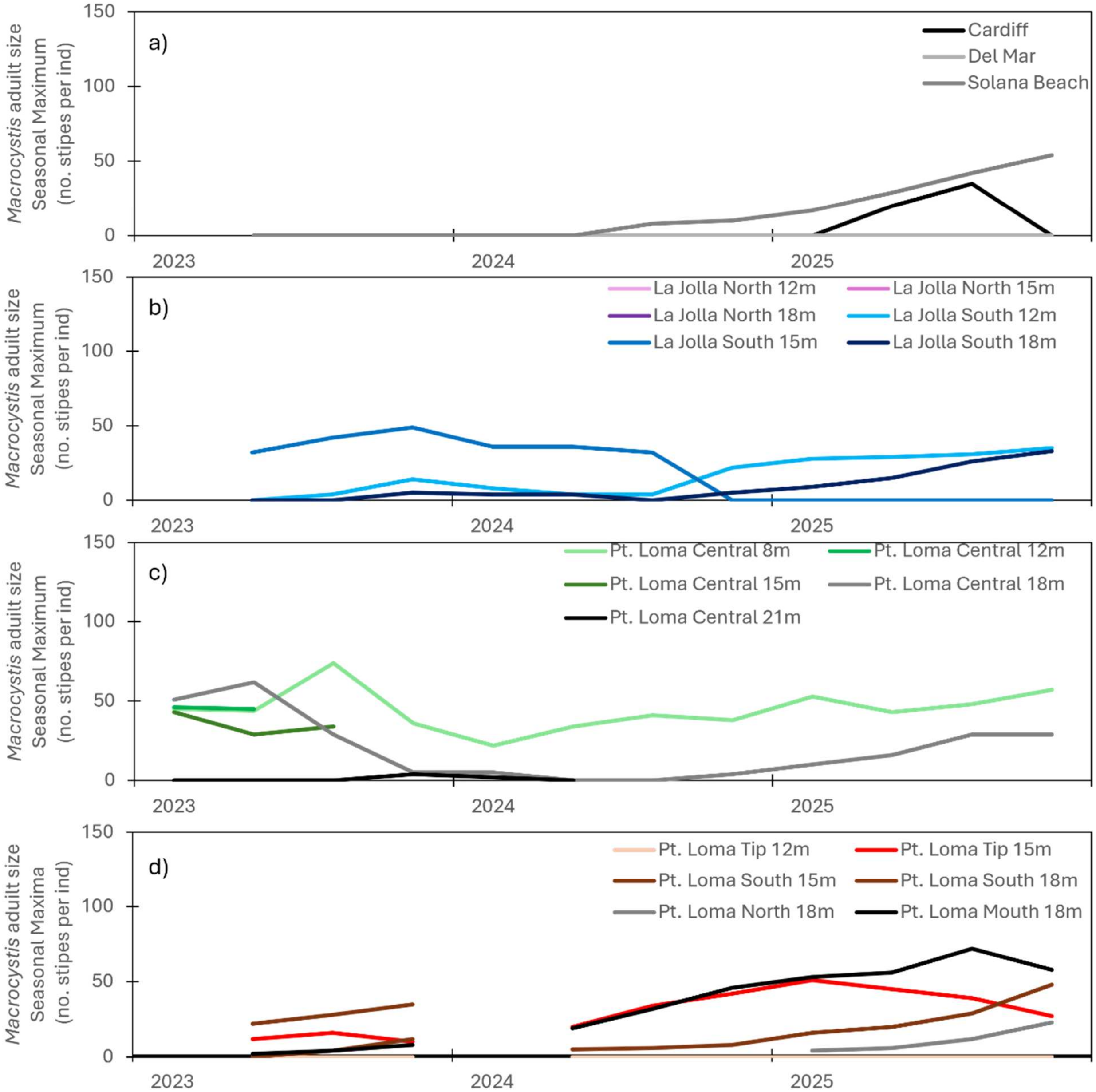


Figure 20: Zoom for reporting period (2023-2025) (no change of scale) of size of *Macrocystis pyrifera* adults (number of stipes per adult individual longer than 1m); seasonal maxima from quarterly monitoring of 400 m^2 in a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites.

Understory kelp species

Laminaria

The understory foliose kelp*, Laminaria farlowii* (Figure 21), showed high densities at some of the monitoring sites in the San Diego region during this reporting period. The North County sites of Cardiff and Solana Beach, the La Jolla South 12 and 15 m sites, and almost all of the Point Loma Central sites showed fairly consistent mean seasonal densities reaching or exceeding 25 individuals per 10 m^2 for the reporting period, whereas Pt Loma Central 18 m only reached those densities in 2025. The Point Loma North 18 m site maintained constant mean densities exceeding 50 individuals per 10 m^2.

Pterygophora

The understory stipitate kelp, *Pterygophora californica* (Figure 22), was also abundant at many of our monitoring sites during this reporting period, with the Point Loma South 18 m and the Point Loma Tip 15 m sites exceeding seasonal mean densities of 75 individuals per 10 m^2.

Eisenia

Density of the understory stipitate kelp, *Eisenia arborea* (Figure 23) during the reporting period was high at two sites in particular: Point Loma Central 8 m, where it was relatively stable at a mean seasonal density of 6 individuals per 10 m^2; and at La Jolla South 12 m, where seasonal mean density was near 15 individuals per 10 m^2 in 2023 and dropped to near 6 individuals per 10 m^2 after 2024.

Kelp reproductive indices

Laminaria farlowii reproduction (Figure 24a) showed seasonal patterns with the percentage of tissue covered by sori being higher in summer and fall, and at the shallow sites in 2023, with all depths showing high reproductive tissue exceeding a mean of 30% of each blade covered with sori in 2024 and especially in 2025.

Pterygophora californica reproduction (Figure 24b) showed active spore production with spring and especially winter peaks, with reproduction for the reporting period being highest in winter 2024 and winter 2025.

Macrocystis pyrifera reproduction (Figure 24c) showed consistently high reproductive indices throughout the reporting period at both the Point Loma 8 m and Point Loma 18 m sites, with sporophylls showing a reproductive state above 3 (sori over most of the sporophyll surface) and 4 (sporophylls with sori over all of the sporophyll surface), except for a brief low period in reproduction at the Point Loma 18 m site in October 2023 when sporophylls were ranked at a level 1 (sporophylls present but no sori). Other sites showed inconsistent reproduction.

Growth of understory kelps

Growth of the understory kelps *Laminaria farlowii* (Figure 25a) and *Pterygophora californica* (Figure 25b) showed seasonal growth rates for spring and summer, with higher growth in spring 2023 and summer 2025.

Invertebrate densities and recruitment

Abalone

Density

The density of all abalone species (Figure 26) has historically been the highest at the Point Loma Central 8 m site, which dominates the time series dating back to 2007, at times reaching a mean over 1 individual per 10 m^2. Additionally, the La Jolla South 18 m site has also ranked high in abalone abundance. While extremely low compared to long-term historical abundances (e.g. pre-1970), the highest abalone mean densities in recent years occurred in spring 2017 and 2018 at the Point Loma 8 m site and in spring 2009 at the La Jolla South 18 m site.

For the reporting period (Figure 27), some abalone densities are still being documented in spring 2023, 2024, and 2025 at the Point Loma Central 8 m site, with densities above 0.3 individuals per 10 m^2. These observations can be seen as encouraging as they indicate some natural abalone recruitment is occurring, even with observed densities not approaching historical levels.

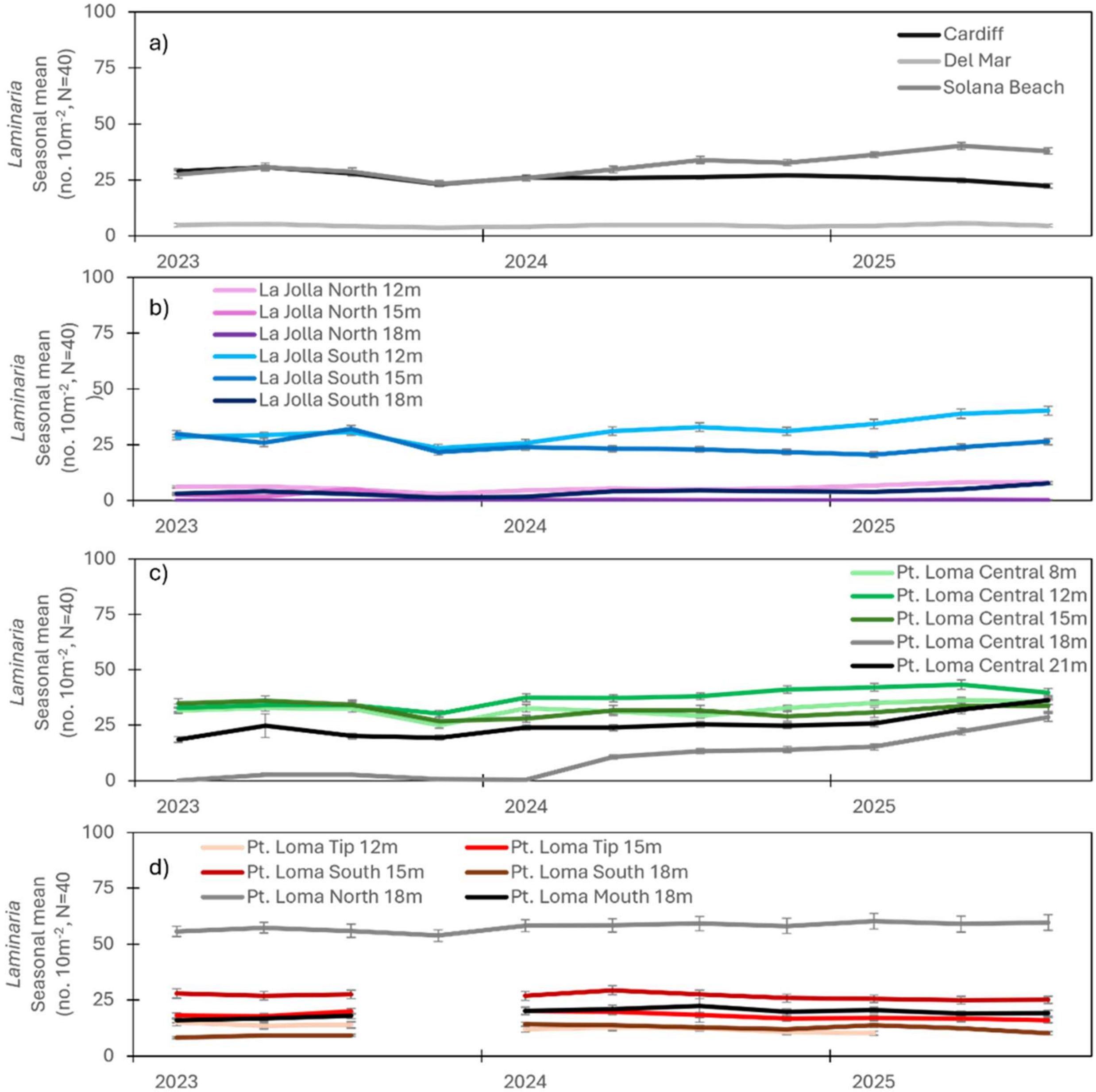


Figure 21: Zoom for reporting period (2023-2025) of density of the understory laminate kelp, *Laminaria* (number of individuals); seasonal means from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

