South Coast Baseline MPA Report

Final report

Baseline characterization of California spiny lobster (*Panulirus interruptus*) in South Coast marine protected areas

Prepared for California Sea Grant
January 2015

Kevin A. Hovel, San Diego State University

Douglas J. Neilson, California Department of Fish and Wildlife

Ed Parnell, Scripps Institution of Oceanography

Travis Buck, CDFW

Derek Stein, CDFW

Baseline characterization of California spiny lobster (*Panulirus interruptus*) in South Coast marine protected areas

A report to California Sea Grant and the California Ocean Science Trust

January 30, 2015

Kevin A. Hovel
Department of Biology, San Diego State University
5500 Campanile Drive
San Diego, CA 92182

Douglas J. Neilson
California Department of Fish and Wildlife
3883 Ruffin Rd
San Diego, CA 92123

Ed Parnell
Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive, Mail Code 0227
La Jolla, CA 92093-0227

Table of contents

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

In 1999, the California Legislature passed the Marine Life Protection Act (MLPA), which directed the state to establish a network of marine protected areas (MPAs) along California's coastline. As part of this legislation, monitoring of MPAs is required to evaluate whether they are achieving the goals set out by the MLPA and to support adaptive management in the future. The South Coast Lobster Research Group (SCLRG) was formed in 2011 in response to interest in how MPAs may affect the abundance, size, and behavior of the California spiny lobster (*Panulirus interruptus*). The California spiny lobster is one of the State's most economically important organisms that supports large commercial and recreational fisheries, has non-consumptive value for recreational divers, and plays an important role in the ecology and stability of coastal ecosystems. The SCLRG is a partnership between scientists, managers, stakeholders, and volunteers, and encompasses personnel from a diverse set of institutions: the San Diego Oceans Foundation (SDOF), San Diego State University (SDSU), Scripps Institution of Oceanography (SIO), the California Department of Fish and Wildlife (CDFW), and the California Lobster Trap Fishermen's Association (CLTFA). Our team initiated lobster monitoring in five South Coast MPAs and addressed the following goals:

1. Form a collegial group of researchers and volunteers representing different perspectives and walks-of-life to successfully evaluate the status of lobsters in and around South Coast MPAs;
2. Estimate spiny lobster abundance, size-frequency distribution, growth, spillover, and mortality through the implementation of a tag-recapture program;
3. Establish baseline estimates of lobster density and behavior through SCUBA-based surveys;
4. Map benthic substrata to link lobster abundance to benthic habitat composition and distribution across a range of spatial scales; and,
5. Determine whether MPAs cause short-term changes in lobster CPUE, and the amount and distribution of lobster fishing effort.

To address **goals 1 and 2**, in 2011 the project leaders teamed with lobster fishermen from the San Diego, Laguna Beach, and Palos Verdes areas to form a tag-recapture program using commercial fishing vessels as research platforms. We also teamed with the San Diego Oceans Foundation, a 501(c)3 nonprofit organization dedicated to educating community members about local marine organisms and the habitats upon which they depend. The San Diego Oceans Foundation relies on thousands of active volunteers to implement a variety of environmental projects, and their role in our monitoring research was to organize and train volunteers to help collect data by accompanying researchers and fishermen on commercial lobster vessels, as well as to disseminate the results to the public. Our team identified five sites at which to work, each with a newly established MPA; these were (1) the Cabrillo SMR in San Diego, (2) the South La Jolla SMR in La Jolla, (3) Swami's SMCA in Encinitas, (4) the Laguna Beach SMR in Laguna Beach, and (5) the Pt. Vicente SMCA in Palos Verdes. Together, we captured and tagged over 19,000 lobsters in and around the MPAs at each site between 2011 – 2013. To compare lobster abundance inside vs. outside of each MPA, traps were fished at discrete, preselected sites inside and outside MPA boundaries. All captured lobsters over 55 mm carapace length (CL) were tagged with individually numbered plastic "t-bar" tags, and were measured (CL), sexed, and scored for reproductive condition and shell condition (hardness and age of the carapace). Trap positions (GPS) were recorded in order to measure distance moved for recaptured lobsters.

From the tag-recapture study, we found that:

1. There are clear gradients in lobster abundance and size from south to north, but at each site there was little difference inside vs. outside the MPA (**Figure 1**). Lobster CPUE was substantially higher to the south in the two San Diego MPAs (Cabrillo SMR and South La Jolla SMR) than in Swami's SMCA, Laguna Beach SMR, and Palos Verdes SMCA.

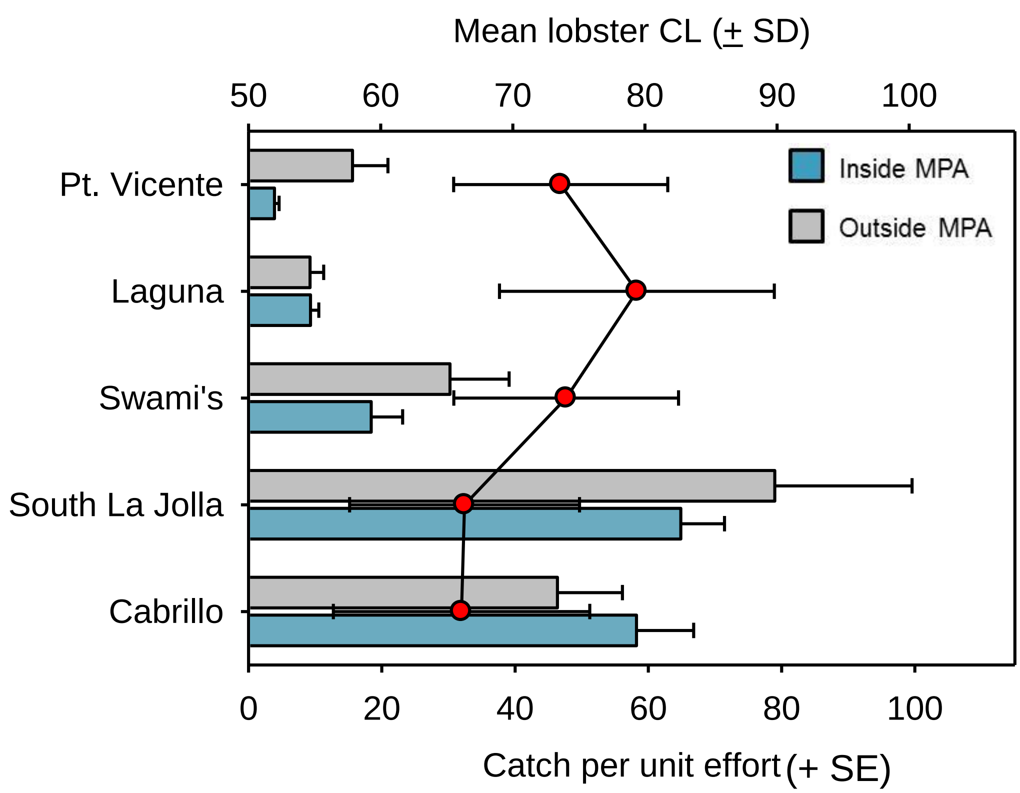


Figure 1. Mean lobster catch-per-unit-effort (CPUE, no. lobsters per trap pull per day) inside and outside of 5 south coast MPAs (bars), and mean lobster carapace length (CL) inside of 5 MPAs (red circles). MPAs are ordered from south (bottom) to north (top). Lobster CPUE was significantly higher at Cabrillo and South La Jolla than at the other three sites, but did not differ significantly between inside and outside MPAs at any of the five sites.

2. Lobsters generally are more abundant, but smaller on average, in southern sites compared to northern sites. Mean and median lobster size were smallest in the two San Diego MPAs, were largest in Laguna Beach, and intermediate at Swami's and Pt. Vicente (**Figure 1**).

3. Lobsters at or above the minimum legal CL were rare at all MPAs, except for Laguna Beach, where they composed nearly 50% of the catch. The two most southern sites in San Diego (Cabrillo and South La Jolla) had truncated length-frequency distributions compared to Laguna, which had a wider range of lobster sizes, and a larger proportion of large lobsters (**Figure 2**). Swami's and Pt. Vicente were intermediate to these extremes. Generally, lobster length-frequency distributions were slightly wider inside vs. outside of MPAs, which was caused by moderately higher frequencies of large lobsters inside vs. outside of MPAs.

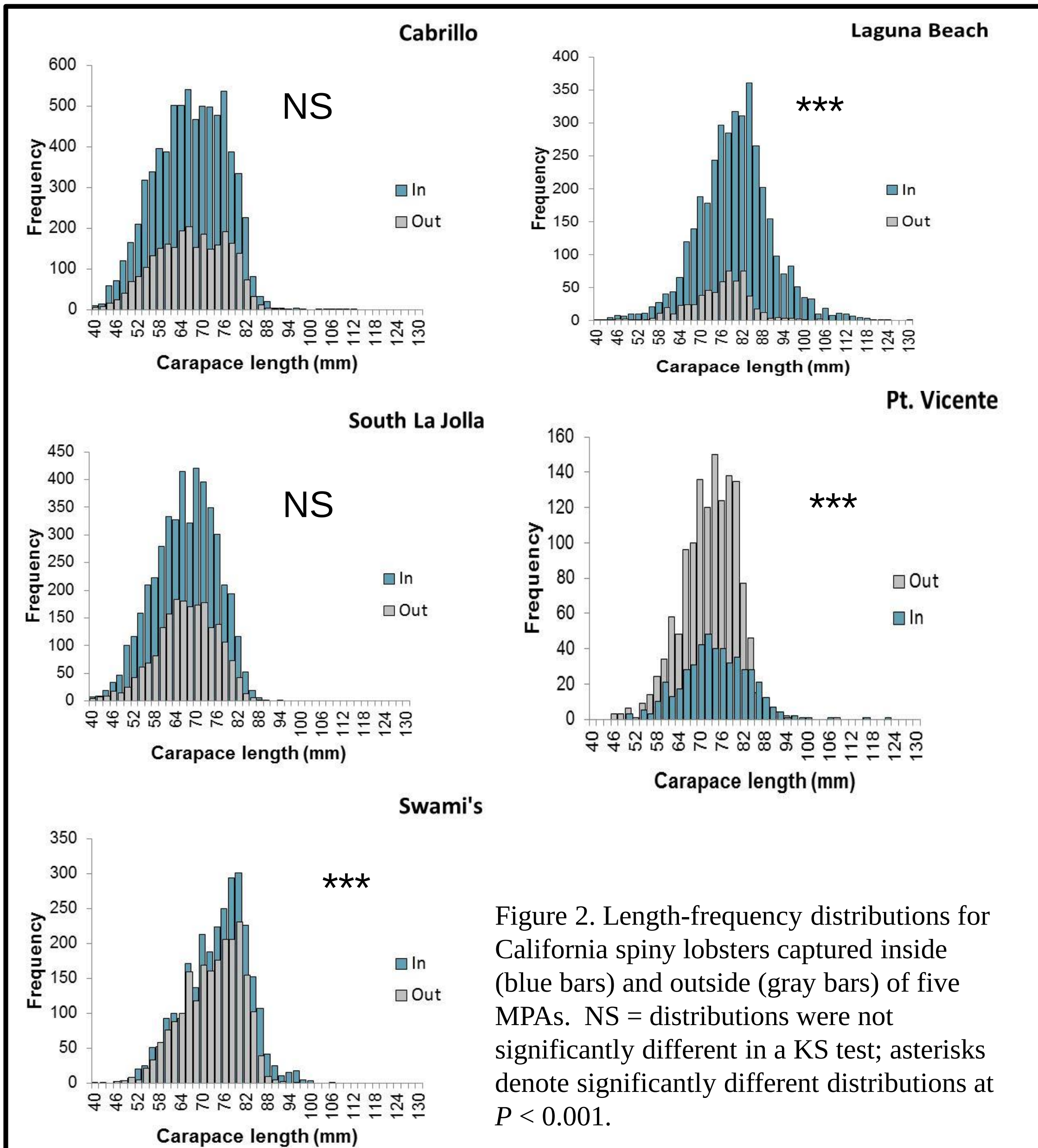


Figure 2. Length-frequency distributions for California spiny lobsters captured inside (blue bars) and outside (gray bars) of five MPAs. NS = distributions were not significantly different in a KS test; asterisks denote significantly different distributions at $P < 0.001$.

4. Lobster growth rates were similar among the five sites, except for Laguna Beach where growth rates were substantially higher than in all other sites (**Figure 3**). Lobsters grew an average of about 3.22 mm per year. Males grew slightly faster than females at Laguna Beach

and Swami's, but not at Cabrillo and South La Jolla. There was no difference in growth rates between lobsters tagged in 2011 vs. 2012.

5. Very few lobsters moved across MPA boundaries. Between 0 and 5% of recaptured, tagged lobsters had spilled over MPA boundaries, or had spilled in to MPAs from outside. This was true even at the smallest MPA, the Cabrillo SMR.