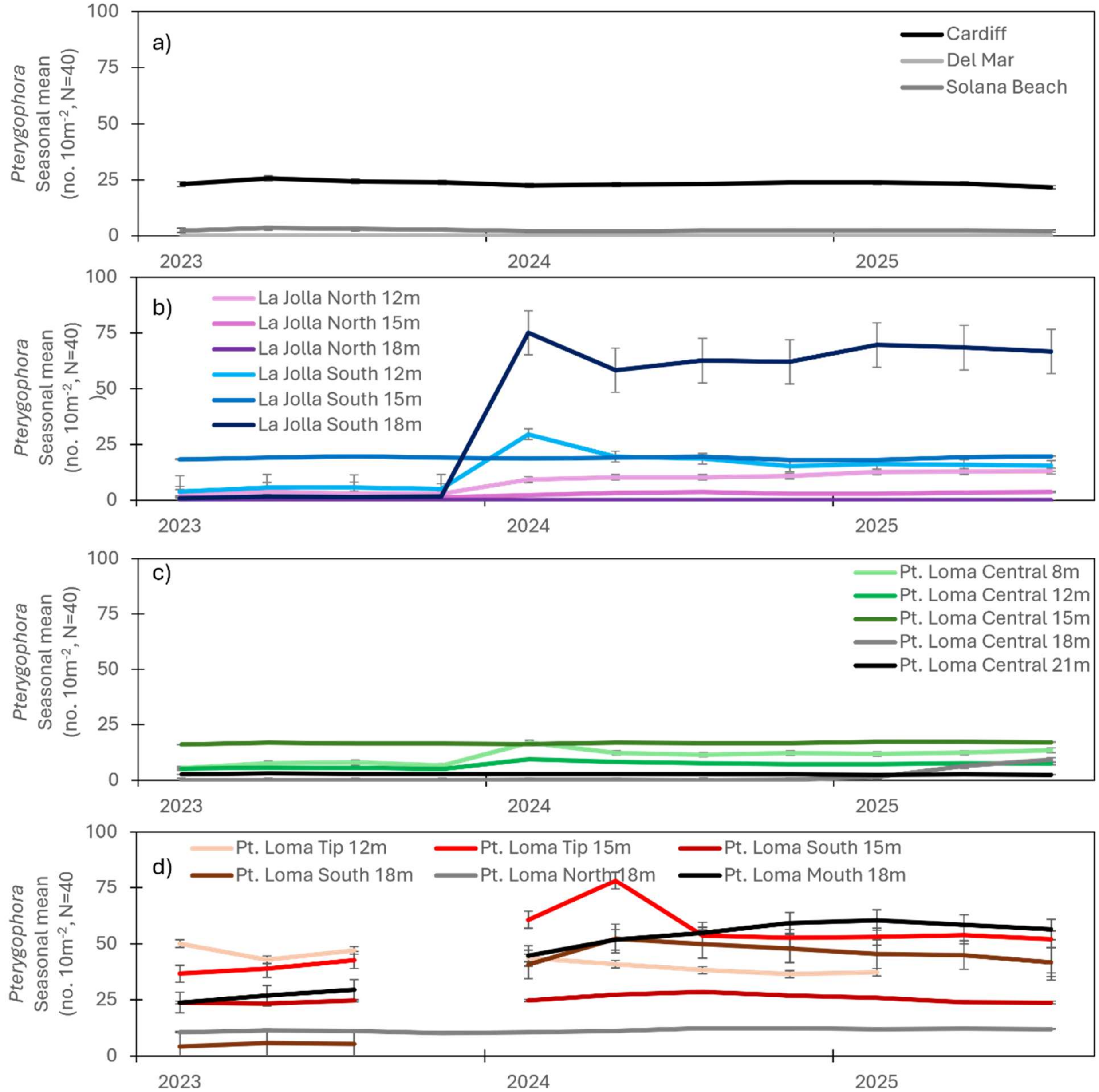


Figure 22: Zoom for reporting period (2023-2025) of density of the understory stipitate kelp, *Pterygophora* (number of individuals); seasonal means from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

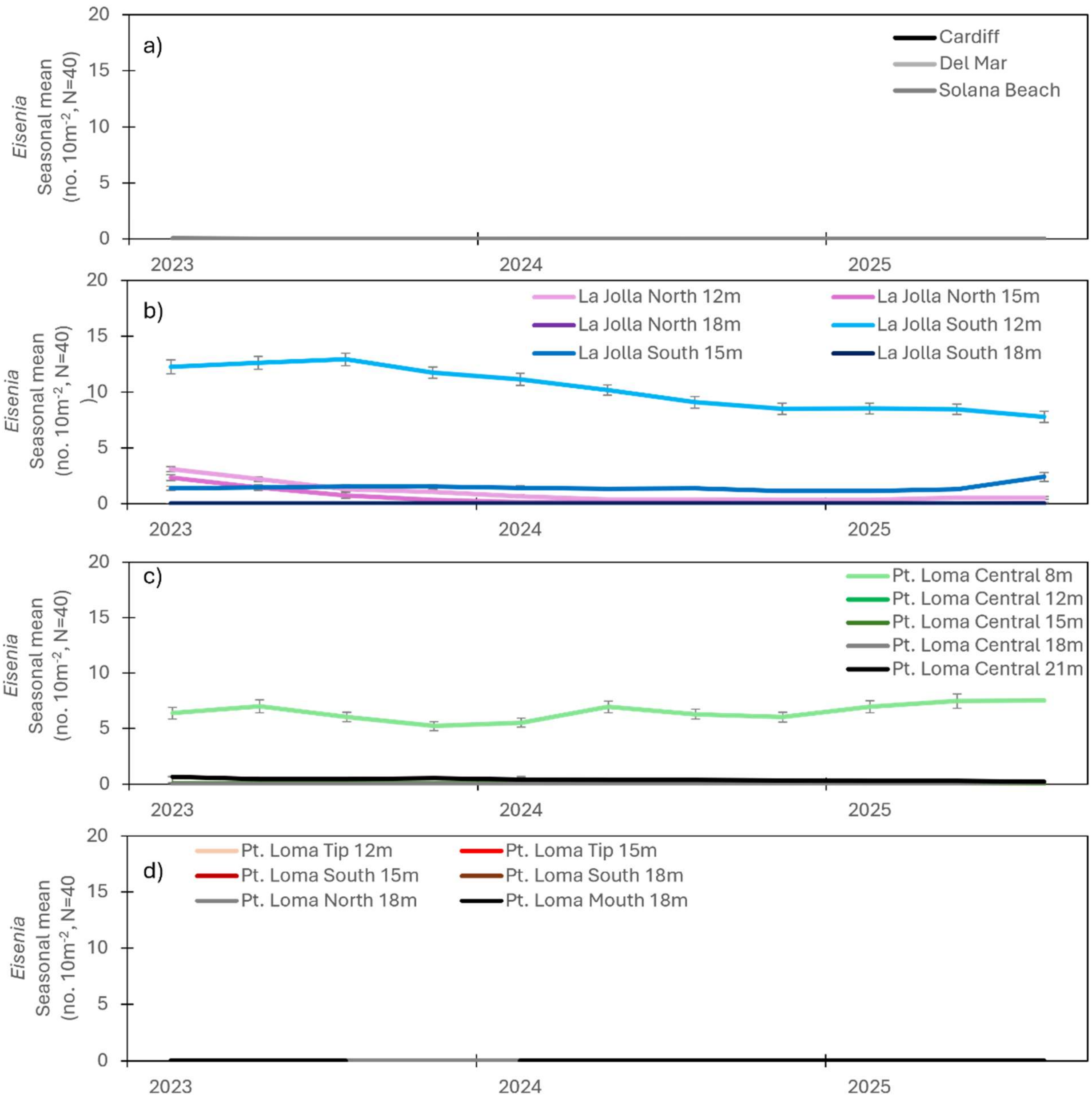


Figure 23: Zoom for reporting period (2023-2025) of density of the understory stipitate kelp, *Eisenia arborea* (number of individuals); seasonal means from quarterly monitoring of 40 quadrants of 5 x 2 m² each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

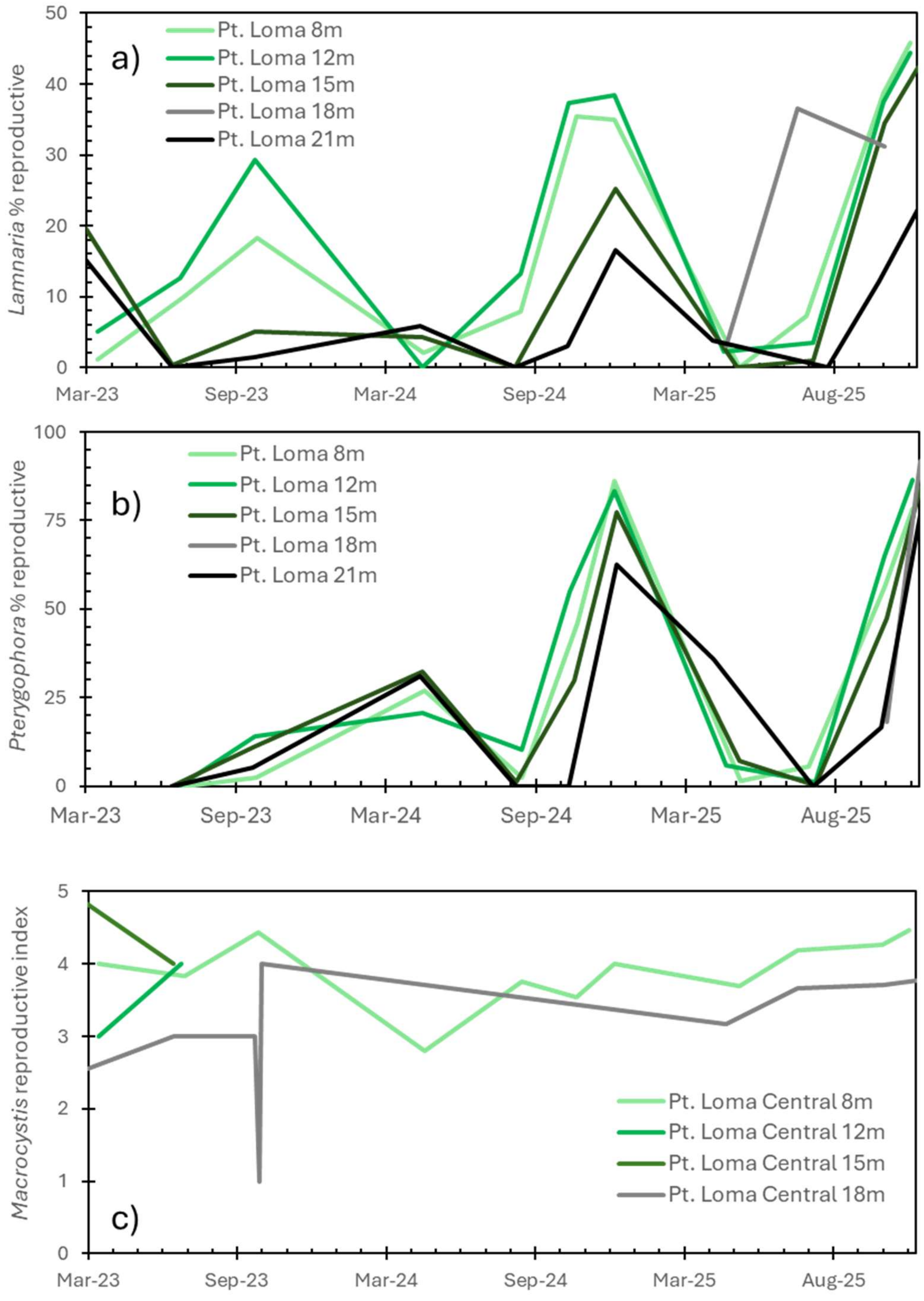
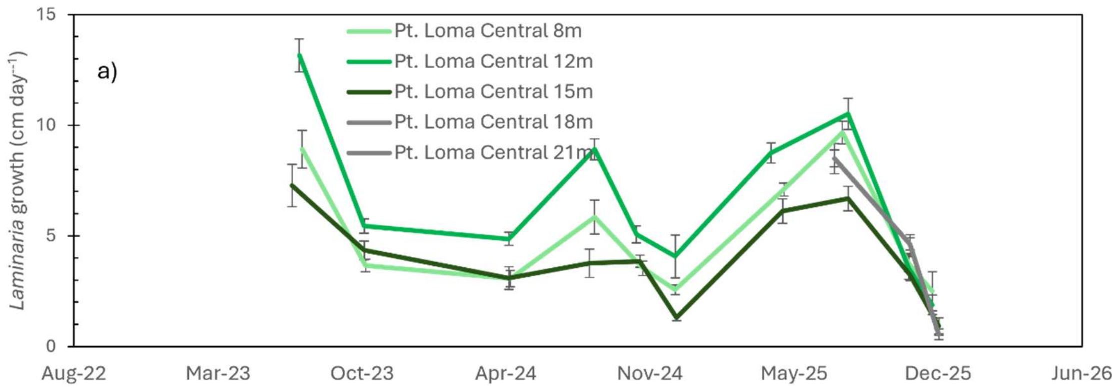


Figure 24: Zoom for reporting period (2023-2025) of the mean of reproductive indices at the Point Loma Central sites for two understory kelps, a) *Laminaria*, and b) *Pterygophora*; and c) the giant kelp, *Macrocystis pyrifera*. See methods for details.