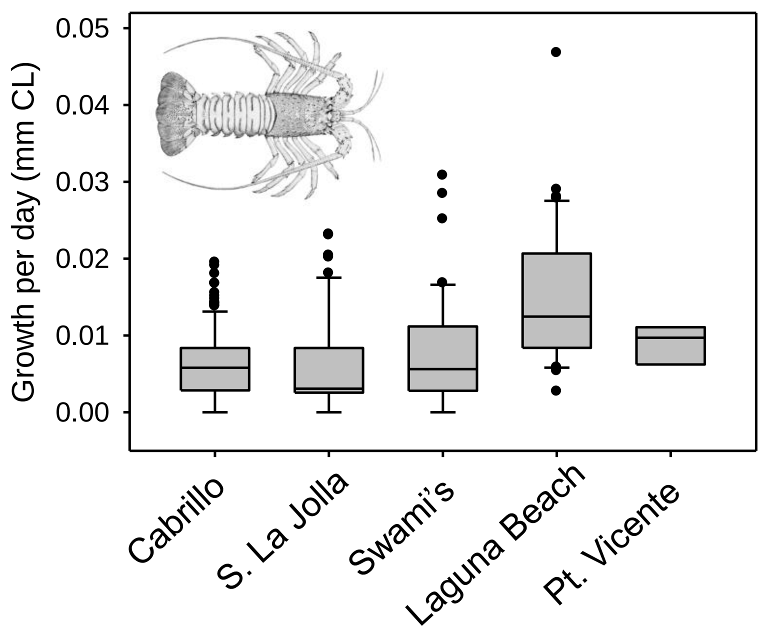


Figure 3. Growth rates of California spiny lobsters captured inside and outside of 5 South Coast MPAs. The boundary of the box closest to zero indicates the 25th percentile, a line within the box marks the median, and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers (error bars) above and below the box indicate the 90th and 10th percentiles. Points above error bars are outliers. Note that only 12 lobsters were recaptured in Pt. Vicente.

To address **goals 3 and 4 (**baseline estimates of lobster density and behavior, and habitat mapping), we conducted SCUBA-based transect surveys in 4 of the 5 MPAs in 2012, and all 5 MPAs in 2013. Surveys took place inside and outside of each MPA. Surveys consisted of counting all lobsters encountered on transects and categorizing each lobster based on size, as well as quantifying bottom cover of macroalgae and geological features. We also quantified lobster shelter use behavior by recording the size of lobster aggregations and the type of shelters being occupied by lobsters. Habitat mapping took place in La Jolla and was performed with a narrow beam (2 degree) 200kHz sonar coupled to an RTK differential GPS. We combined data on benthic features from habitat mapping with results from past and present SCUBA surveys to create a predictive model for lobster distribution and habitat use.

In contrast to the trapping study, benthic surveys suggested that lobster densities differed inside vs. outside the MPA at Cabrillo SMR and Swami's SMCA, and that that there was only a weak trend for decreasing abundance from south to north (**Figure 4**). Lobster density was higher inside vs. outside the MPA at Cabrillo, and higher outside vs. inside the MPA at Swami's. Lobster densities outside the South La Jolla SMR were higher outside than inside the MPA, but not significantly so due to high variability in lobster density outside the MPA. We found no lobsters on our surveys at the Pt. Vicente SMCA.

Different trends for lobster abundance between trapping and benthic surveys can be attributed to the fact that these techniques measure lobster abundance in different ways. Traps capture lobsters moving out of shelters at night, and are a better measure of large-scale trends in abundance. Additionally, research traps more efficiently enumerated small lobsters that hide in deep crevices and are harder to detect on dive surveys. Because small lobsters were prevalent in southern sites (particularly at Cabrillo where extensive surfgrass beds likely provide nursery habitat), dive surveys did not detect a strong trend in lobster abundance from south to north that occurs when juvenile lobsters are included in population estimates. However, dive surveys better captured differences in lobster density inside vs. outside MPAs, because these differences likely can be attributed to distribution of lobster habitat. For instance, at Cabrillo, a mixture of shallow rocky habitat and surfgrass is prevalent inside the MPA, resulting in a higher density of lobsters inside vs. outside the MPA. Additionally, trapping was conducted in the proximity of MPA boundaries to monitor for spillover, whereas dive surveys were distributed more widely within and outside of MPAs.

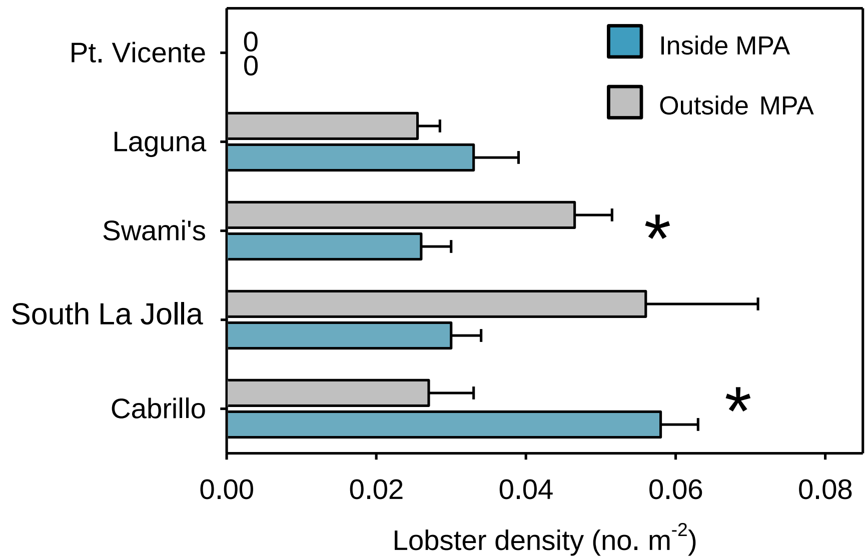


Figure 4. Mean lobster density (+ SE) inside and outside of the 5 MPAs as measured using SCUBA-based transect surveys. MPAs are ordered from south (bottom) to north (top). No lobsters were found in Pt. Vicente. Asterisks denote significant differences in density inside vs. outside MPAs.

Benthic surveys revealed different habitat associations for lobsters among the four MPAs in which we found lobsters. At the Cabrillo SMR and the South La Jolla SMR, the odds of finding lobsters were higher on reefs with low cover of large kelps (giant kelp *Macrocystis pyrifera* and feather boa kelp *Eisenia arboria*). In contrast, the odds of finding lobsters increased with kelp cover at the Laguna Beach SMR, though the association was weaker. At Swami's SMCA, greater amounts of low-relief flat rock and red algae increased the odds of finding lobsters. *A key result of benthic surveys is that no single variable or combination of variables reliably predicted the odds of finding lobsters across the entire study region*.

Benthic habitat mapping revealed that the shelf supporting the La Jolla kelp forest is composed of two large ridges oriented cross-shore, bisected by a drainage valley in the middle portion of the forest. The ridges exhibit complex bedding and compressional fracturing at multiple angles and scales that present spiny lobster with an abundance of shelter habitat. The best predictors of lobster density included bottom curvature features at the 10 and 50 m scales and bottom depth. The predictive model (**Figure 5**) exhibited strong depth dependence with the greatest predicted lobster densities in shallow water, and a steep decline in lobster abundance between 12 and 18 meters depth, despite abundant and adequate rocky habitat at these depths. This indicates that the deeper habitats are underutilized by spiny lobsters despite the greater fishing effort targeting the shallower portions of the shelf. Thus, while spiny lobsters are observed at deeper depths off southern California, their occupancy of similarly-structured bottom habitats at the deeper depths of the acoustic study (35 m) is depth limited. This strongly suggests that bottom structure as a factor for lobster occupancy is subsumed by other factors at depths > ~20 m, or that bottom structure interacts differently with other such factors at different depths. These factors include but are not limited to the provision of food, temperature, differential lobster predator densities with depth, and differential depth distributions of potential biogenic shelters such as algae or surfgrass. It should be noted that human exploitation effort, perhaps the greatest source of adult spiny lobster mortality, is focused in relatively shallow water yet the shallow distribution of spiny lobster

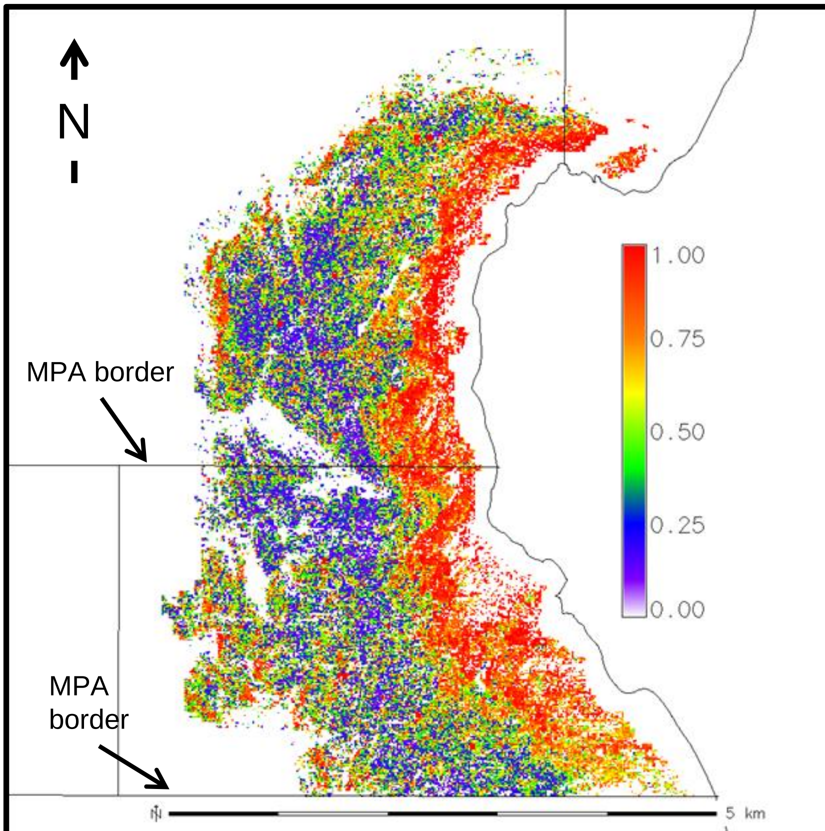


Figure 5. Spatial distribution of relative expected spiny lobster density as a function of bottom terrain features. Predictions were based on a random forest analysis of acoustically-derived terrain features and depth with intensive in situ estimates of lobster density derived from in situ SCUBA-based band transect surveys. Red areas indicate maximum abundance, and purple areas indicate minimal abundance. The northern and southern borders of the South La Jolla SMR are shown.

persists indicating that at least one these other factors is apparently very important relative to bottom structure.

To address **goal 5** (short-term changes in lobster CPUE, and the amount and distribution of lobster fishing effort), we used current and historical data held by the CDFW to quantify the number of commercial fishermen engaged in lobster fishing before and after MPA establishment, as well as their effort and catch. We found that commercial lobster fishermen remained in their usual locations until they were forced to relocate their effort when MPAs were implemented on January 1, 2012. CPUE dropped only slightly in all MPAs except Swami's SMCA, where CPUE dropped more substantially. Fishing effort and catch changed very little in the two San Diego area MPAs (Cabrillo SMR and the South La Jolla SMR), where fishermen were able to fish in waters adjacent to the new closures. In contrast, the distribution of fishing effort changed substantially in the Pt. Vicente SMCA and Laguna Beach SMR, where the newly closed areas took up much of the former fishing block and fishermen were displaced to adjacent blocks. Nonetheless, the total catch and CPUE did not substantially change. Overall, fishermen adapted to the presence of the MPAs and, where possible, moved to adjacent fishing grounds. On a bight-wide scale, the MPAs did not appear to impact the level of catch, and while some fishermen may have been impacted, the level of catch and effort does not appear to be significantly different than in previous seasons. In 2010, 939,485 traps were pulled and 450,549 lobsters landed (landed CPUE of 0.48). In 2012, effort increased to 1,131,700 traps pulled, but landings increased as well to 565,118 lobsters (for a slightly increased CPUE of 0.50).

INTRODUCTION

The California spiny lobster (*Panulirus interruptus*) is an abundant, large-bodied fishery species inhabiting the coastal waters of Southern California USA and Baja California Mexico. California spiny lobsters are one of the more conspicuous members of kelp forest, rocky intertidal, and estuarine ecosystems, where they are widely considered to play important ecological roles as predators and prey. As predators, California spiny lobsters affect the ecosystems in which they live by preying upon key species that play large roles in their communities (e.g., mussels that are dominant competitors for space in intertidal zones: Robles et al. 1990). Lobsters are prey for large fishes and marine mammals, and therefore form a link between benthic invertebrates and large roaming predators in coastal waters. California spiny lobsters are heavily fished in both the US and Mexico, and have supported a commercial fishery in Southern California since 1872 (**Figure 6**). Statewide for the last 10 years, the commercial fishery has been consistently harvesting 600,000 pounds each season (which runs early October to March), with 80% of the season total landed before the end of January (and usually by the end of December). The commercial fishery in the US centers on San Diego County, where commercial lobster landings average approximately 250,000 pounds per season with a subsequent value of ca. $2.5 million, accounting for approximately 34% of the total state landings (CDFW fishery data). The historical trends for lobster landings depict a fishery that has fluctuated significantly but today is considered to be stable.