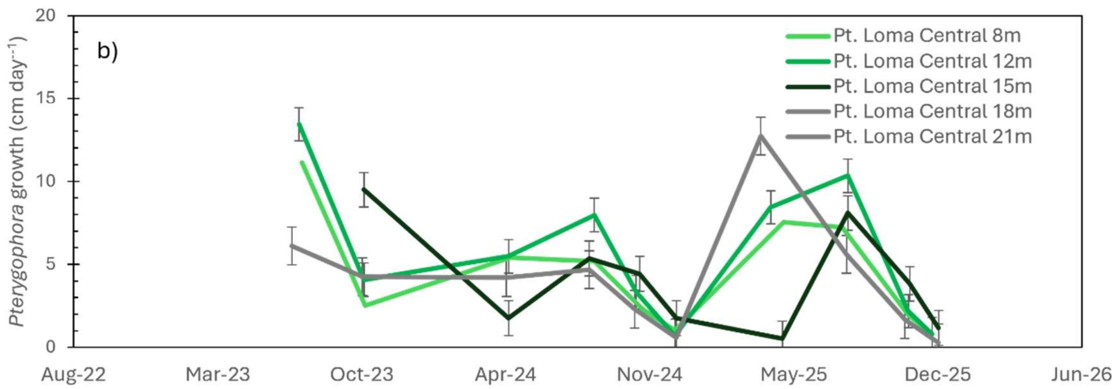


Figure 25: Zoom for reporting period (2023-2025) of mean growth rates at the Point Loma Central sites for two understory kelps, a) *Laminaria*, and b) *Pterygophora* (see details in methods).

Purple Sea Urchins

Density

Historically, the highest mean densities of purple sea urchins exceeded 100 individuals per 10 m^2 in spring 2012 and 2013 at the Point Loma Tip 15 m site, with mean densities above 50 individuals per 10 m^2 in spring 2010, 2011, 2012, and 2013, at the Point Loma Tip 12 m and 15 m sites, as well as at the Point Loma Mouth 18 m and Point Loma South 18 m sites. Most of the other sites show low or no purple urchin presence (Figure 28).

For the reporting period (Figure 29), none of the sites and periods were within the top 10% of the mean density of purple sea urchins in the time series dating back to 2007, with only the Point Loma Mouth 18 m site for spring 2023, the Point Loma Central

8 m site for spring 2023 and 2024, and the Point Loma Tip 15 m site for spring 2024 and 2025 within the top 20% of the historical time series dating back to 2007. Only the following sites and seasons for the reporting period exceeded 10 purple sea urchins per 10 m^2: Point Loma Tip 15 m in spring 2024 and 2025, Point Loma Central 18 m in spring 2023 and 2024, and Point Loma Mouth 18 m in spring 2023.

Recruitment

For this reporting period (Figure 30-32), both fall 2023 and fall 2024 showed higher numbers of purple sea urchins in the smaller size class near the La Jolla North 12 m site. Some sites, particularly in La Jolla, exceeded 50% of the purple urchins measured in the < 25 mm size class for most seasons, suggesting that more than half of the population entailed recruits, for example in fall 2023 (La Jolla North 12 and 18 m, and La Jolla South 12 m), spring 2024 (La Jolla North 12 m), fall 2024 (La Jolla North 12, 15 and 18 m), spring 2025 (La Jolla North 12 m) and fall 2025 (La Jolla North 12 and 18 m).

Notably, although the La Jolla North 18 m site showed more than 50% of the population in the smaller size classes at times, demographic evaluations there required a search effort of more than 15 quadrants to find enough purple urchins for all seasons evaluated except for in spring 2023. Additionally, for fall 2024 and spring 2025, more than 15 quadrants were required for the site west of Point Loma Central 18 m; as well as for the La Jolla South 15 m site in fall 2025.

Red Sea Urchins

Density

Historically, the highest mean densities of red sea urchins occurred in the Point Loma Mouth 18 m and Point Loma Tip 12 and 15 m sites, exceeding 10 individuals per 10 m^2 in spring 2012, 2013, 2014 and 2015 (Figure 33).

For the recent reporting period (Figure 34), only the Point Loma Central 18 m (spring 2023, 2024 and 2025), La Jolla North 15 m (spring 2023 and 2024), La Jolla North 18 m (spring 2023), and Point Loma Mouth 18 m (spring 2023) sites were within the top 10% of the historical time series of red sea urchin densities dating back to 2007, exceeding a mean of 2 red sea urchins per 10 m^2.

Recruitment

For this reporting period (Figure 35-37), higher numbers of red sea urchins in the smaller size class were detected in fall 2023 and fall 2024 near the La Jolla North 12 m site, and to a lesser degree in Fall 2024 near the Point Loma Mouth 18 m and Point Loma Central 21 m sites.

The following seasons and sites exceeded 50% of the red sea urchins found with a size lower than 35 mm (considered recruits for this analysis): spring 2023 at La Jolla North 12 m; fall 2023 at La Jolla North 12 m (reaching 100%), La Jolla South 12 and 15 m, Point Loma Central 8 and 15 m; spring 2024, La Jolla North 12 and 15 m, Point Loma Central 8 and 12 m, Point Loma South 15 m and La Jolla South 15 m; fall 2024, La Jolla North 12 m (reaching 90%), and La Jolla North 15 m, Point Loma Central 12 m, Point Loma Tip 15 m and Point Loma Mouth 18 m (reaching 88%), La Jolla South 15 m, Point Loma Central 21 m and west of Point Loma South 18 m; spring 2025, La Jolla North 12 and 15 m, La Jolla South 15 and 18 m, Point Loma Tip 15 m and Point Loma Mouth 18 m, and Point Loma South 18 m and west of Point Loma South 18 m; and fall 25, La Jolla North 12 and 15 m, La Jolla South 18 m, Point Loma Central 8 and 21 m, and Point Loma Tip 15 m.

Notably the following sites required more than 15 quadrants to find and measure sufficient red urchins: in spring 2023, La Jolla North 18 m, Point Loma Tip 12 and 18 m, La Jolla South 12 and 15 m, Point Loma North and South at 18 m; for fall 23, La Jolla North 18 m and La Jolla South 15 and 18 m, and Point Loma South 15 m (which needed 28 quadrants), and Point Loma North 18 m; for spring 2024 many of the sites repeated, for example La Jolla North and South 18 m, and Point Loma North 18 m; for fall 2024, only La Jolla North 18 m as well as Point Loma Central 18 m and west of that site required more than 15 quadrants to find sufficient urchins; for spring 2025, only La Jolla North 18 m as well as west of Point Loma Central 18 m required 15+ quadrants; and for fall 2025 again many sites did, including La Jolla North and South 15 m, Point Loma Mouth, Central and South at 18 m as well as Point Loma Central at 15 m.

Wavy Top Snails

Density

Historically, the highest mean densities of the wavy top turban snail occurred at the Point Loma Central 15 m in spring 2025 with a mean of 13.2 individuals per 10 m^2. Mean densities exceeding 8 individuals per 10 m^2 include the Point Loma Central 15 m (spring 2021, 2022, 2023 and 2025) and 18 m sites (spring 2022 and 2023), the Point Loma Tip 12 m site (spring 2023 and 2024), Point Loma Central 8m site (spring 2018), and La Jolla North 15 m site (spring 2020) (Figure 38).

For the reporting period (Figure 39), some of the highest historical mean densities dating back to 2007 have been recorded, with the Point Loma Central 8, 15, and 18 m sites, along with the Point Loma Tip 12 m site showing the highest abundances of wavy top turban snails.

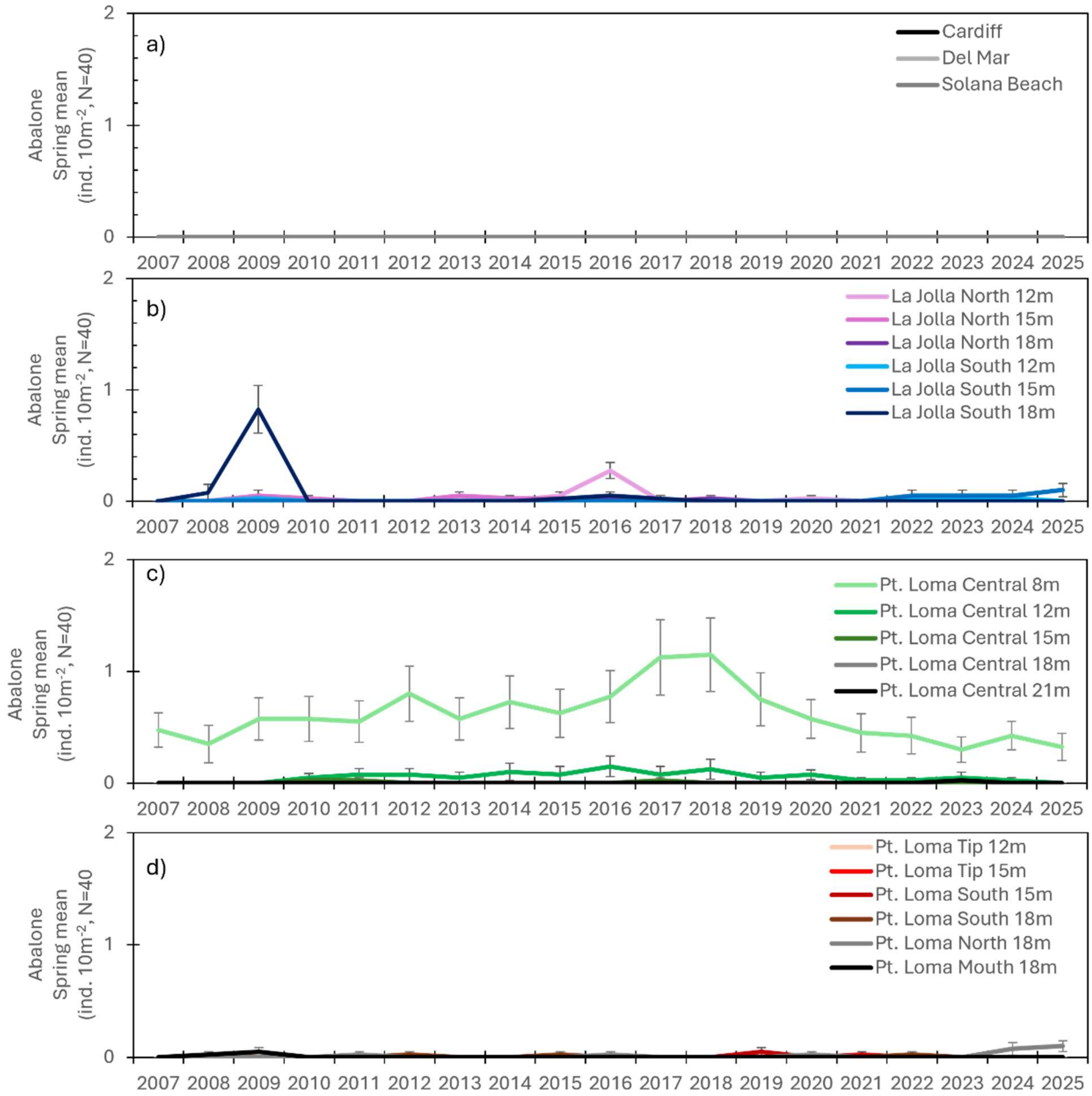


Figure 26: Density of Abalone (number of *Haliotis* spp. individuals); seasonal means (Winter 2007 to Fall 2025) from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

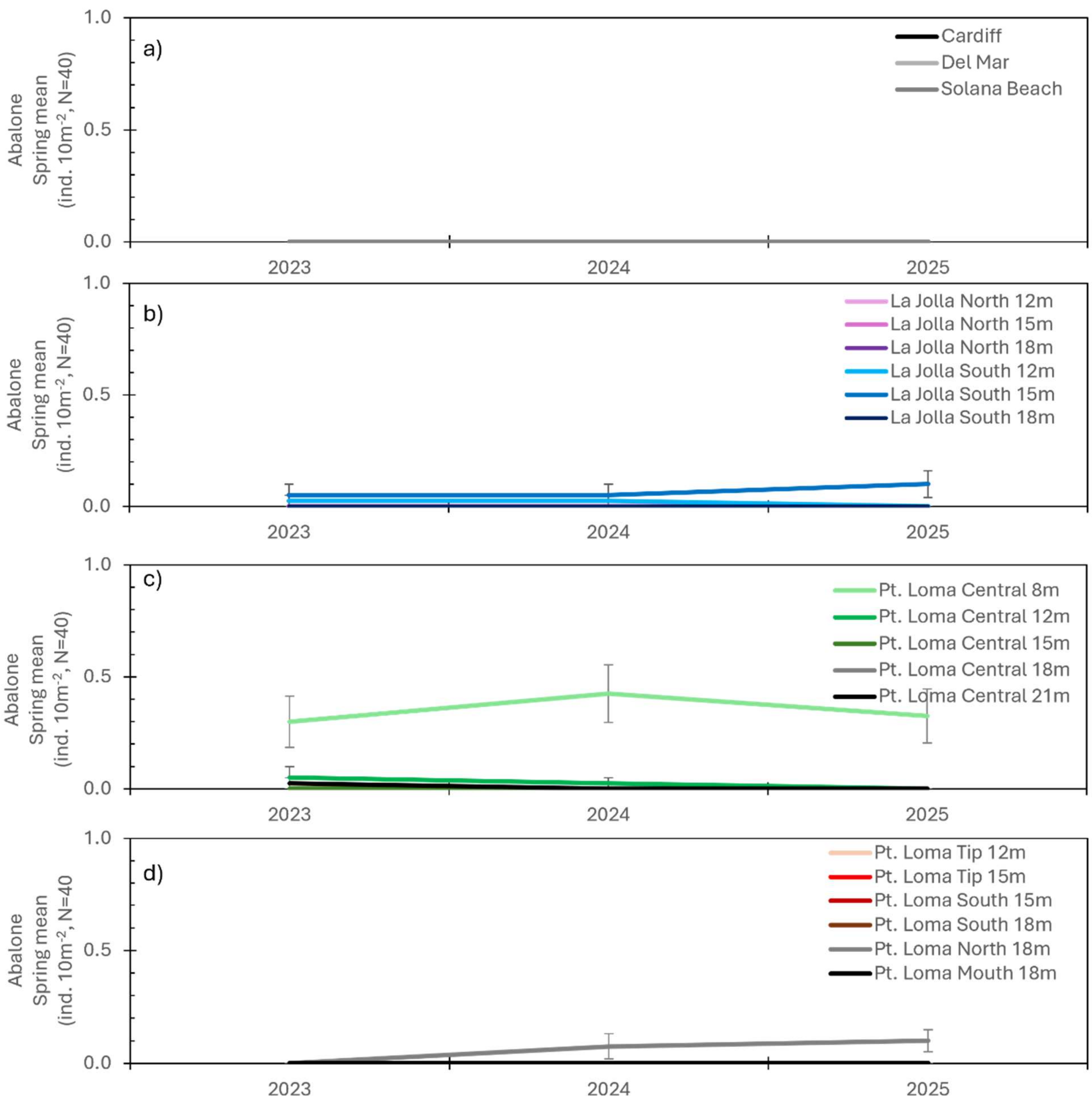


Figure 27: Zoom for reporting period (2023-2025)(note change of scale) of density of Abalone (number of *Haliotis* spp. individuals); seasonal means from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

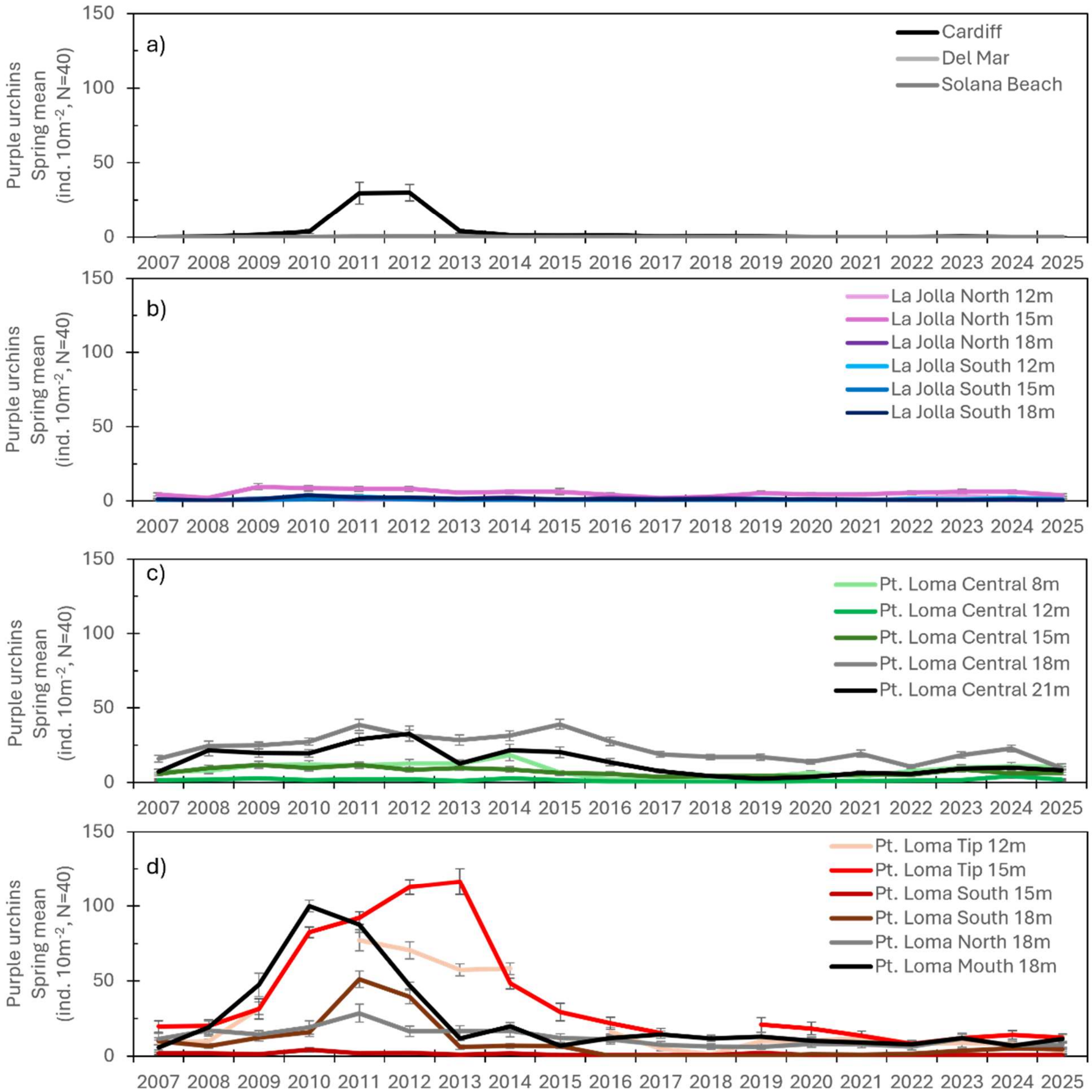


Figure 28: Density of Purple Sea Urchins (number of *Strongylocentrotus purpuratus* individuals); seasonal means (Winter 2007 to Fall 2025) from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