There is substantial interest in determining whether California's newly implemented South Coast MPAs will impact spiny lobster populations. In addition to the economic and ecological importance of California spiny lobsters, there are building uncertainties to suggest that the fishery is operating close to MSY and that catch may not be stable for the long term. First, a recent increase in effort (number of traps being fished) has not resulted in a matching increase in catch. Second, the recreational fishery has changed virtually overnight

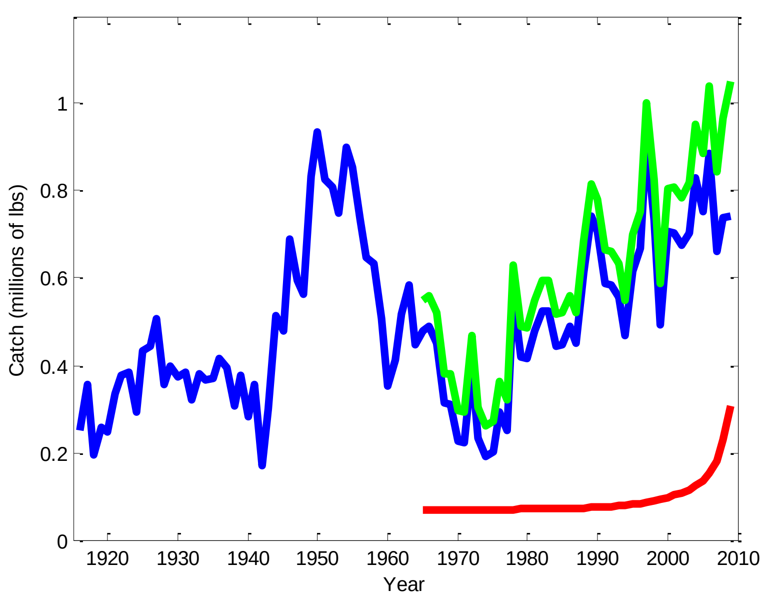


Figure 6. California statewide spiny lobster catch (millions of lbs) for the last 100 years in the commercial fishery (blue), the recreational fishery (red), and for the two fisheries combined (green). Source: California Dept. of Fish and Wildlife.

with the introduction and popularization of hoop nets. Preliminary data suggest that the take is substantial, adding the equivalent of another 30% to 60% to the commercial harvest (**Figure 6**). Thus, a major uncertainty in California spiny lobster fishing is whether the current amount of harvest pushes the total combined (commercial and recreational) fishery over MSY. Recruitment estimates based on depletion models suggest that the amount of lobster recruitment needed to achieve seasonal catch totals in recent years is increasing when recreational catch is included, but stable or declining when considering only commercial catch. Moreover, since most published studies of the South Coast region's lobster population occurred prior to the current stable period beginning in 2000, comparisons today are made with baselines that themselves have shifted substantially.

Though California's network of MPAs was not designed specifically to protect spiny lobsters, one of their potential benefits is enhanced abundance and size of this heavily harvested species. MPAs have been used in many places throughout the world to enhance spiny lobster populations and to maintain fisheries via the creation of source populations and spillover, and results from other locations indicate that spiny lobster populations can respond relatively quickly to protection within MPAs, and enhance fisheries in nearby waters (e.g., Kelly and MacDiarmid 2003, Goñi et al. 2006). However, spiny lobsters have very long larval durations, small home ranges, and strong dependence on benthic habitat, which creates uncertainty regarding the degree to which an MPA, or network of MPAs may result in larger lobster populations, particularly at regional spatial scales.

Our goal in this project was to support California's need to evaluate the effect of MPAs on spiny lobsters by providing baseline information on lobster abundance, size distribution, growth, and behavior inside and outside of several South Coast MPAs. To do this we formed the South Coast Lobster Research Group (SCLRG) and initiated three forms of lobster baseline monitoring: (1) boat-based tag-recapture, (2) SCUBA-based surveys accompanied by benthic habitat mapping, and (3) evaluations of short-term changes to the lobster fishery. The SCLRG is a partnership between scientists, managers, stakeholders, and volunteers, and encompasses personnel from a diverse set of institutions and walks-of-life. In addition to providing baseline information about California spiny lobsters, we set out to demonstrate the power of collaborative research involving people with diverse backgrounds but a common interest in effectively and accurately conveying the status of California spiny lobsters to the public. More information about our partnership can be found under "Research Partnerships" below.

Five sites were targeted for this study (**Figure 7**). From south to north, these were Cabrillo SMR ("Cabrillo"), South La Jolla SMR ("South La Jolla"), Swami's SMCA ("Swami's"), Laguna Beach SMR ("Laguna"), and Point Vicente SMCA ("Vicente"). At each site, data were collected inside and outside of MPA boundaries. We selected these sites for our project because the area in which they are contained generates a substantial fraction of statewide annual landings (in excess of 30%), and because historical baselines of fishing effort have been established for the most productive lobster fishing grounds in southern California (La Jolla and Pt. Loma). Thus, working in this region (both short-term and long-term) not only provides the most relevant information on the effects of MPA establishment on the lobster population, but also allowed us to examine short-term changes in lobster fishing resulting from MPAs. Additionally, because our group includes scientists who work in this region as well as stakeholders who fish in this region, we had detailed knowledge of our sites with which to direct and inform our monitoring and data analyses.

Below, we divide our methodology, results, and discussion into three sections: (1) spiny lobster tag-recapture program, (2) SCUBA-based lobster surveys and habitat mapping, and (3) analyses of short-term changes in lobster fishing. We also present (4) conclusions and recommendations, including information about our research partnerships and implications for long-term monitoring.

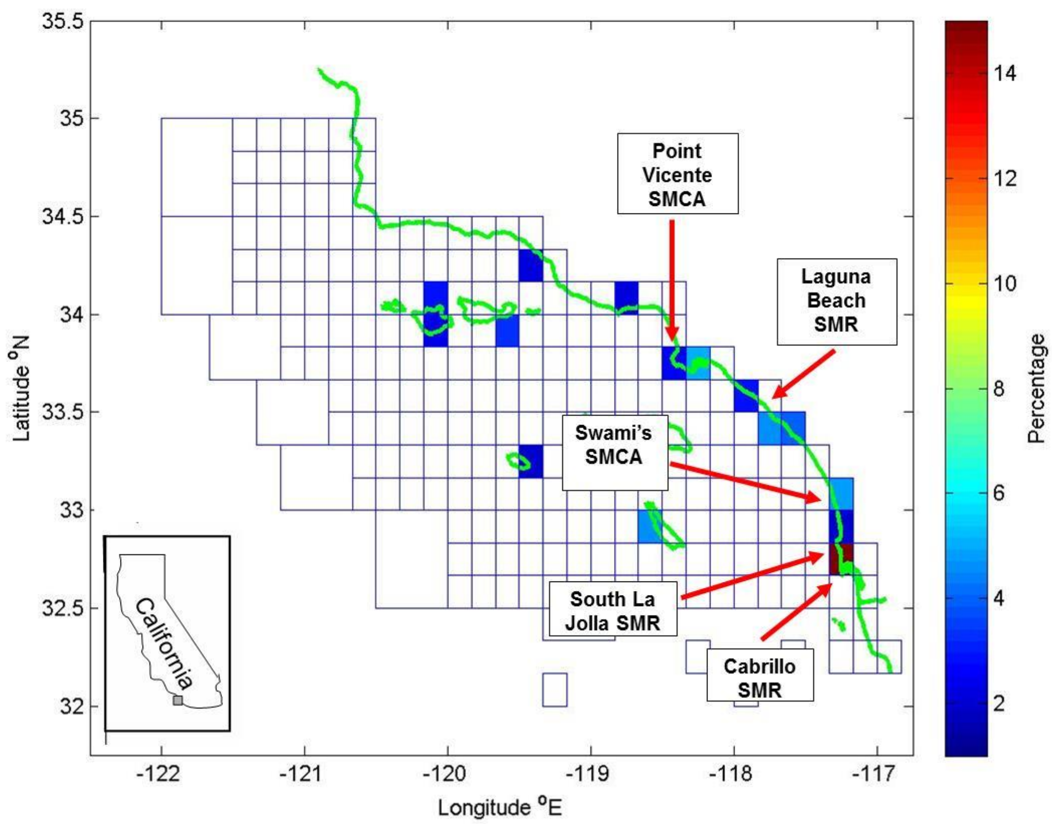


Figure 7. Location of the five sites monitored for California spiny lobsters, and statewide proportional lobster landings from nearby 10 x 10 mile CDFW blocks (colored boxes). Note the high percentage of lobsters extracted from the block that includes La Jolla and Point Loma.

California spiny lobster tag-recapture program

Introduction and Methods

Our tag-recapture program was designed to provide information on lobster population size, size distribution, growth rates, and movement for lobsters living inside and outside of each of the five MPAs (sites) involved in our project. Our basic methodology was to capture lobsters inside and outside of each MPA with customized research traps, tag lobsters with individually numbered plastic tags, and release lobsters at the point of capture. This process was repeated several times for each site over three seasons. Tagging allowed us to determine growth rates and if lobsters crossed MPA borders during their time-at-large. Trapping is widely used to estimate lobster abundance and size distribution because many more lobsters can be measured than those found on dive surveys. We accompanied our trapping data with dive surveys (see *lobster surveys* below) in order to estimate lobster density (number per unit area of bottom) and in order to evaluate habitat associations for lobsters, which cannot be done by trapping.

We trapped lobsters within and outside of each MPA using customized, wire mesh traps (hereafter "research traps"). Research traps were the same size as standard commercial lobster traps (28 x 36 x 16 inches) but with a smaller mesh size (1 x 1 inch PVC-coated steel mesh) and no escape ports (**Figure 8**). The traps had a 13 twist outside funnel and an 11 twist funnel between the outside and inside chambers. The purpose of using research traps for our study (as opposed to commercial traps) was to better characterize the size distribution of lobsters at each site. We felt it was important to characterize lobster size distribution and abundance for as much of the population as possible, but commercial traps are designed to retain lobsters at and above the minimum legal size (82.5 mm carapace length (CL)). Small lobsters frequently are captured in commercial traps, but likely are undersampled relative to larger lobsters. However, a concern of using small mesh traps is that they may undersample larger lobsters, which may avoid traps that retain many smaller lobsters. Therefore, to assess the range of lobster sizes captured in

Figure 8. Photos of a research trap (A), and standard commercial lobster trap (B).

research traps, and to compare these traps to the catch from commercial traps, we conducted a study over a 2 week period in San Diego in June, 2013. Paired sets of research and commercial traps, with traps in each pair separated by $\geq$ 300 m, were set in each of six zones within South La Jolla and fished for eight nights each (N = 1 trap per type * 2 types * 6 zones * 8 nights = 96 trap pulls). The results (**Figure 9**) show that research traps retained a larger proportion of small lobsters than did commercial traps, while retaining a similar proportion of large lobsters as commercial traps. Research traps caught a smaller number of lobsters per unit effort (an average of 54.5 ($\pm$ 16 SD) lobsters per trap-pull for research traps vs. and average of 66.3 ($\pm$ 14.3 SD) lobsters per trap-pull for commercial traps), but this difference was not significant (*t*-test: df = 14, t = 1.53, P = 0.14).

Trapping to evaluate lobster populations at all five sites took place in the summers of 2011, 2012, and 2013 (note that MPAs officially took effect in January 2012). Trapping in 2011 consisted of a pilot study at Cabrillo, South La Jolla, and Laguna designed to try out research traps and to standardize methodology among locations and personnel before our major tagging efforts in summer 2012 and 2013. We also wanted to have some tagged lobsters in the water before the 2011 commercial and recreational fishing season opened in October, so that we could develop and test our tagged lobster reporting program (see "Research Partnerships", below). Lobsters in the pilot study were tagged with green t-bar tags provided by the CDFW (Floy FD-94, ¾"

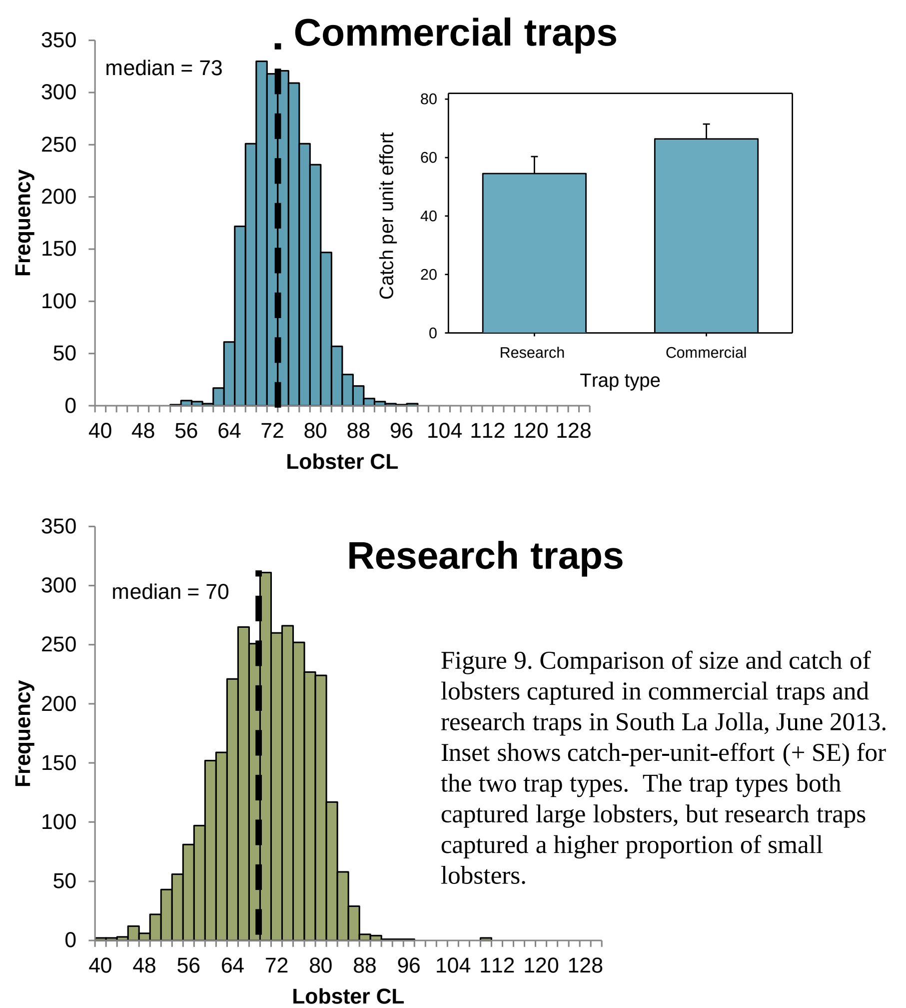


Figure 9. Comparison of size and catch of lobsters captured in commercial traps and research traps in South La Jolla, June 2013. Inset shows catch-per-unit-effort (+ SE) for the two trap types. The trap types both captured large lobsters, but research traps captured a higher proportion of small lobsters.

monofilament MED-T). Thereafter (2012 and 2013), lobsters were tagged with individually numbered, Floy FD-94, ¾" monofilament extra-long t-bar tags that were color coded based on whether lobsters were trapped inside or outside of MPAs (**Figure 10**). Each tag was printed with the tag number as well as the phone number and webpage address (of the San Diego Oceans Foundation) where recovered tags could be reported.