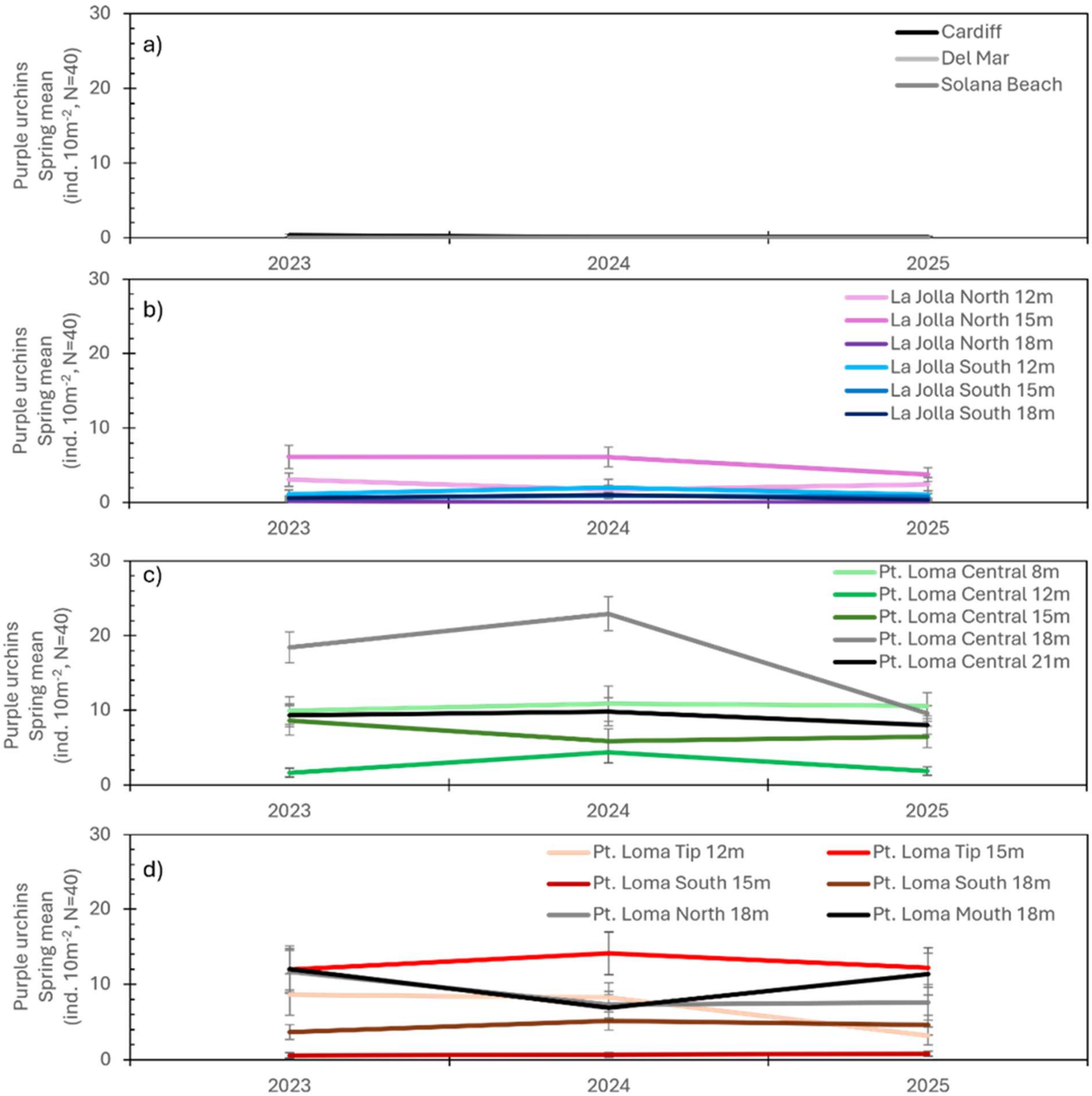


Figure 29: Zoom for reporting period (2023-2025) (note change of scale) of density of Purple Sea Urchins (number of *Strongylocentrotus purpuratus* individuals); seasonal means from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

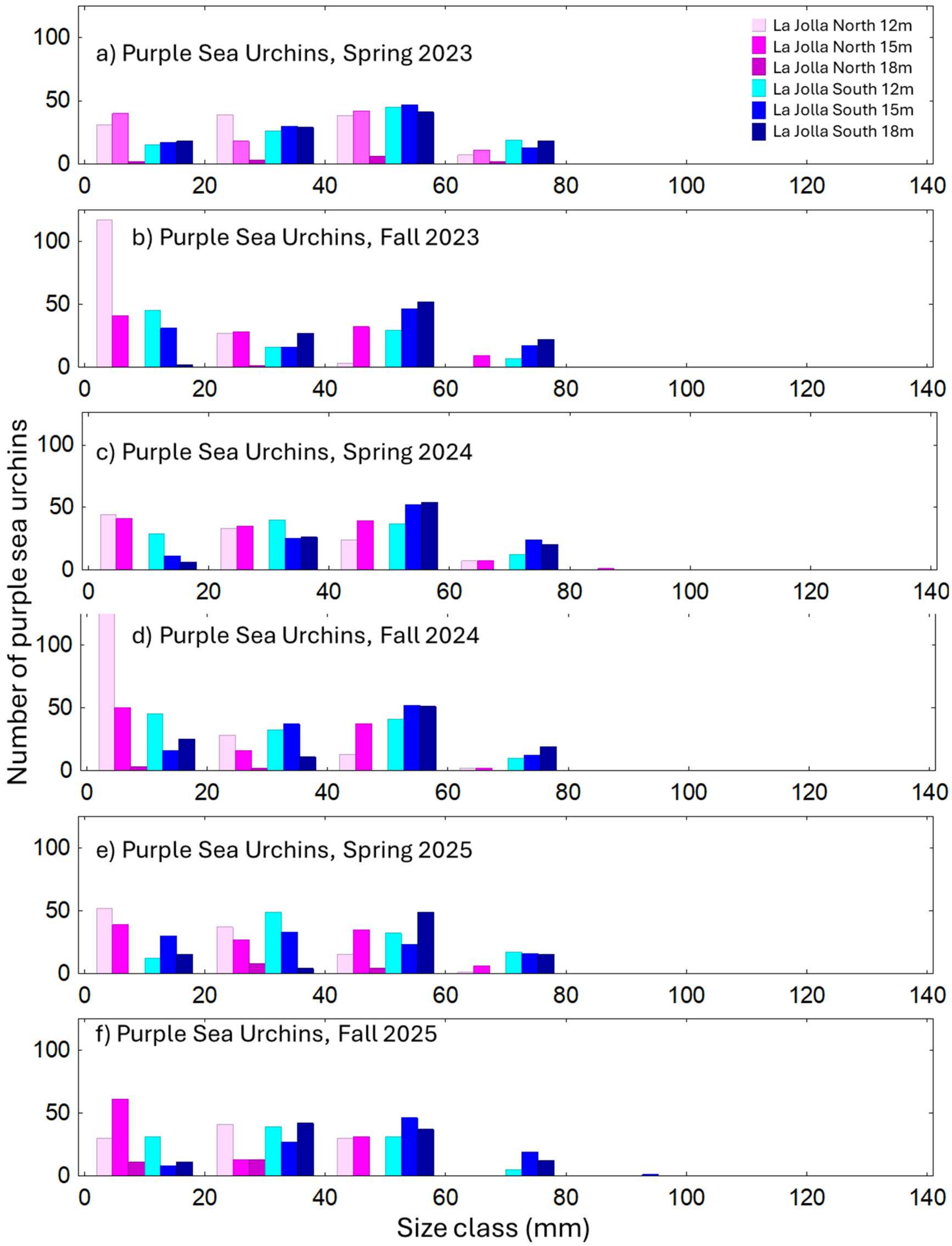


Figure 30: Size Structure (test size in mm) of Purple Sea Urchins (number of *Strongylocentrotus purpuratus* individuals in each 20 mm size class) for the La Jolla sites in spring and fall of 2023, 2024 and 2025, covering the reporting period.

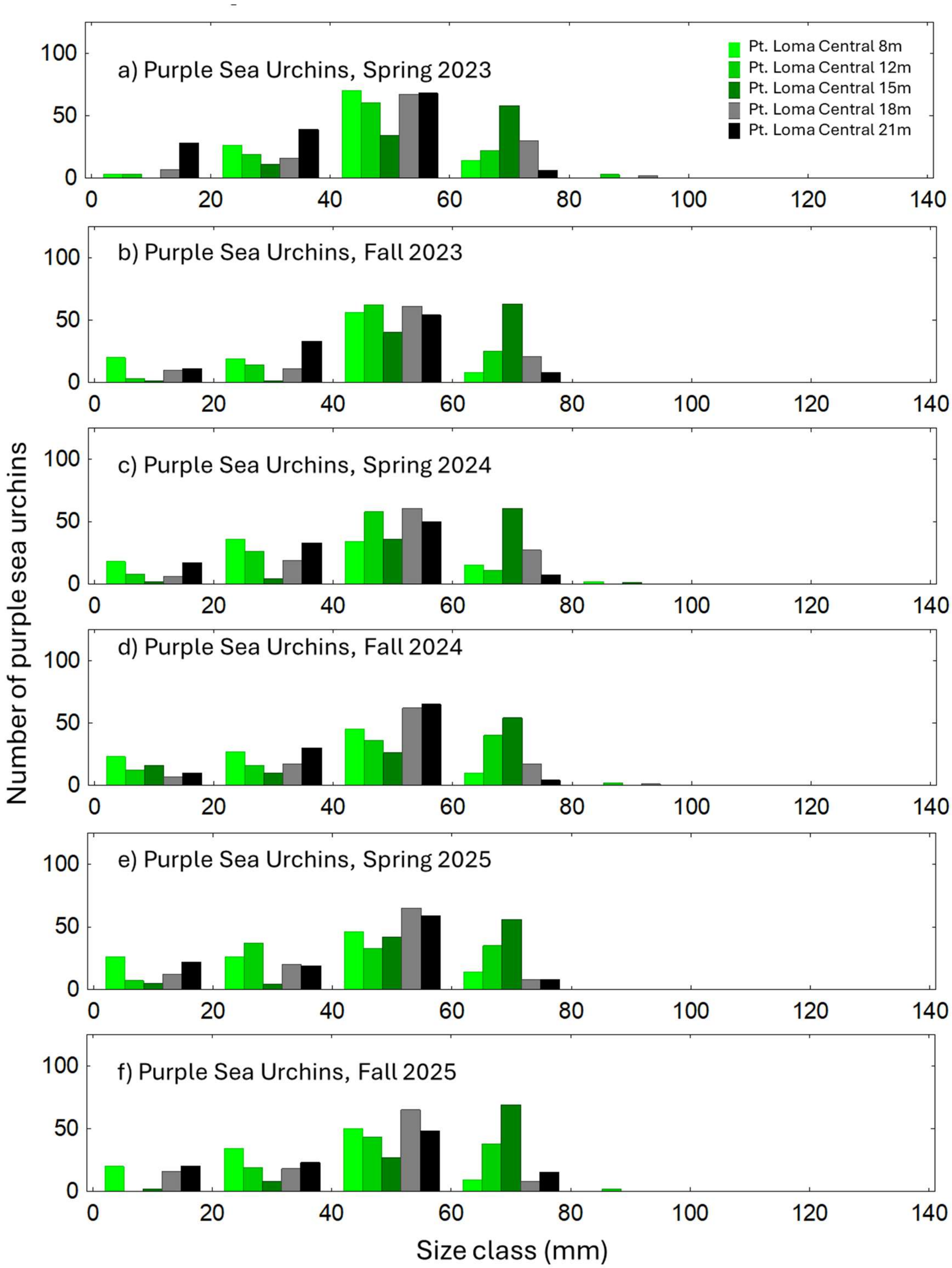


Figure 31: Size Structure (test size in mm) of Purple Sea Urchins (number of *Strongylocentrotus purpuratus* individuals in each 20 mm size class) for the Point Loma Central sites in spring and fall of 2023, 2024 and 2025, covering the reporting period.