Figure 10. California spiny lobster tagged with a yellow t-bar tag.

Trapping was conducted once per month, typically over 2 consecutive days, inside and outside of the MPA at target sites (**Appendix A**). Not all sites were sampled in each month, and effort among sites was adjusted depending on how many lobsters had been caught and tagged at each site to date. For instance, in South La Jolla and Cabrillo, we had captured and tagged thousands of lobsters by the end of the 2012 season, and we therefore shifted our focus to Swami's for much of 2013 where our catch had been substantially lower to date (see **Appendix A**). This helped us boost the sample size for calculating CPUE as well as boost our lobster recapture rate. Each month's trapping required 3 field days to complete and used either 12 or 24 traps per site, and was conducted by one commercial fishermen accompanied by at least two project participants (usually, one project scientist and one or two volunteers). The traps were surface marked with floats and labels identifying them as research traps. The bait used was determined individually by fishermen based on their personal experience and no effort was made to standardize bait between sites. Traps were set on the first day and then allowed to soak overnight before pulling once per day for two consecutive days. In a few cases, because of low catch or inclement weather, traps were allowed to soak for two days between pulls. Traps were re-baited between pulls and removed from the water at the end of each 3 day sampling period. This resulted in 24 – 48 trap-pulls per site per month.

At each site, traps were concentrated along the northern or southern boundaries, and divided evenly between inside vs. outside locations. For instance, in the case of 12 traps, a set of three traps would be set both inside and outside the northern MPA boundary with a similar arrangement at the southern MPA boundary. We felt it was important to document movement out of an MPA into fishable waters, and since some of the targeted MPAs border on other MPAs that prohibit lobster fishing, trapping was moved to the closest MPA boundary on a fishable area. The exact placement for individual traps was determined by four commercial fishermen contracted for their expert knowledge on where to find lobster in and around these MPAs. In order to ensure that any lobster tagged inside an MPA but recaptured outside had actively moved towards and across the boundary, all inside traps were set no closer than 300 m to the boundary. Outside traps, however, could be set up against the boundary by the fishermen. If an MPA boundary was situated in an area dominated by poor lobster habitat (e.g., sand flats), traps along that boundary could be moved farther away or dispensed with entirely (in which case those traps would be moved to the other MPA boundary). Every effort, however, was made to maintain traps, both inside and out, within approximately 600 m of a boundary. Because of its small size, the 300 m inside buffer was not possible to adhere to at Cabrillo.

For each trap pulled, the date, time, GPS location, depth, and trap number were recorded. For all lobsters caught, the carapace length (CL) and tail width (TW) at the 2nd abdominal segment (the first with pleopods) were measured to the nearest millimeter, and the sex and reproductive condition recorded. Females were recorded as being plastered (i.e. a spermatophore was present), unplastered, or berried (= ovigerous). For plastered females, the color (white, gray, or black, with darker colors signifying more time since mating) was noted, as was the color of the eggs for berried females. For males and females, shell condition was classified as (i) old hard shell, (ii) old soft shell, (iii) new hard shell, or (iv) new soft shell. This was assessed by visually inspecting the carapace for the presence of fouling organisms (e.g. barnacles, algae) and pressing on the carapace to qualitatively assess hardness. If a lobster was previously tagged, the tag number also was recorded. Lobsters were tagged ventrally by inserting tags into the musculature between the first and second abdominal segments using a Floy MKII tagging gun. We did not tag any lobsters less than 55 mm CL due to the high chance of injury to small lobsters. Lobsters were immediately returned to the water after being tagged.

Approximately every 20th lobster was double tagged to test tag retention rates. In these cases, the lobster was tagged ventrally, as usual, and then tagged dorsally into the muscle between the carapace and abdomen just off the center line. We found that 23 out of 1104 double-tagged, recaptured lobsters lost one tag (ca. 2%). This nearly always was the dorsal tag (21 out of 23 cases). This retention rate is in close agreement to other studies on lobster tag retention, which suggest that retention rates are no less than 94% and are slightly higher for ventral tags than for dorsal tags.

From our trapping data, we calculated:

1. *Catch-per-unit-effort (CPUE) inside and outside of the MPA for each site*, calculated as the total number of lobsters captured per day divided by the number of traps fished. Data for this analysis were combined among years, to achieve an acceptable sample size for each site and because environmental conditions (particularly water temperature, which varied substantially among years) affects lobster catch. Therefore, any potential short-term changes in lobster CPUE after MPA establishment in January 2012 are confounded with a host of known and unknown factors. We used a two-way analysis of variance (ANOVA) to test for effects of site, inside vs. outside the MPA, and their interaction on CPUE. We used a separate two-way ANOVA to test for differences in CPUE between males and females at each site. Post-hoc

tests for differences among means were performed with Tukey's HSD test. Due to previous studies that suggested the possibility of low catch for female lobsters during spring compared to summer, we compared catch of male vs. female lobsters among months (May – September) in 2012, the year we had high trapping effort at each site throughout the season.

2. *Lobster size summaries*. We calculated summary statistics for lobster length (mean, median, range, and variance), and created length-frequency distributions for inside and outside of the MPA at each site. Differences in length-frequency distributions inside vs. outside of each MPA were evaluated with Kolmogorov-Smirnov (KS) tests.
3. *Growth rates.* We calculated lobster growth by subtracting the starting CL from the final CL for recaptured lobsters at each site, and then dividing this by days-at-large (the number of days between initial capture and recapture). Lobsters that were recaptured within the same fishing season were not included in growth calculations. We compared mean growth rates among sites with a two-way ANOVA followed by a Tukey's HSD test.
4. *Displacement.* We calculated the straight-line distance between capture and recapture locations for all lobsters at large for at least 30 d. We also calculated the proportion of lobsters tagged at each site that crossed a boundary, whether moving from inside the MPA to outside (spillover), or outside the MPA to inside (spill-in).
5. *Reproductive condition*. For each site in each month, we summarized the proportion of female lobsters that were unplastered (had no spermatophore), plastered (had a spermatophore), and ovigerous ("berried", i.e., were carrying eggs on the abdomen).

Results and discussion

1. CPUE. We captured a total of 19,861 lobsters over the course of the study (**Table 1**), and tagged a total of 17,762 lobsters (3 – 16% of captured lobsters were too small to tag at each site). Spiny lobster CPUE varied among sites, but not between inside vs. outside

Table 1. Summary of lobsters captured in research traps at each site, combining the catch from all years.

MPA	**Total captured**	**Males captured**	**Females captured**	**M/F ratio**	**Total tagged**	**Percent tagged**	**Percent recaptured**
Cabrillo	7,652	3,979	3,672	52/48	6,412	84	2.7
South La Jolla	6,479	2,759	3,719	43/57	5,799	90	5.4
Swami's	2,986	1,389	1,596	47/53	2,896	97	7.1
Laguna	1,928	1,109	819	58/42	1,868	97	3.2
Vicente	816	319	497	39/61	787	96	1.3
TOTAL	**19,858**	**9,555**	**10,303**		**17,762**		

MPAs, and there was no interactive effect of site and inside/outside the MPA on CPUE (**Figure 11**, **Table 2**). Spiny lobster CPUE was significantly higher in Cabrillo and South La Jolla (the southern, San Diego MPAs) than in Swami's, Laguna, and Vicente. Differences between inside vs. outside MPAs were slight at each site, except for Vicente where CPUE was three times higher outside vs. inside the MPA (albeit with overall low lobster abundance).

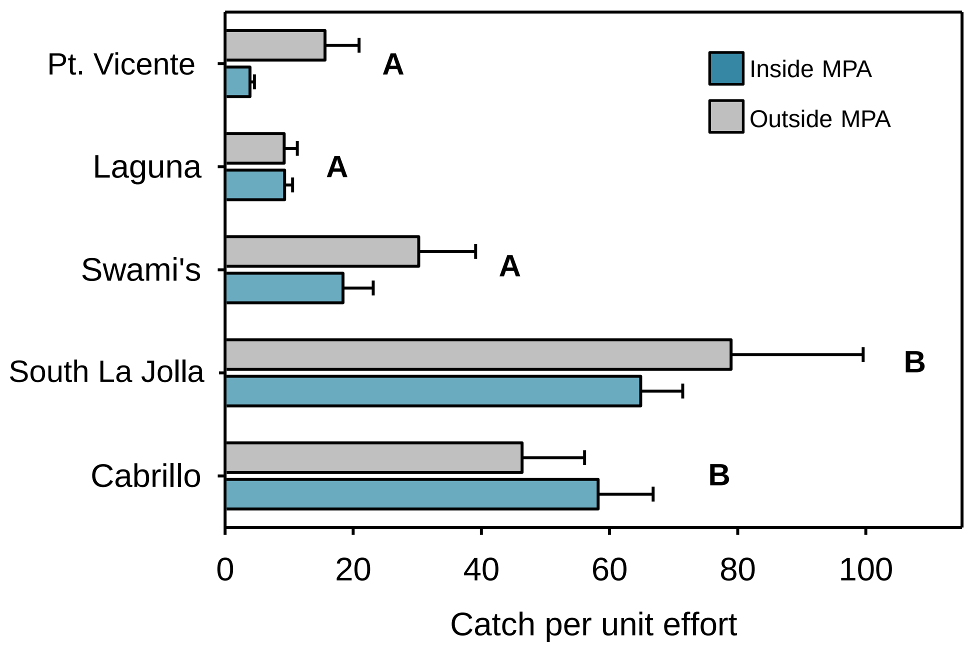


Figure 11. Catch-per-unit-effort (CPUE + 1 SE, in number of lobsters per trap pull per day) inside and outside of the five sites. Unlike letters next to bars indicate that Cabrillo and South La Jolla had significantly higher CPUE than the other sites. There was no difference in CPUE inside vs. outside the MPA at any site.

Table 2. Analysis of variance (ANOVA) results for catch-per-unit-effort, testing for effects of (A) site and location (inside vs. outside), and (B) site and sex. Data for (B) were log transformed.

A.

Source	**df**	**MS**	**F**	**P**
Site	4	14050	27.8	<0.001
Location	1	595	1.18	0.28
Site*Location	4	614	1.2	0.31
Residual	96	504		

B.

Source	**df**	**MS**	**F**	**P**
Site	4	7.4	28.4	<0.001
Sex	1	0.07	0.27	0.61
Site*Sex	4	0.35	1.3	0.25
Residual	202	0.26		

There were no differences in CPUE for males vs. females among sites, though there was a trend for higher catch of females vs. males at South La Jolla. At each site except Laguna, there was a general pattern for males to be proportionally more abundant in traps than females in May or June, in contrast to July – September when females often were as abundant or more abundant than were males (**Figure 12**). This likely is a product of the reproductive cycle. Females generally are egg-bearing in spring, and remain in shallow protective habitats like surfgrass beds until they release larvae in May or June, at which point they become more active. This pattern also was seen in a trapping study in San Diego Bay (Hovel and Neilson 2011) and reported for the Santa Catalina spiny lobster population by Lindberg (1955).

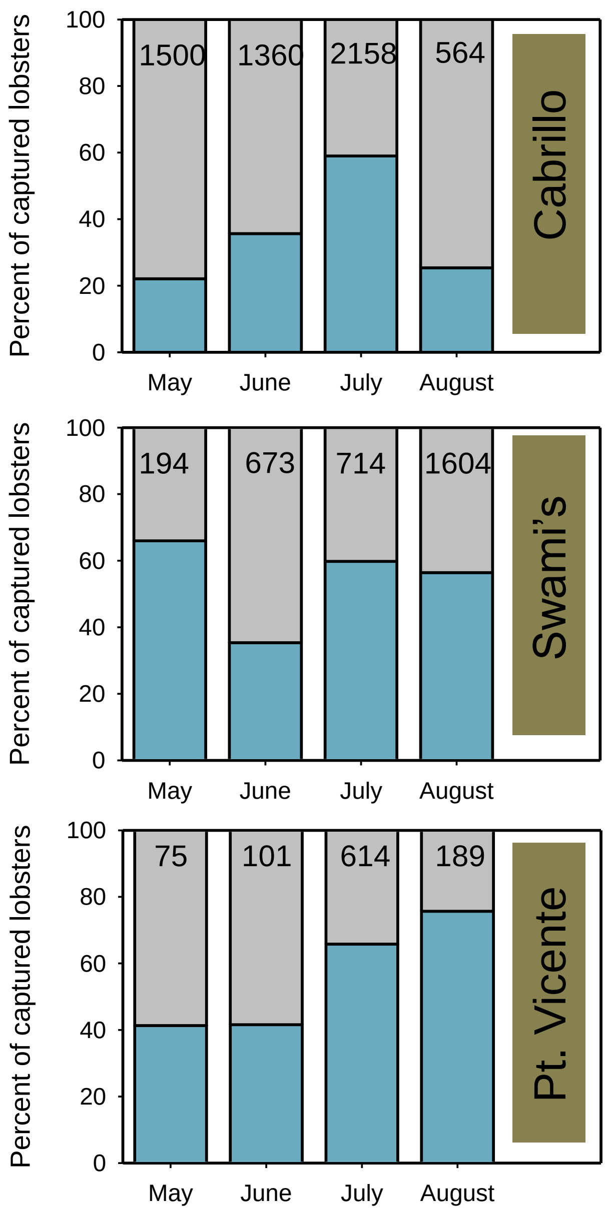


Figure 12. Proportion of the catch from each site composed of females (blue) and males (gray) in each month during 2012. Note that trapping in Laguna Beach was delayed one month. Numbers in bars indicate the total number of lobsters trapped each month at each site. Data includes lobsters trapped both inside and outside of MPAs.

2. Lobster size summaries. Summary statistics for lobster carapace length (CL) from each site are shown in **Table 3**, and frequency distributions for each site are shown in **Figure 13**.

Table 3. Summary for spiny lobster sizes for each site, inside vs. outside MPAs. Sizes are expressed at mm carapace length (CL). "Shorts" refers to lobsters < 82.5 mm CL, the minimum legal size for the fishery. "Combined" = all MPAs combined.

Site	Inside/outside MPA	Mean CL ± SD	Median CL	Minimum CL	Maximum CL	Percent shorts
Cabrillo	Inside	66.1 (9.7)	66	36	112	97.9
Cabrillo	Outside	66.1 (9.7)	66	36	104	97.9
South La Jolla	Inside	66.3 (8.9)	67	33	93	99.6
South La Jolla	Outside	66.4 (8.5)	67	37	87	98.9
Swami's	Inside	74.0 (8.8)	75	38	105	96.2
Swami's	Outside	72.1 (8.0)	73	42	95	92.6
Laguna	Inside	79.4 (10.5)	80	40	123	62.0
Laguna	Outside	74.9 (8.9)	76	39	134	52.5
Vicente	Inside	73.6 (9.4)	73	50	122	83.2
Vicente	Outside	72.2 (7.6)	73	46	115	93.8
Combined	Inside	70.1 (10.3)	71	36	123	88.9
Combined	Outside	69.2 (9.3)	70	36	134	95.5

Generally, mean and median lobster size increased from south to north, with the two most southern sites in San Diego (Cabrillo and South La Jolla) having truncated length-frequency distributions compared to Laguna, which had a wider range of lobster sizes, and a larger proportion of large lobsters. Swami's and Vicente were intermediate to these extremes. Cabrillo and South La Jolla had the smallest mean and median lobster size, and a distribution skewed toward smaller lobsters, with only 2 and 1.5% of trapped lobsters being above legal size, respectively (**Figure 14**). In contrast, nearly half of lobsters trapped in Laguna, both inside and outside of the MPA, were at or above the minimum legal size for the fishery.

Overall, lobster length-frequency distributions were slightly wider inside vs. outside of MPAs (**Figure 15**). KS tests revealed significant differences in lobster size-frequency distributions between locations at Swami's, Laguna, and Vicente, but not at the southern sites, Cabrillo and South La Jolla. Differences in length-frequency distributions at Swami's, Laguna, and Vicente were caused by higher frequencies of large lobsters (i.e., a larger right-hand tail to the distribution) inside vs. outside of MPAs, though the differences between inside vs. outside were not extreme, except at Laguna. Long-established MPAs generally house larger lobsters than do fished areas outside of MPAs; for example, at the Channel Islands, Kay et al. (2012)

found that legal sized lobsters inside six-year-old MPAs were 5 – 10% larger than lobsters in nearby fished waters. Iacchei et al. (2005) reported that legal-sized California spiny lobsters were 8% larger inside a 25 year old MPA than in a commercially fished area at Santa Catalina Island. Future monitoring may find differences in lobster sizes between locations at Cabrillo and South La Jolla, and increased differences between locations at Swami's, Laguna, and Vicente.

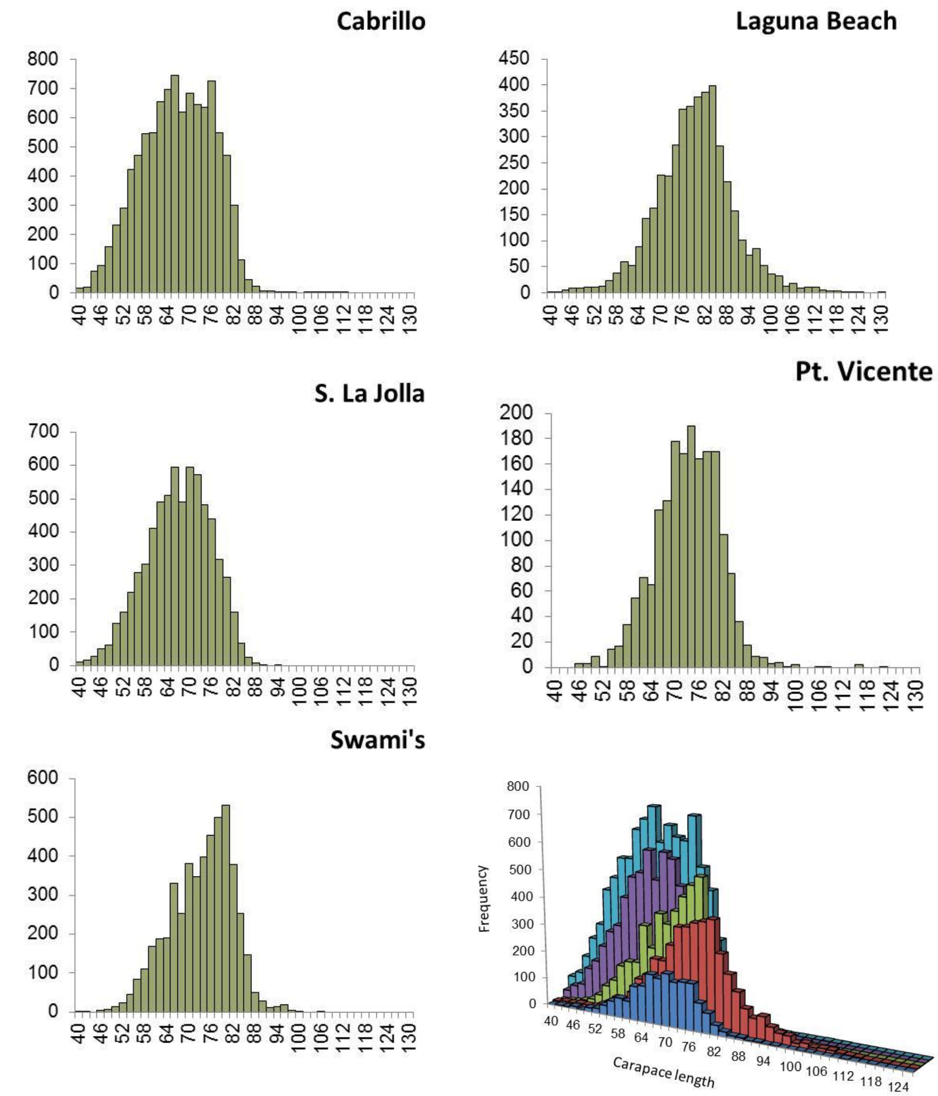


Figure 13. Length-frequency histograms for California spiny lobsters captured at five south coast sites. X axis = lobster carapace length (mm) and Y axis = frequency. Data were combined for lobsters captured inside vs. outside MPAs. Colored figure at bottom shows histograms for each MPA on the same scale. From front to back, MPAs are: Vicente (dark blue), Laguna (red), Swami's (green), South La Jolla (purple), and Cabrillo (light blue).

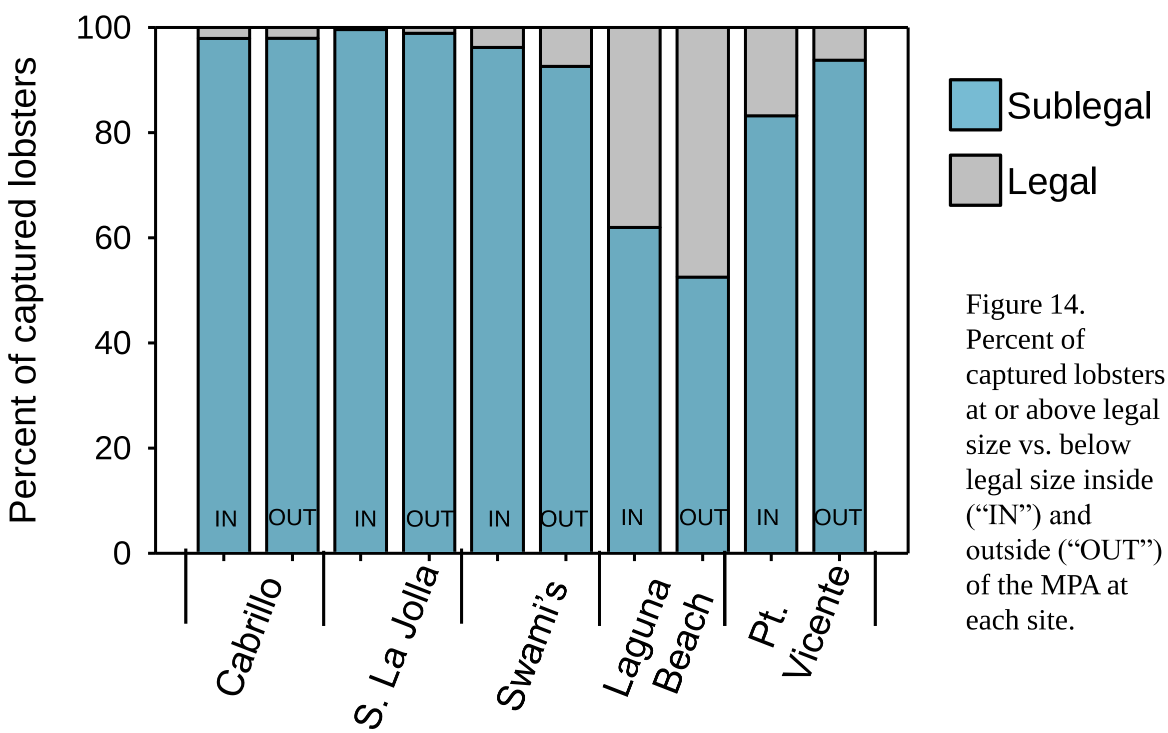


Figure 14. Percent of captured lobsters at or above legal size vs. below legal size inside ("IN") and outside ("OUT") of the MPA at each site.

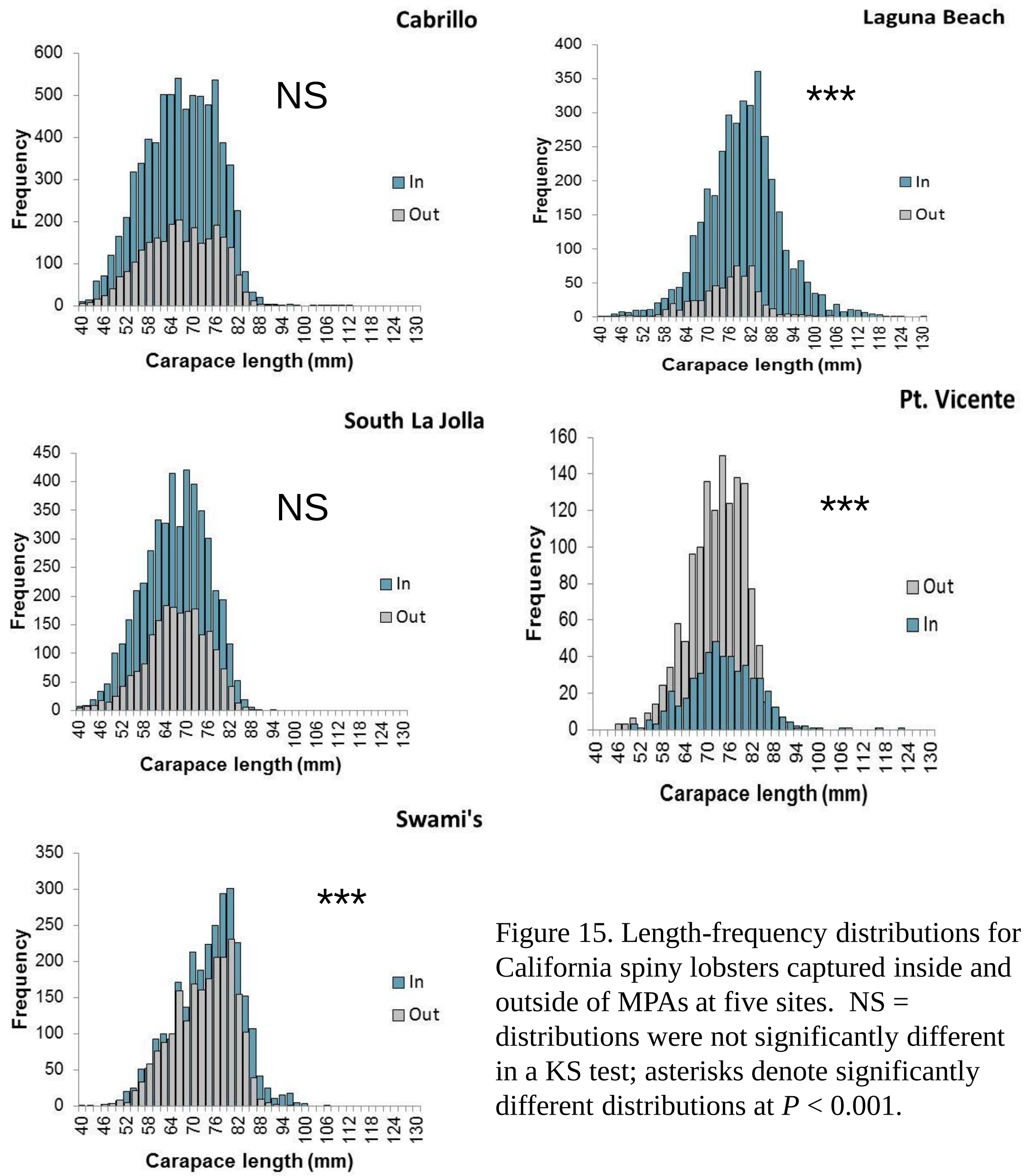


Figure 15. Length-frequency distributions for California spiny lobsters captured inside and outside of MPAs at five sites. NS = distributions were not significantly different in a KS test; asterisks denote significantly different distributions at $P < 0.001$.