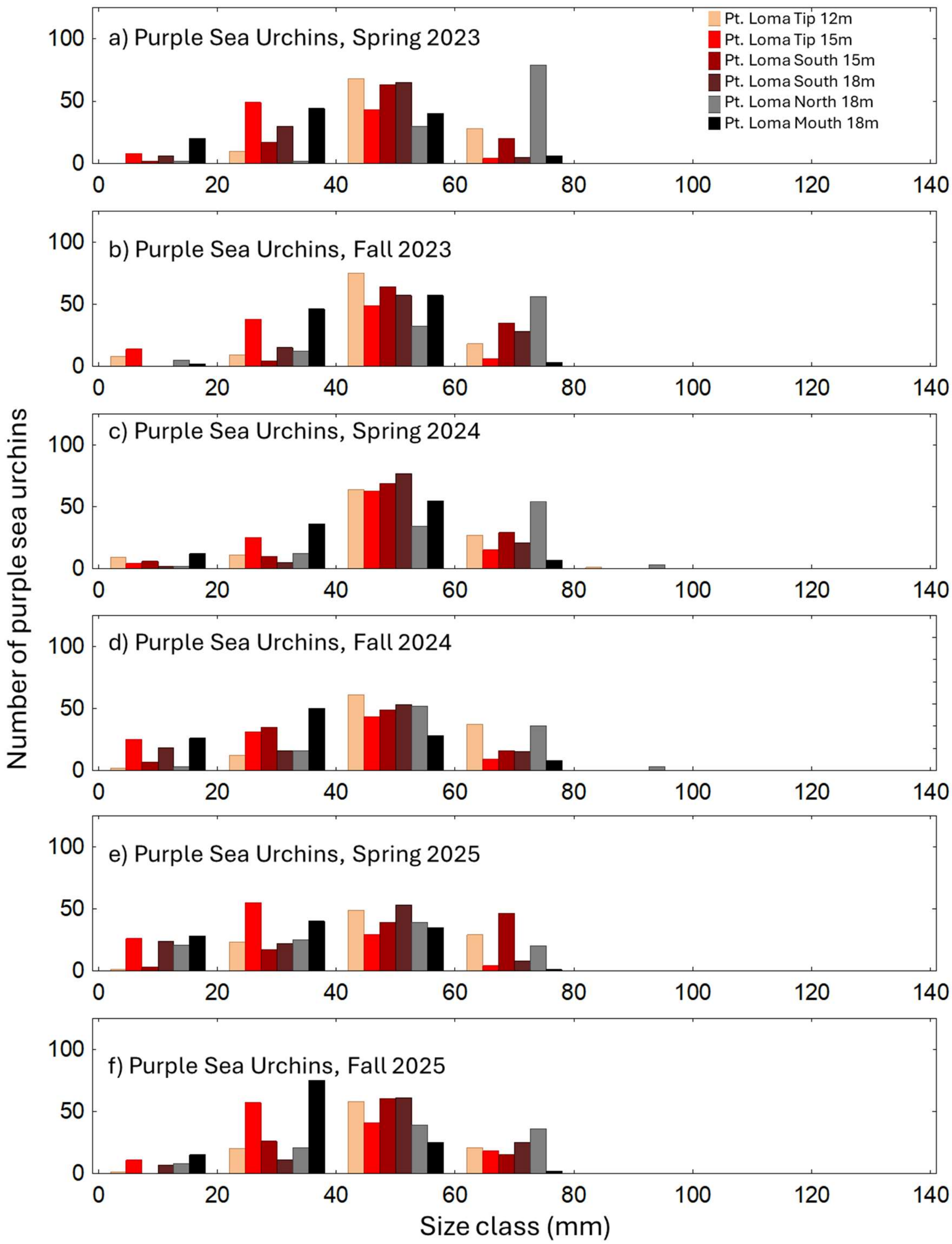


Figure 32: Size Structure (test size in mm) of Purple Sea Urchins (number of *Strongylocentrotus purpuratus* individuals in each 20 mm size class) for the Point Loma additional sites in spring and fall of 2023, 2024 and 2025, covering the reporting period.

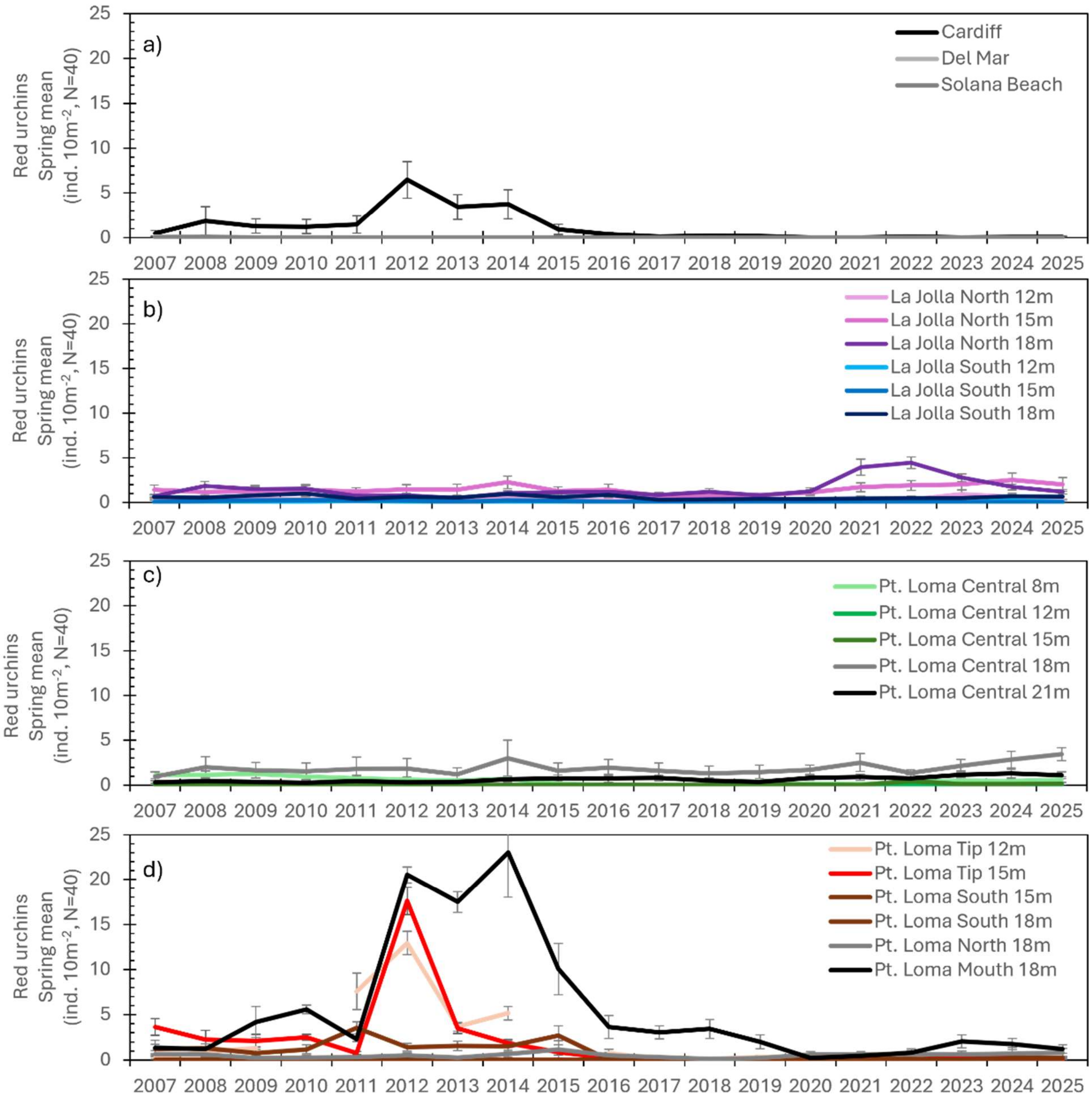


Figure 33: Density of Red Sea Urchins (number of *Mesocentratus franciscanus* individuals); seasonal means (Winter 2007 to Fall 2025) from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

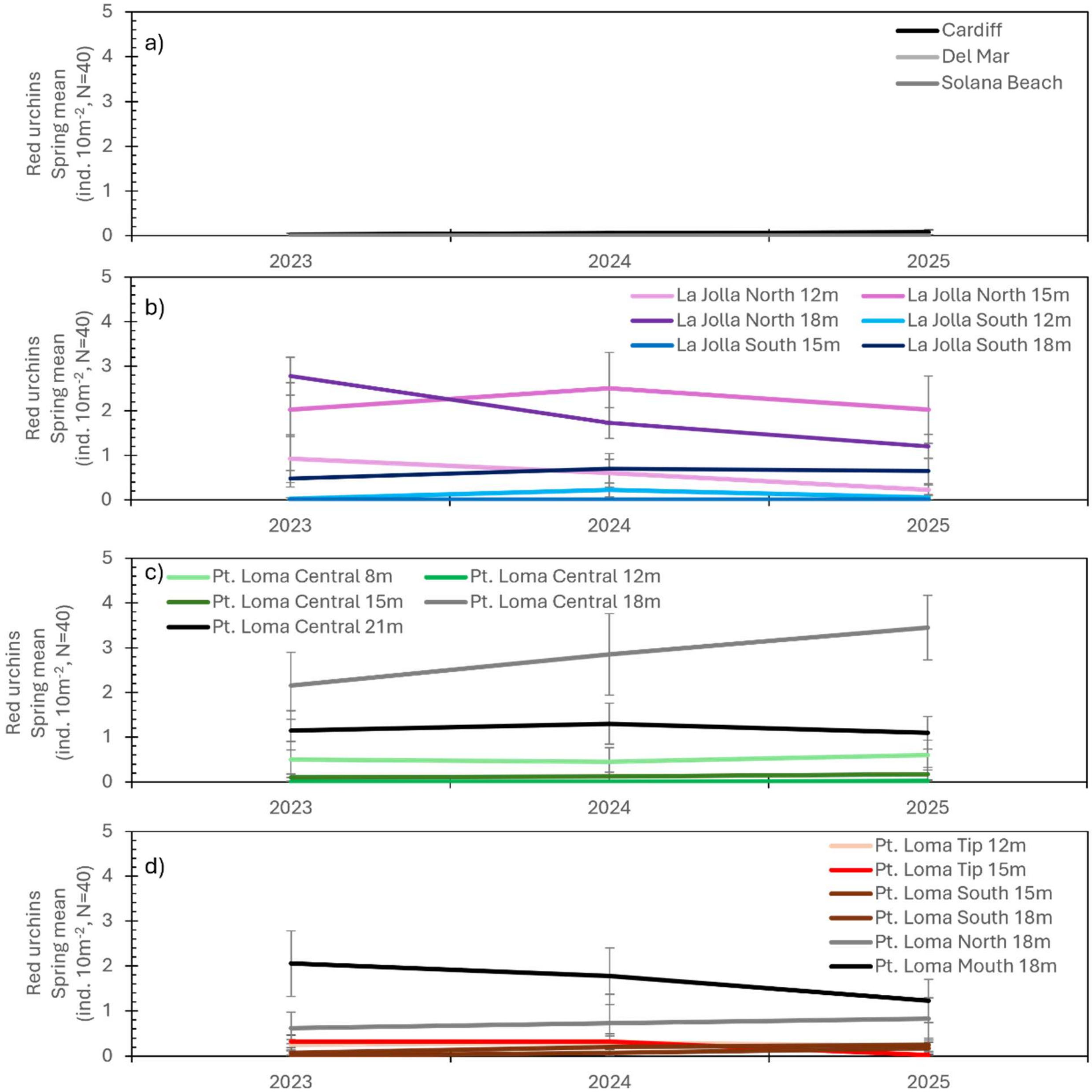


Figure 34: Zoom for reporting period (2023-2025)(note change of scale) of density of Red Sea Urchins (number of *Mesocentratus franciscanus* individuals); seasonal means from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