3. Lobster growth rates. The proportion of tagged lobsters that were recaptured at each site is shown in **Table 1**. There was an interactive effect of site and sex on lobster growth rates (two-way ANOVA: *site*: df = 3, 266, F = 25.3, $P < 0.001$; *Sex*: df = 1, 266, F = 7.3, $P = 0.007$; *site x Sex*: df = 3, 266, F = 3.7, $P = 0.01$; **Figure 16**). This difference was caused by higher growth rates for males than for females at Swami's and Laguna, but not at Cabrillo and South La Jolla. For both sexes, growth was higher at Laguna than at all other sites. There was no difference in lobster growth rates between years (i.e., lobsters that were captured in 2011 and recaptured in 2012, vs. lobsters that were captured in 2012 and recaptured in 2013; df = 276, t = 0.31, $P = 0.75$). The median growth rate for males was 3.22 mm per year (range: 0.86 – 17.0 mm per year) and for females was 3.1 mm per year (range: 0.53 – 10.5 mm per year).

Growth rates measured in our study generally were comparable to other studies, though on the low end of the range. However, California spiny lobster growth rates have varied widely among studies, and some studies report higher growth rates for male lobsters (which ultimately achieve a larger size than females), whereas some do not (e.g. Mitchell et al. 1969). Odemar et al. (1975) reported on lobster growth rates for lobsters in a mark-recapture study conducted in Santa Catalina Island. Males grew faster than females, with males growing between 1.5 - 5.6 mm per year, and females growing 1.3 – 4.8 mm per year. Growth rates were strongly dependent on lobster size in that study (larger lobsters grew more slowly) whereas we found no such relationship (linear regression of growth on lobster CL: df = 1, 276, F = 0.2, $P = 0.66$, $r^2 = 0.002$). A key

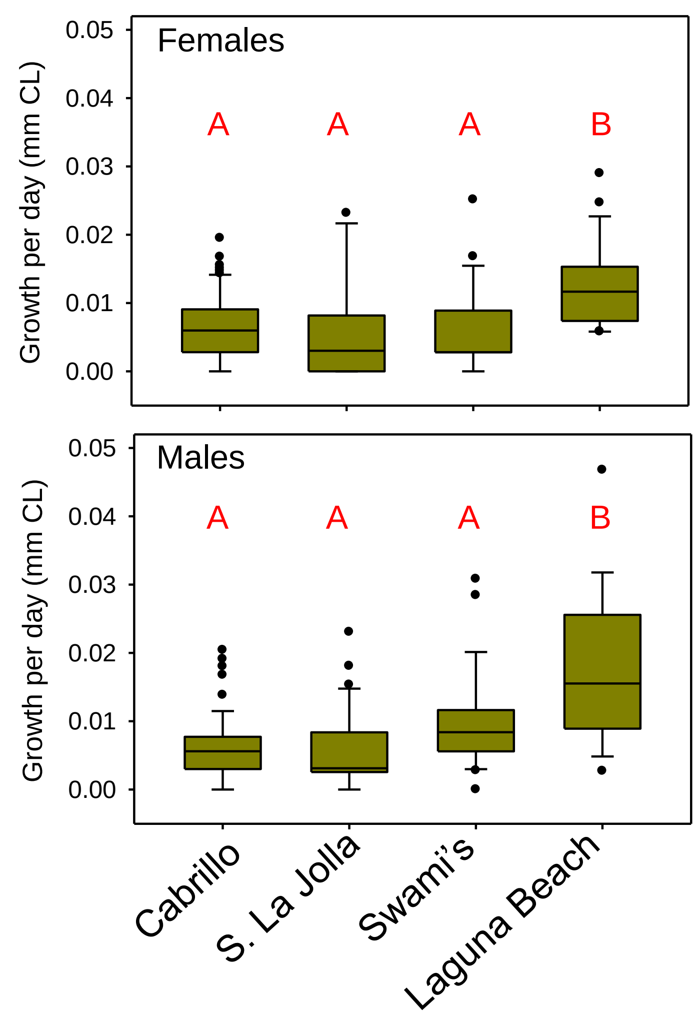


Figure 16. Growth rates for male and female California spiny lobsters recaptured at least one year after initial capture at each site. Unlike red letters above boxes indicate means that differed in a Tukey's post-hoc test. See Figure 2 for explanation of box plots.

finding of our study is that growth rates are variable among sites across the Southern California region. Growth rates are used in models for lobster population size and growth. Our findings can contribute to new population modeling techniques, such as the Management Strategy Evaluation (MSE) presently being used to model lobster populations in Southern California for the state's spiny lobster fishery management plan. Models such as these incorporate variability in population parameters across the region, rather than assuming a single number for the entire lobster population, as has been done in the past.

One caveat regarding lobster growth rates is that they can be difficult to measure. Mark-recapture is the only way to obtain estimates of growth for animals inhabiting natural environments, but whether marking lobsters affects growth rates (via added stress to animals or altered behavior) is unknown. Lobsters grow only upon molting, which likely occurs once per year for lobsters larger than 50 mm CL (Odemar et al. 1975). We measured lobster growth for lobsters at-large for at least one year, which should have permitted most lobsters to molt at least once. However, it is possible that some recaptured lobsters did not molt during their time at-large.

4. Movement. A small proportion of recaptured lobsters crossed MPA boundaries at each site (**Figure 17**). The largest proportion of lobsters crossing boundaries was found at Cabrillo,

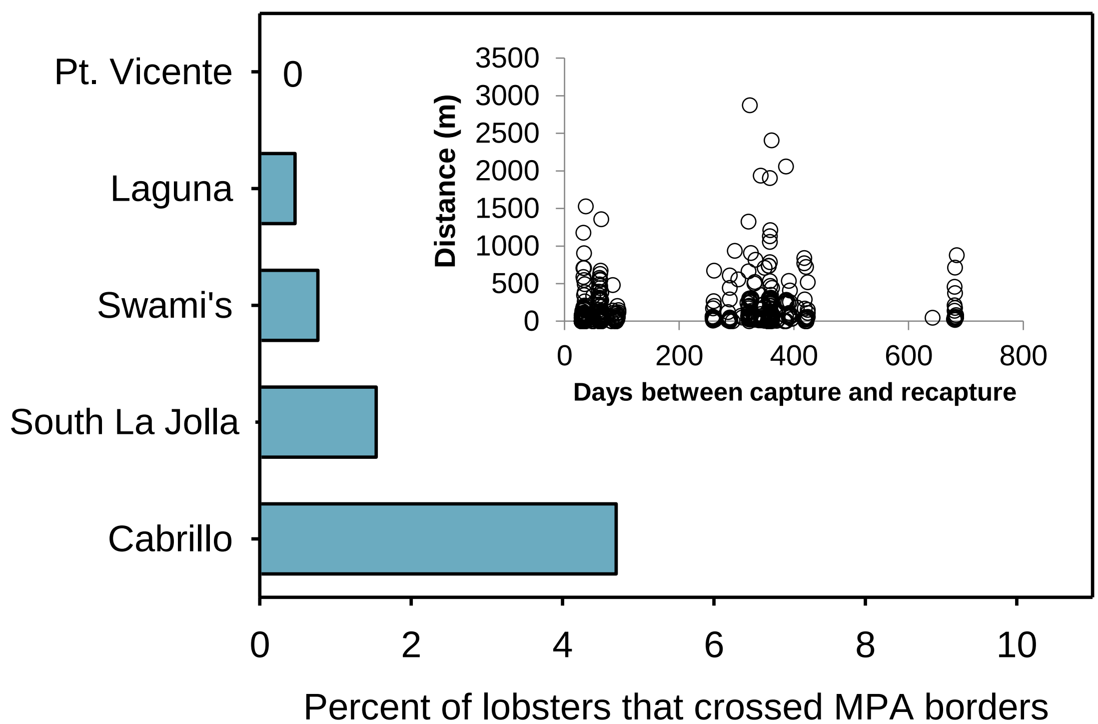
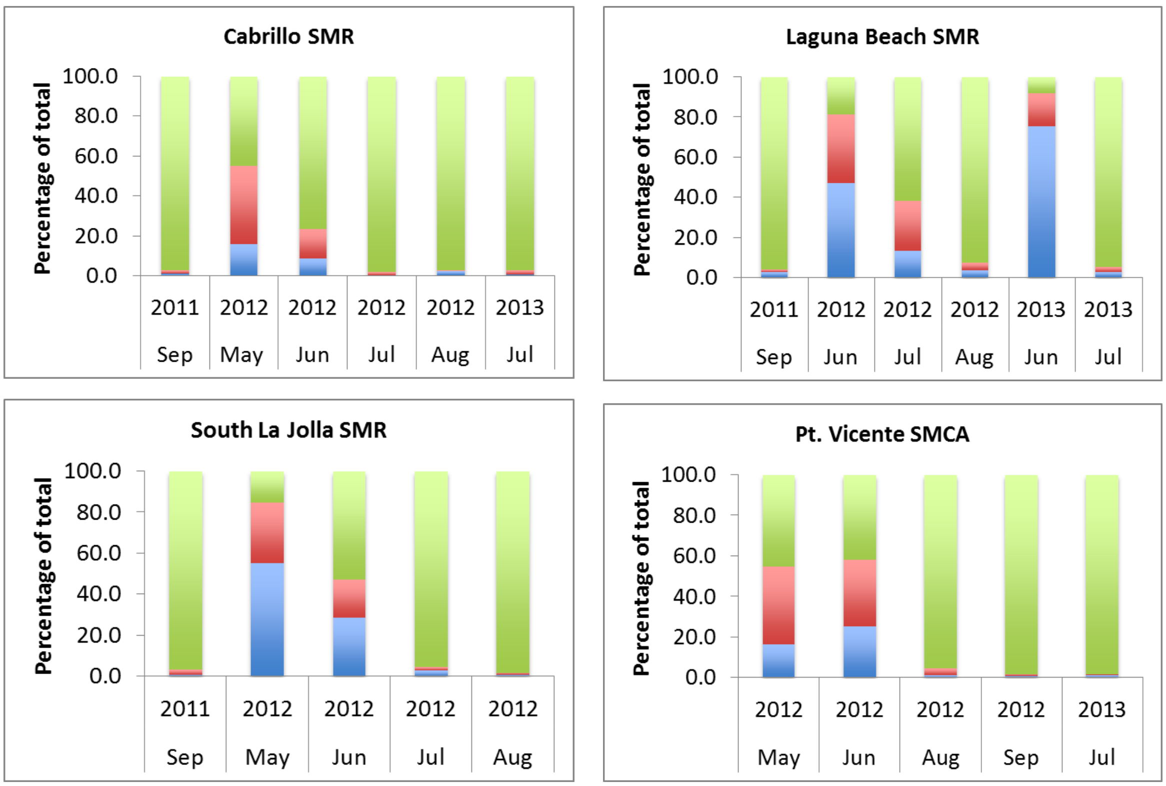


Figure 17. Percent of recaptured lobsters that were recaptured on the other side of an MPA border for each site. Inset shows the actual straight-line displacement vs. time between capture and recapture. Note that displacement is heavily dependent on trap spacing.

where 4.7% of recaptured lobsters had crossed boundaries (out of 13 lobsters that crossed boundaries, 11 spilled out of MPAs, and 2 spilled in). No recaptured lobsters had crossed into or out of the MPA at Vicente. Lobsters generally were displaced small distances, even over a two-year period, and there was no relationship between time-at-large and displacement (**Figure 17, inset**). Including lobsters at-large for at least 30 d, the mean displacement was 128 m ($\pm$ 10.2 m SE) and the median displacement was 41 m. The farthest displaced lobster was from Laguna which was displaced 2,873 m over a 323 d period. We note that our measures of lobster displacement depend heavily on the distances among traps at each site, with traps generally set at distances of several hundred meters apart. Moreover, traps can only record the minimum distance moved by lobsters, as if they had traveled in a straight line. Nonetheless, the relatively small amount of spillover and small displacements are not unexpected for spiny lobsters, particularly when MPAs have just been established and lobster density and mean size (both of which may influence movement rates and distances) have not increased within MPA borders. Lobsters maintain relatively small home ranges that are strongly influenced by habitat, suggesting that spillover rates may often be low, and are dependent on the characteristics of benthic features at MPA boundaries. Though California spiny lobsters are known to move into shallower water at night to forage, lobsters tracked in the San Diego area moved short distances within kelp, boulder and understory habitat and homed back to areas around their starting shelters (Withy-Allen and Hovel 2013). Small home ranges are common for spiny lobsters; for instance, a tag and recapture study in the Mediterranean Sea for a period of 10 years found that approximately 61% of *Panulirus elephas* remained within 2 km of the initial release site (Follesa et al. 2009), and a similar tagging study in Australia demonstrated that spiny lobster *P. versicolor* moved only ca. 500 m per year from release sites (Frisch 2007). Lobster spillover may increase through time if lobster density and average size increase within MPAs, though this may take decades to be realized; spillover was not enhanced for California spiny lobsters in Channel Island MPAs six years after establishment, where over 90% of recaptured lobsters were not displaced outside of their initial trapping location (Kay et al. 2012). Because spillover of fishery species may be a major benefit of MPAs, it is important that future monitoring efforts quantify lobster movement, and design monitoring to determine spillover rates from MPAs. An optimal design for this would include tagging and trapping as well as tracking lobsters using acoustic transmitters.

It is important to note that the capture of lobsters in the fishery also can help account for apparent low spillover from MPAs (Kay et al. 2012). Some of the lobsters we tagged may have been captured in the commercial or recreational fishery, and not reported to us by fishers. However, only 22% of the lobsters we tagged were above legal size (or close enough to legal size to have grown to legal size when they were captured), so loss to the fishery likely was relatively small in our study.

5. Reproductive condition. The proportion of female lobsters in each stage of reproduction changed throughout the trapping season (**Figure 18).** Fifty to 95% of female lobsters were plastered or berried in May and June, but most lobsters had released eggs in July, leaving nearly all females unplastered for the duration of the summer, except for Laguna where 20 and 16% of females remained plastered and berried, respectively. These trends corresponded to trends in catch of female vs. male lobsters; at most sites, females composed an increasing proportion of the catch in July, when they likely became more active after releasing larvae. The same trends were seen in a comprehensive survey of California spiny lobsters from Southern California (Lindberg 1955) and in a tag-recapture study in San Diego Bay conducted in 2009-2010.



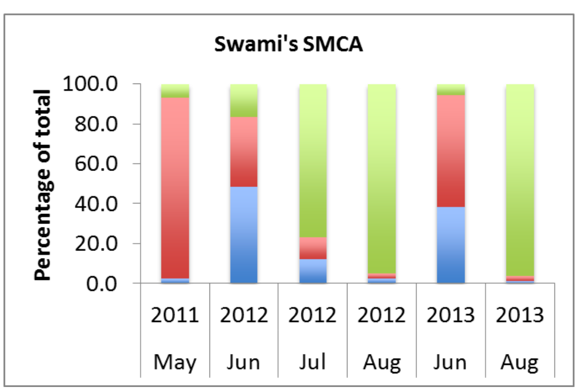


Figure 18. Reproductive condition of female lobsters captured at each site by month. Green = unplastered, red = plastered, blue = berried. Note different time series on X axes.

Basic statistics for the size of ovigerous ("berried", i.e. egg bearing) female lobsters are shown in **Figure 19**. The general increase in the median size of ovigerous females from south to north reflects the increase in median lobster size from south to north (see **Figure 12**). One major difference between our study and other censuses of California spiny lobsters is the size at which females were ovigerous. We found ovigerous lobsters as small as 53 mm CL, which contrasts other studies that found a minimum size of approximately 70 mm CL for reproductive maturity (Lindberg 1955, Odemar 1975, Goforth and U'Ren 1980). It is not known if this difference reflects a change over time in the mean size at which female lobsters become reproductively mature and can bear eggs, or if this is more of a product of our more comprehensive study using smaller mesh traps. Both of these causes may apply.

The presence of small ovigerous females encountered during this study will have immediate utility with existing CDFW models for lobster populations and management. Size at maturity is a key parameter used to define the spawning stock in population models, some of which are highlighted in **Table 4**. Recruitment and egg production, factors used to determine population health, are based on size at maturity, and in turn these help to determine sustainable levels of fishing. For example, during the CDFW stock assessment effort (Neilson, 2011), CDFW relied on a related parameter, age at maturity. Age at maturity was implemented as a single value ranging from 3 to 7 years (the rule of thumb is about 5 years to maturity), and in the model at the given age all lobsters became mature. Another key parameter, age at recruitment to the fishery, is generally estimated at 7 years, and thus the estimate for age at maturity provides 2 spawning years before lobsters potentially are harvested. As part

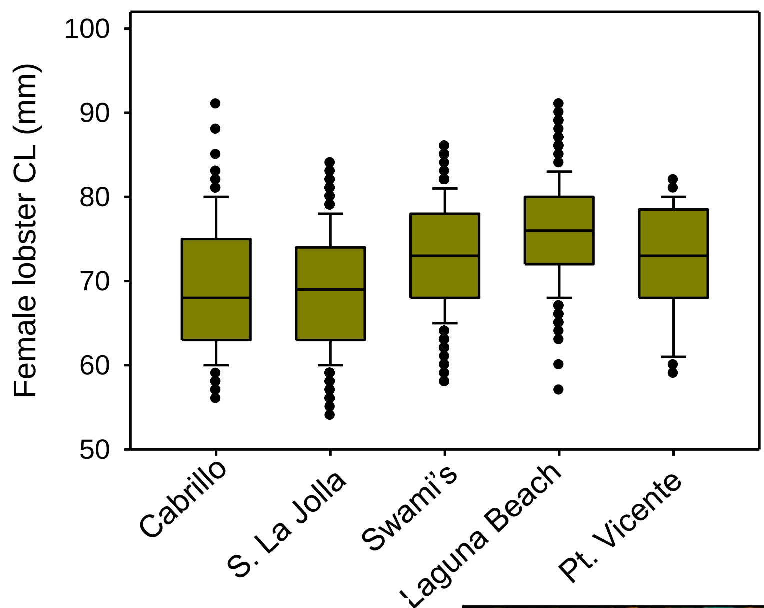
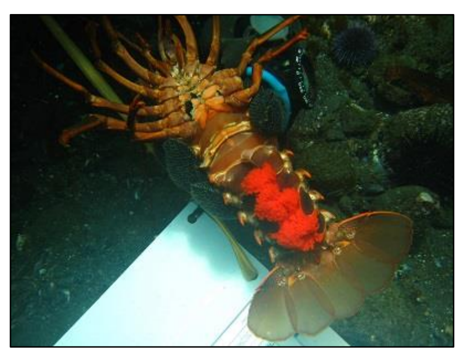


Figure 19. Descriptive statistics for sizes (carapace length, CL) of berried (i.e. ovigerous) female lobsters. Median CL of ovigerous lobsters for each site is shown at the top. See Figure 2 for explanation of box plots. Right: picture of an ovigerous California spiny lobster (credit: Derek Stein, CDFW).



of the CDFW fishery management plan effort targeting lobster, CDFW moved away from this single value formulation and adopted a probability spectrum based upon length in both its management strategy evaluation (MSE) and spawning potential ratio (SPR) models.

Table 4. Comparison of maturity estimates and methodologies used by CDFW models.

Source	Maturity Calculation	Reference values	When are 100% Mature?
Lindberg (1955)	Based on field observations	20% are mature at 59mm CL	79 mm CL
FISMO Model	All lobster older than a given age are considered mature	NA	70 mm CL (5 years old)
SPR Model	A proportion of each size class is considered mature.	50% 76mm-79mm CL	92 mm CL
MSE	Each individual, immature lobster has probability of maturing at molt based on size.	follows Lindberg (1955)	80 mm CL approximately

Summary for the lobster tag-recapture program

From the tag-recapture study, we found that:

1. There are clear gradients in lobster abundance and size from south to north, but at each site there was little difference inside vs. outside the MPA.
2. Lobsters generally are more abundant, but smaller on average, in southern sites compared to northern sites. Lobsters at or above the minimum legal CL were rare at all MPAs, except for Laguna Beach, where they composed nearly 50% of the catch. Generally, lobster length-frequency distributions were slightly wider inside vs. outside of MPAs, which was caused by moderately higher frequencies of large lobsters inside vs. outside of MPAs.
3. Lobster growth rates were similar among the five sites, except for Laguna Beach where growth rates were substantially higher than in all other sites. Lobsters grew an average of about 3.22 mm per year.
4. Very few lobsters moved across MPA boundaries. Between 0 and 5% of recaptured, tagged lobsters had spilled over MPA boundaries, or had spilled in to MPAs from outside.

Lobster surveys and habitat mapping

Introduction and Methods

We complemented our trapping study with observations of spiny lobsters in benthic habitats, and mapping of benthic habitat features at the site with the highest lobster abundance (South La Jolla). Benthic surveys do not permit observations of as many lobsters as boat-based trapping surveys, but they allow calculation of lobster density (number of individuals per unit area) and habitat associations to be established. Benthic surveys also allow behavior to be quantified. These two major factors, habitat association and behavior, often are not considered in the design of MPAs or in MPA monitoring. However, many ecological processes are tied to species-habitat interactions, and MPAs may have little effect on populations if complex habitat or the appropriate mix and juxtaposition of habitats (i.e. landscape structure) is lacking within the MPA. MPAs also may not succeed if behaviors of the target species, including habitat preferences, movement patterns and home range, and antipredator strategies are not incorporated into MPA design. This may be particularly important for species vulnerable to predators because predator abundance and body size often increase in MPAs. In light of this, MPA monitoring programs, which typically focus on organismal density, biomass, and diversity also should characterize and quantify important aspects of organismal behavior and how behaviors change over time.

The main objective of this part of our study was to quantify baseline levels of lobster density, habitat utilization, and sheltering behavior within and outside of our targeted South Coast MPAs. We implemented two analyses for this part: (i) SCUBA-based surveys for lobster density and habitat use inside and outside of the MPA at each site, and (ii) coupling lobster density data to acoustic mapping data of benthic substrata in La Jolla to develop maps of preferred lobster habitat. This was implemented to increase our understanding of lobster habitat occupancy and movement and to support future studies of stock assessment in the South La Jolla area.

SCUBA surveys. To determine lobster habitat use within and outside of target MPAs, we conducted daytime SCUBA-based transect surveys of rocky reefs (5 – 15 m depth) between May and September of 2012 and 2013. All sites were sampled in each year, except for Vicente in 2012 due to logistical issues. Transects were 8 m wide × 30 m long, and a total of no less than 18 transects within and outside of the MPA at each site (N = 144 total) were conducted. Because *P. interruptus* primarily associates with rocky habitat and associated macroalgae during the day, we chose sampling locations that were dominated by the canopy-forming giant kelp *Macrocystis pyrifera*, a variety of foliose understory algae, and surfgrass *Phyllospadix* spp. and were known to have a high proportion of hard substrata. California spiny lobsters generally exhibit high site fidelity, returning to the same or nearby shelters at dawn (Lindberg 1955) and maintaining small home ranges. Therefore, once a site was selected, transects were haphazardly placed and at least 50 m apart and sites outside of MPAs were located at least 300 m away from sites sampled inside to maintain independence.

Each transect was subdivided into twenty 4 m wide × 3 m long "boxes" (10 boxes east and west of the transect line). Divers recorded substrate relief every meter and substratum cover within each box by visually estimating the percent cover of flat rock, boulder, cobble, and sand. Vegetation cover within each box was quantified by visually estimating kelp density (number of *M. pyrifera* holdfasts per box), and the percent cover of surfgrass and common understory algae, including: *Pterygophora californica*, *Laminaria farlowii*, *Eisenia arboria*, *Egregia menziesii*, *Cystoseira osmundacea*, *Plocamium cartilagineum*, other red algae, and articulated coralline algae. These algal species were selected because they represented > 95% of the algal cover within sites. Measures of substrate and vegetation cover were then averaged across boxes to describe habitat type along each transect. When lobsters were encountered, we recorded the number of lobsters per aggregation and relative size (CL) based on categories: < 5.0 cm, 5.0 – 6.5 cm, 7.0 – 8.0 cm, 8.0 – 9.0 cm, and > 10.0 cm, which correspond to juvenile lobsters, subadults transitioning from surfgrass to rocky reef habitat, sublegal (for harvest) adults, legal adults, and large (i.e. rare) lobsters, respectively. Shelter type was also classified as a ledge (rock overhang), crevice (rounded hole made of stacked boulders), holdfast (*M. pyrifera* holdfasts hollowed out by grazers), or none (if lobsters were found outside of shelter).

Habitat mapping. The data acquisition system included a single beam echo sounder (Hydrobox™ Hydrographic Echo Sounder), an inertial measurement system (an XSENS MTi-G™), and a high resolution GPS (Hemisphere V110) all interfaced to a recording laptop computer. A single beam system was used because of the difficulty of maneuvering a multibeam sonar system through heavy kelp canopy. Data were acquired from a 7 m long vessel equipped with kelp cutting blades on twin outboard engines enabling vessel passage through heavy kelp canopy without degradation of the acoustic returns. Navigation tracks were oriented across-shore from the shallows (~1 m) to a depth of ~36 m. Acoustic data acquisition was conducted along cross-shelf transects separated ~10 m alongshore. Routes and vessel navigation were supported utilizing Fugawi™ Marine ENC software[1] running on a separate laptop. The spatial extent of transect coverage was determined from the fullest extent of kelp canopy observed in a time series of aerial canopy coverage between 1967 and 2000. Calm days were targeted to minimize error. Binary Hydrobox™ data files were extracted and imported into Matlab. Acoustic ping data were then analyzed within Matlab using custom scripts to estimate bottom depth and algal canopy guild. A 20-second Butterworth highpass filter was applied to the MTi-G altitude data using the Matlab signal processing toolbox to eliminate vertical position drift. The resulting signal was then differenced from the acoustic depth signal to minimize the effects of vessel heave on depth estimation. Ping depth data were imported into GRASS GIS (GRASS Development Team, 2012) and interpolated using a regularized spline with tension method – the sum of a trend function and a radial basis function (Mitasova and Mitas, 1993). Tension and smoothing parameters were chosen using cross-validation of predictive error (Mitasova et al. 1995).