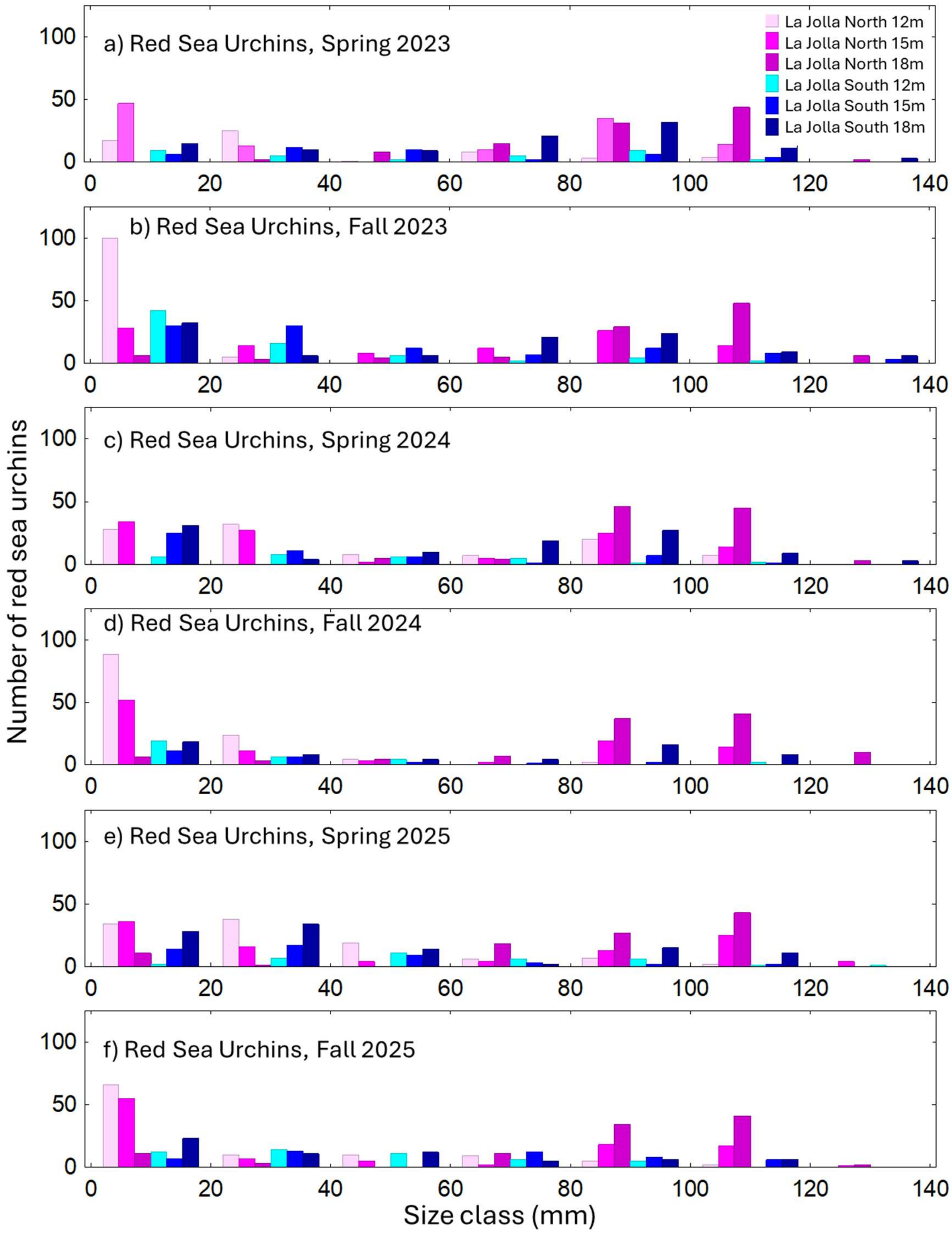


Figure 35: Size Structure (test size in mm) of Red Sea Urchins (number of *Mesocentratus franciscanus* individuals in each 20 mm size class) for the La Jolla sites in spring and fall of 2023, 2024, and 2025, covering the reporting period.

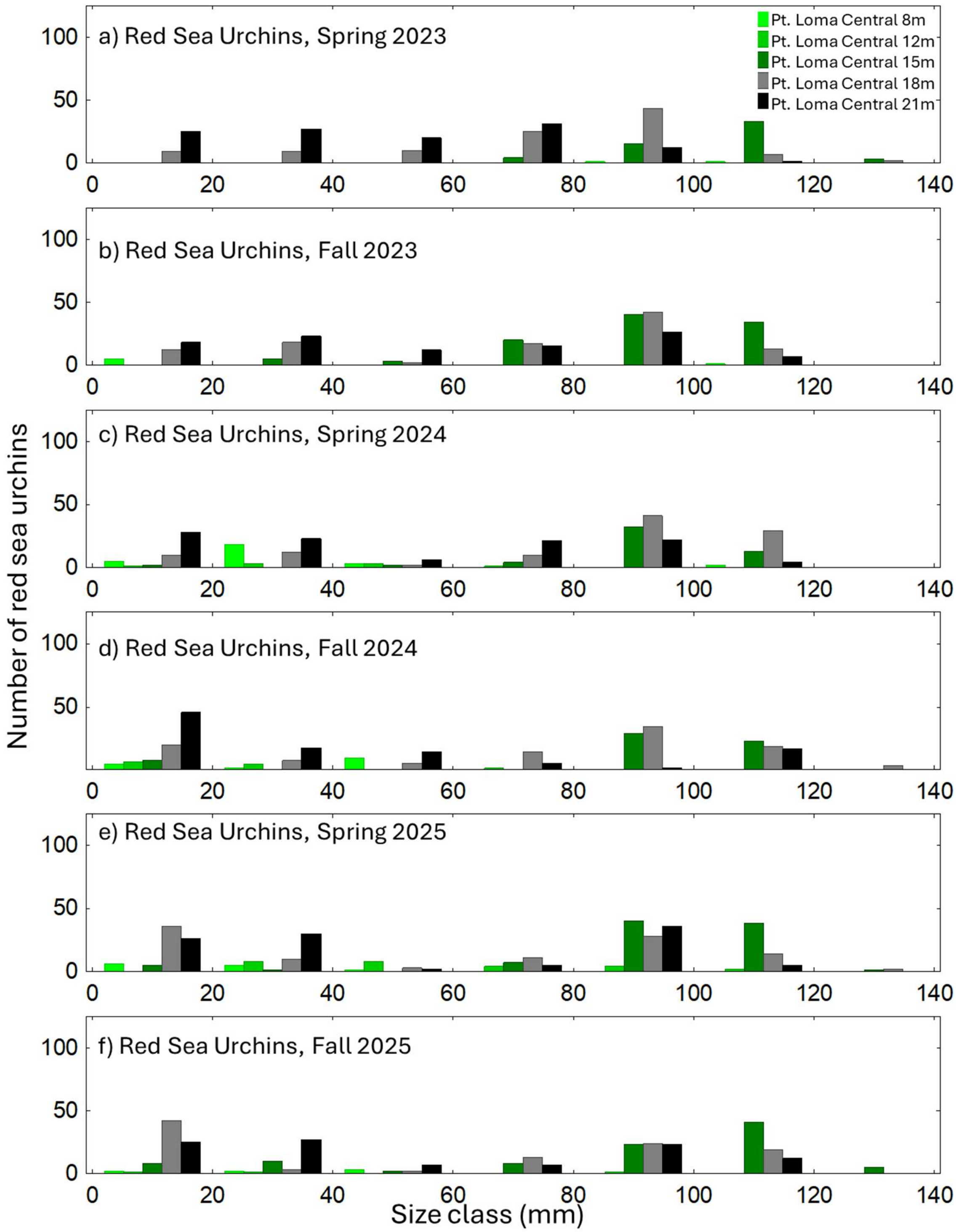


Figure 36: Size Structure (test size in mm) of Red Sea Urchins (number of *Mesocentratus franciscanus* individuals in each 20 mm size class) for the Point Loma Central sites in spring and fall of 2023, 2024 and 2025, covering the reporting period.

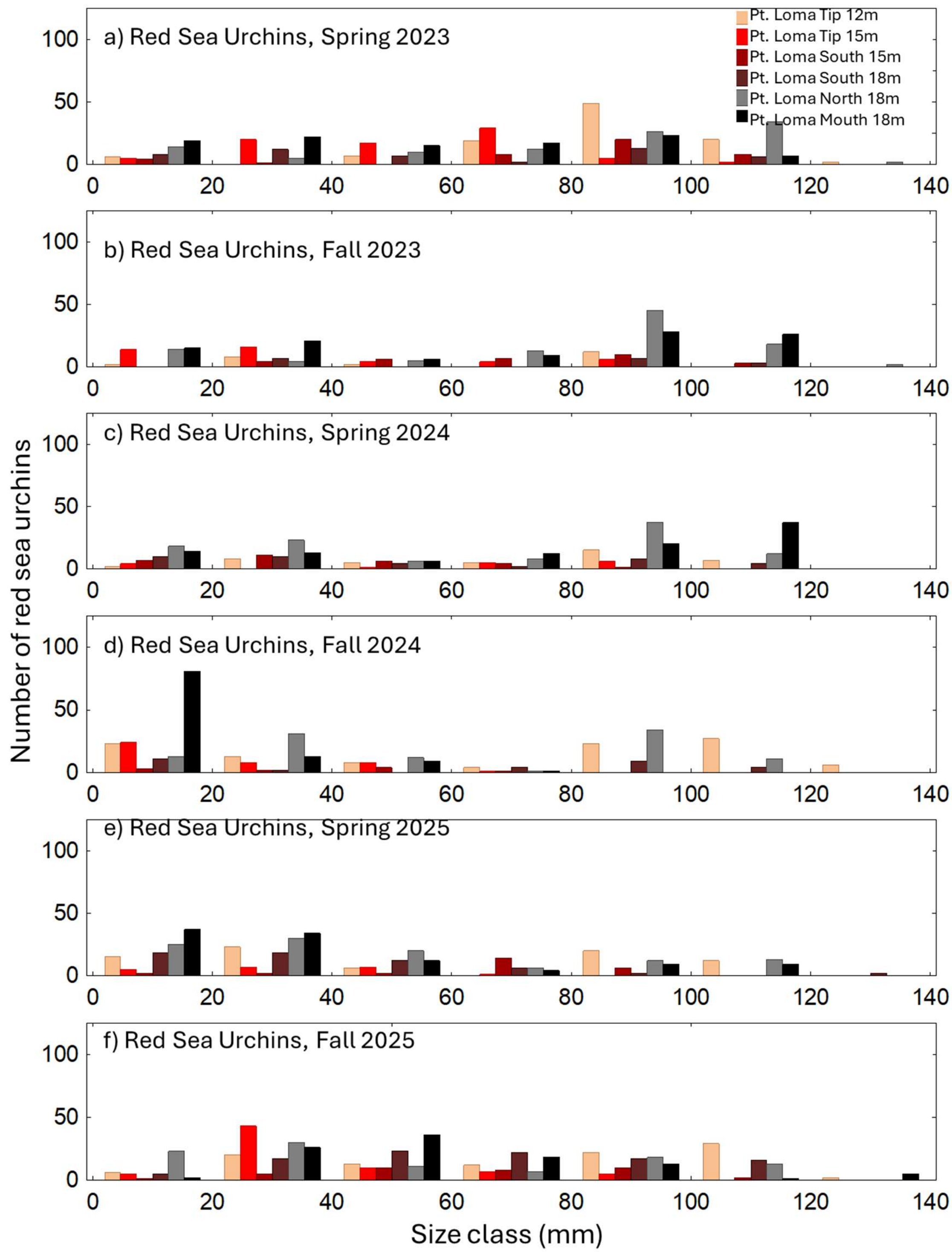


Figure 37: Size Structure (test size in mm) of Red Sea Urchins (number of *Mesocentratus franciscanus* individuals in each 20 mm size class) for the other Point Loma additional sites in spring and fall of 2023, 2024, and 2025, covering the reporting period.

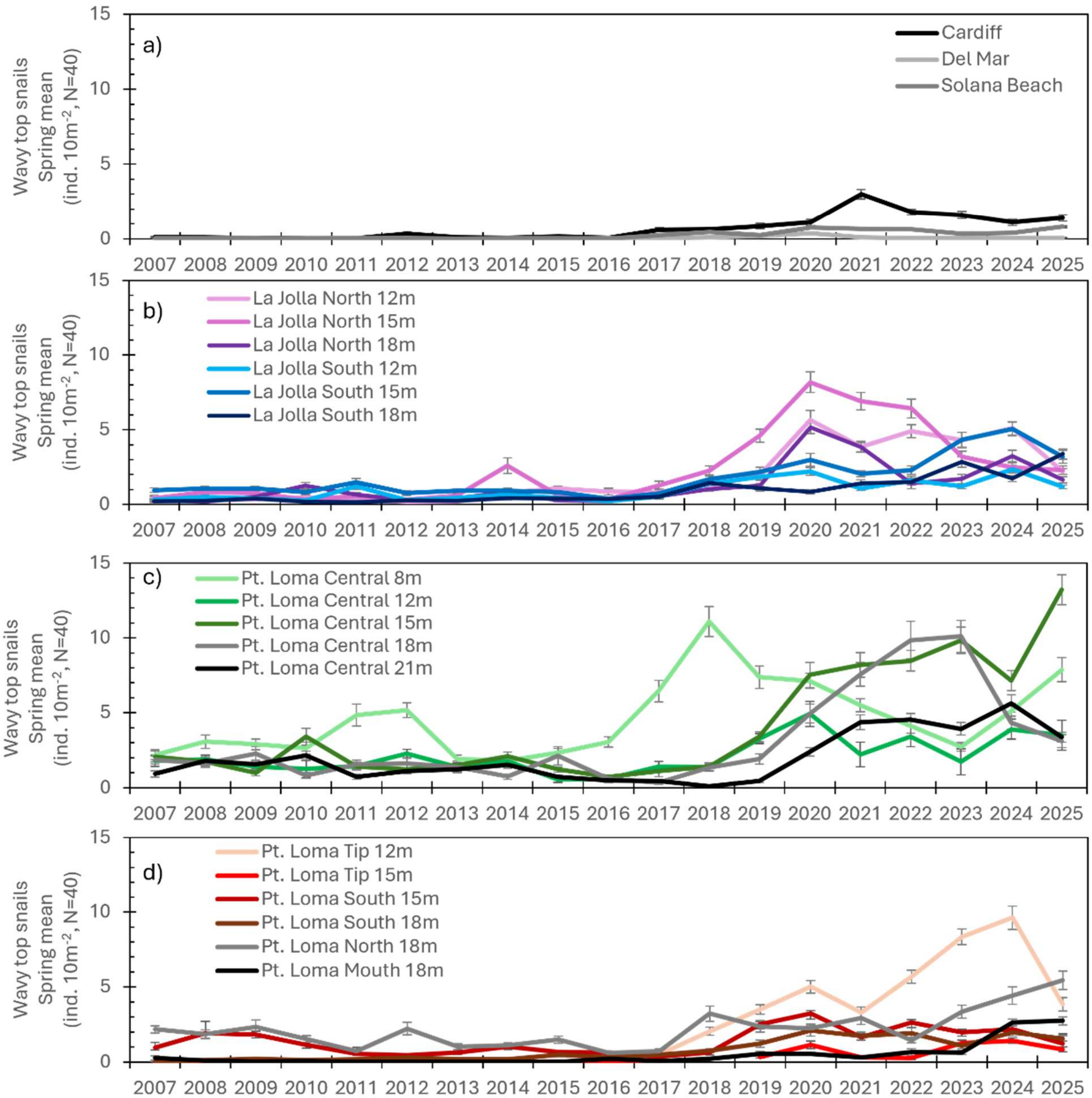


Figure 38: Density of Wavy Top Snails (number of *Megastrea* spp. individuals); seasonal means (Winter 2007 to Fall 2025) from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

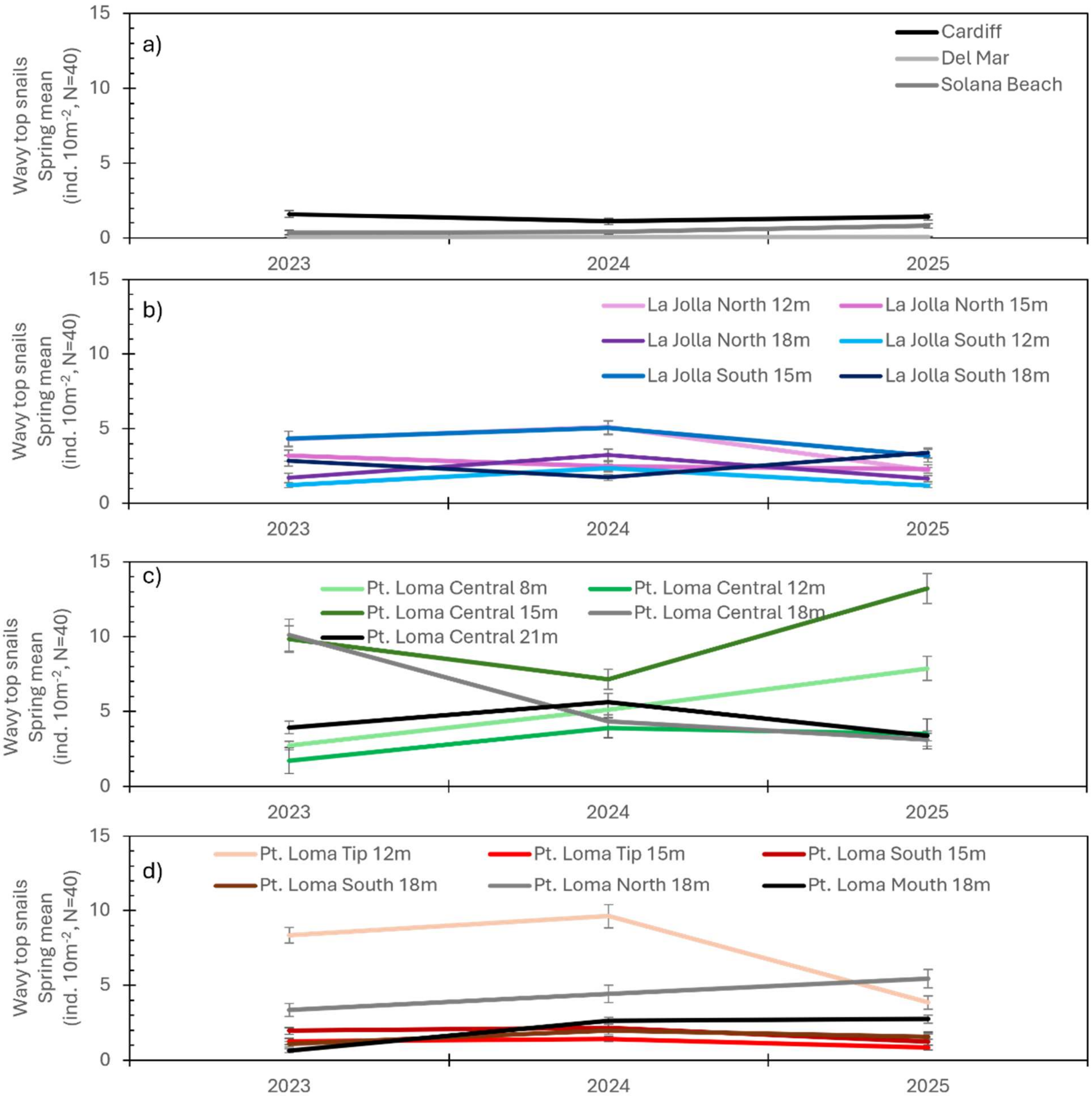


Figure 39: Zoom for reporting period (2023-2025) (note change of scale) of density of Wavy Top Snails (number of *Megastrea* spp. individuals); seasonal means from quarterly monitoring of 40 quadrants of 5 x 2 m^2 each, at, a) North County sites, b) La Jolla sites, c) Point Loma Central long-term sites, and d) Point Loma additional sites. Error bars show standard error of the mean.

CONCLUSION

The results shown in this biennial report (spring 2023 to fall 2025) of the City of San Diego's kelp forest monitoring program designed to evaluate anthropogenic impacts on the kelp forests in San Diego County, support the conclusion that the San Diego region giant kelp forests have demonstrated recent recruitment and growth at some of the monitoring sites with some recovery of density. Spatial variability was evident, recovery did not reach historical maxima, and some populations continue to show reduced persistence. In general, for much of the recent reporting period, the San Diego kelp forests appear to have benefited from cooler nutrient-rich waters and higher light exposure, supporting reproduction and growth, as well as reduced wave and herbivory disturbance reducing mortality. Overall, the results continue to show highest kelp growth and resilience at Point Loma relative to the rest of the San Diego region. As in past sampling and monitoring periods, the relative persistence of the kelp forest at Point Loma when compared with other sites along the coast, continues to suggest that point source impacts of the Point Loma outfall are not controlling kelp population fluctuations. Other factors most likely influencing kelp abundance in the San Diego area are sea water temperatures and temperature fluctuations, oceanic nutrient availability, light, especially for early life stage kelps, and benthic competition for space. This report documents spatially variable episodic kelp recruitment, with increasing abundance and plant growth at numerous sites in the monitoring program. It remains to be seen how the recently recovered populations will fare considering the potential for a significant El Niño event predicted by NOAA for late 2026-2027, which for the San Diego region could result in widespread warmer, nutrient-poor waters, with increased subtropical hurricane wave impacts.

CITED LITERATURE

Dayton, P. K., & 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., & Tresca, D. V. (1984). Patch dynamics and stability of some California kelp communities. Ecological Monographs, 54(3), 253-289.

Dayton, P. K., Tegner, M. J., Parnell, P. E., & Edwards, P. B. (1992). Temporal and spatial patterns of disturbance and recovery in a kelp forest community. Ecological Monographs, 62(3), 421-445.

Dayton, P. K., Tegner, M. J., Edwards, P. B. & Riser, K. L. (1999). Temporal and spatial scales of kelp demography: the role of oceanographic climate. Ecological Monographs, (69), 219-250.

Dean, T. A., & Jacobsen, F. R. (1984). Growth of juvenile *Macrocystis pyrifera* (Laminariales) in relation to environmental factors. Marine Biology, 83(3), 301-311.

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

Deysher, L. E., & Dean, T. A. (1984). Critical irradiance levels and the interactive effects of quantum irradiance and dose on gametogenesis in the giant kelp *Macrocystis pyrifera*. Journal of Phycology, 20(4), 520-524.

Jackson, G., & Winant, C. (1983) Effect of a kelp forest on coastal currents. Continental Shelf Research, 2(1), 75-80.

Ladah, L. B. (2003). The shoaling of nutrient-enriched subsurface waters as a mechanism to sustain primary productivity off Central Baja California during El Niño winters. Journal of Marine Systems 42, 145-152.

Leichter, J. J., Ladah, L. B., Parnell, P. E., Stokes, M. D., Costa, M., & Dayton, P. K. (2023). Alongshore variation in nutrient exposure associated with thermal variability and internal waves in southern California Giant Kelp beds. Frontiers in Marine Research. 10,1007789.

Lüning, K., & Dring, M. J. (1975). Reproduction, growth and photosynthesis of gametophytes of *Laminaria saccharina* grown in blue and red light. Marine Biology, 29(3), 195-200.

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

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.

Parnell, P. E., Cody, C. E. L., Ladah, L. B, Riser, K. L., Bulach B., Leichter, J. J., Latker, A. K., Schroeter S. C., & Dayton, P. K. (2026). Demography and dynamics of Giant Kelp Cohorts across four decades: Lessons for conservation and resilience planning. Ecological Applications 36(1): e70181.

Seymour, R. J., Tegner, M. J., Dayton, P. K., & Parnell, P. E. (1989). Storm wave induced mortality of giant kelp, *Macrocystis pyrifera*, 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., & Tegner, M. J. (2002). Kelp forest ecosystems: biodiversity, stability, resilience and future. Environmental Conservation, 29(4), 436-459.

Tegner, M. J., & Dayton, P. K. (1977). Sea urchin recruitment patterns and implications of commercial fishing. Science, 196(4287), 324-6.

Zimmerman, R. C., & Robertson, D. L. (1985) Effects of El Niño on local hydrography and growth of the giant kelp, *Macrocystis pyrifera*, at Santa Catalina Island, California, Limnology and Oceanography, 30(6), 1298-1302.