[1] (http://www.fugawi.com/web/products/fugawi_marine_enc-in.htm)

Statistical analyses. We compared lobster density across sites (four levels; no lobsters were found at Vicente) and inside vs. outside of MPAs using a two-way analysis of variance (ANOVA), followed by Tukey's HSD tests for pairwise comparisons. Data were log (x + 1) transformed to meet the test assumptions of homogeneity of variances and normality. We conducted separate analyses for two measures of lobster density: (1) density calculated using the total area surveyed along transects (i.e. 240 m^2), and (2) density calculated using only the area of hard substratum observed within transects. The latter was used to account for those transects in which hard bottom was scarce and sand (presumably poor lobster habitat) was abundant.

Since many biotic and abiotic habitat variables were positively or inversely correlated with one another, we used principal component analysis (PCA) to reduce the data set into several linearly uncorrelated principle components (PCs). Resulting eigenvalues (loadings) were used to determine which variables strongly contributed to each PC. We then used forward stepwise logistic regressions, with the presence or absence of lobsters as the dependent variable, to determine whether the odds of finding lobsters along transects at the regional level (all MPAs combined) and at each reserve (individually) were correlated with the first four principal components. We chose logistic regression over least-squares regression to analyze lobster abundance due to the large proportion of observations having zero lobsters per transect. Data were normalized to account for different scales used to measure habitat variables, and any models not meeting the goodness-of-fit criteria of Hosmer and Lemeshow (1989) were rejected.

We performed Kolmogorov-Smirnov (KS) tests to examine differences in the distribution of group sizes (number of lobsters per aggregation) among sites. We also compared the distribution of group sizes at the regional and site levels with the truncated Poisson distribution using a Pearson chi-square goodness-of-fit test; this assessed the randomness associated with group formation as rejection of the truncated Poisson model indicates that lobster aggregations are larger (or smaller) than expected by chance. We further examined social behavior of lobsters by comparing the number of shelters containing solitary vs. communal lobsters in each size class at both regional and site levels using Pearson chi-square analyses (Yates correction was used where necessary to adjust analyses for low sample sizes).

For habitat mapping, we calculated surface morphometrics (derived parameters of acoustically derived bottom shapes, **Table 5**) at 3 spatial scales (10, 30, and 50 m) within GRASS GIS, and imported these from GRASS into R (R Core Team, 2012) using the 'spgrass6' library (Bivand, 2007) to model lobster distribution using a random forest model approach[2]. Lobster densities from the band transects were located within the acoustically derived maps and surface morphometrics at these locations were extracted and used to derive a statistical spatial model of lobster habitat. Two versions of modeled spatial lobster occupancy (i.e., local density) were calculated. The first, included depth and several terrain features while the second utilized the same terrain features as the first model but did not include depth.

[2] (http://stat-www.berkeley.edu/users/breiman/RandomForests)

Table 5. Geologically-based morphometrics used in the random forest model to model and map lobster habitat.

Morphometric	**Description**
Slope	Magnitude of maximum gradient (steepest slope angle)
Aspect	Direction of maximum gradient
Profile Curvature	Curvature intersecting with the plane defined by Z axis and maximum gradient direction (positive values describe convex profile curvature, negative values concave profile curvature)
Plan Curvature	Horizontal curvature, intersecting with the XY plane
Longitudinal Curvature	Curvature intersecting with the plane defined by the surface normal and maximum gradient direction.
Cross-Sectional Curvature	Tangential curvature intersecting with the plane defined by the surface normal and a tangent to the contour - perpendicular to maximum gradient direction
Maximum Curvature	Maximum curvature in any direction
Minimum Curvature	Curvature in direction perpendicular to the direction of maximum curvature

Results and discussion

Lobster density. We encountered a total of 1,319 lobsters in surveys: 12 lobsters < 5.0 cm CL, 420 lobsters 5.0 – 6.0 cm CL, 671 lobsters 7.0 – 8.0 cm CL, 216 lobsters 8.0 – 9.0 cm CL, and no lobsters > 10.0 cm CL. We found an interactive effect of site and inside vs. outside the MPA on lobster density, suggesting that lobster density differed across boundaries (inside vs. outside) at some sites but not at others (**Table 6**, **Figure 20**). There was relatively little correspondence to the strong pattern of decreasing density from south to north from the trapping study. Lobster density was highest at Cabrillo, and lowest at Vicente (zero lobsters, though we note that Vicente could not be sampled in 2012). Lobster density was intermediate, and similar among the other sites (South La Jolla, Swami's, and Laguna). At Cabrillo, both the number of lobsters per total transect area, and the number of lobsters per m^2 hard bottom were almost twice as high inside compared to outside of the MPA (*t*-test total area: df = 36, $t = 2.35$, $P = 0.024$; *t*-test hard bottom: df = 36, $t = 3.06$, $P = 0.004$). In contrast, lobster density per m^2 hard bottom was almost seven times higher outside vs. inside of the MPA at South La Jolla, but high variability in lobster density among transects outside of the MPA resulted in no statistically significant difference. At Swami's, lobster density per m^2 hard bottom was twice as high outside vs. inside of the MPA (df = 37, t = -2.63, P = 0.012). There was no difference in lobster density between boundaries at Laguna.

Different trends for lobster abundance between trapping and benthic surveys can be attributed to the fact that these techniques measure lobster abundance in different ways. Traps capture lobsters moving out of shelters at night, and are a better measure of large-scale trends in abundance. Additionally, research traps more efficiently enumerated small lobsters that hide in deep crevices and are harder to detect on dive surveys. Because small lobsters were prevalent in southern sites, dive surveys did not detect the real, strong trend in lobster abundance from south to north. However, dive surveys better captured differences in lobster density inside vs. outside MPAs, because these differences likely can be attributed to distribution of lobster habitat. For instance, at Cabrillo, a mixture of shallow rocky habitat and surfgrass is prevalent inside the MPA, resulting in a higher density of lobsters inside vs. outside the MPA. It should be noted that lobster distribution also may depend on the distribution of their prey, and therefore habitat preferences of their prey, including sea urchins, mussels, gastropods, and other benthic organisms. Lobsters are known to forage in the intertidal (Robles et al. 1990) as well as subtidally, and it is possible that a high abundance of lobsters in shallow, nearshore waters is partially attributable to lobster access to prey (or a variety of foraging habitats).

Table 6. Results of two-way analyses of variance (ANOVAs) for lobster density, testing for effects of site and location (inside vs. outside). (A) "Total area": lobster density calculated for entire area surveyed; (B) "Hard bottom": number of lobsters divided by the area of rocky bottom found on transects.

A. Total area

Source	**df**	**MS**	**F**	**P**
Site	3	0.28	1.2	0.32
Location	1	0.03	0.11	0.74
Site*Location	3	1.2	4.98	0.003
Residual	96	0.54		

B. Hard bottom

Source	**df**	**MS**	**F**	**P**
Site	3	0.5	1.58	0.19
Location	1	0.17	0.54	0.46
Site*Location	3	1.7	5.4	0.002
Residual	96	0.98		

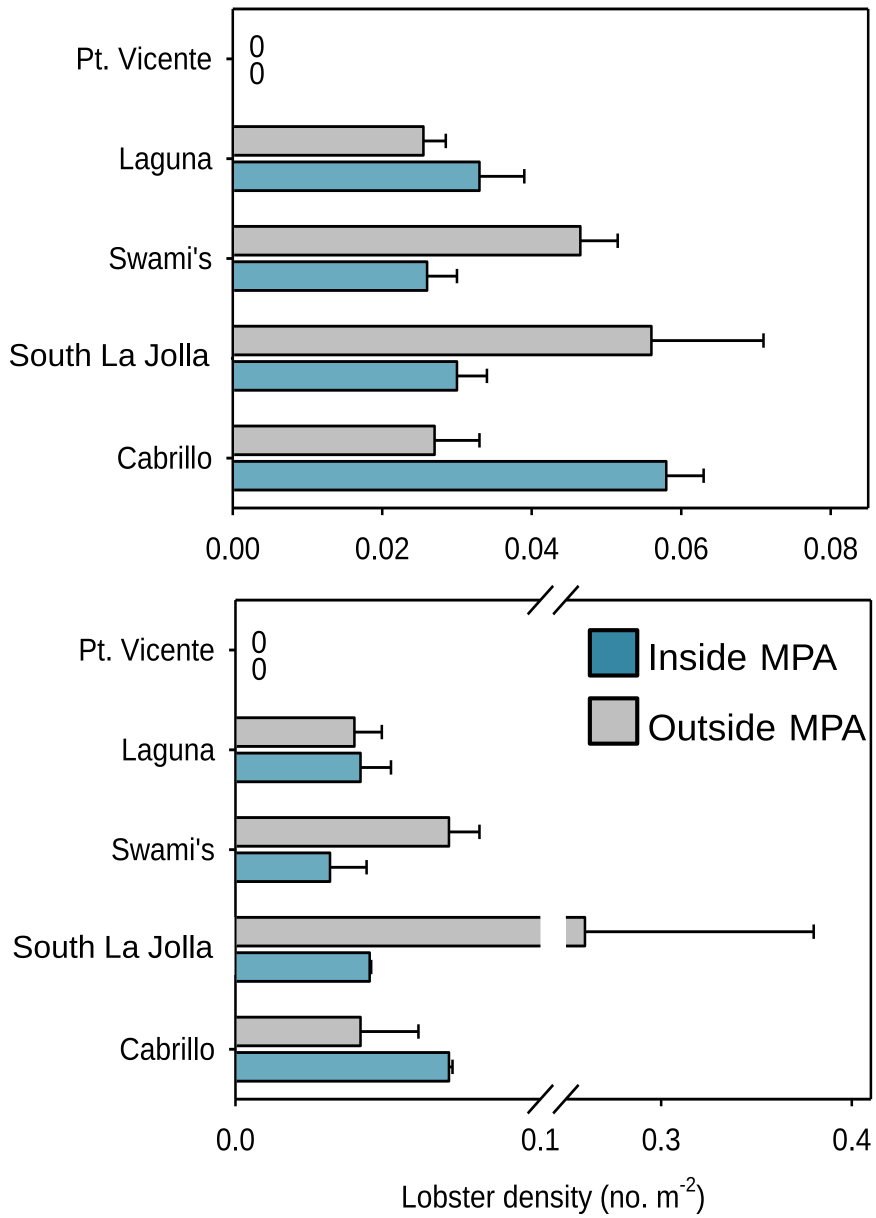
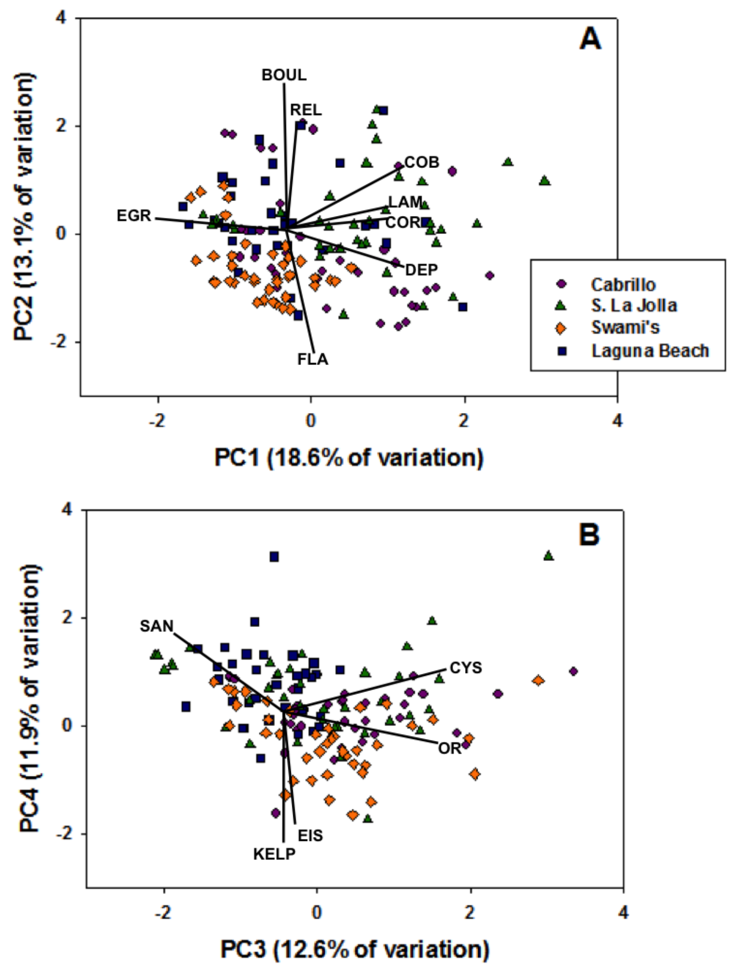


Figure 20. Density of lobsters (+ 1 SE) from SCUBA-based transects. Top: total lobster density; Bottom: lobster density calculated using the area of hard bottom substratum only.

Habitat associations. Substrate composition and algal assemblage varied across the region, and each site had distinct habitat characteristics. As such, the odds of finding lobsters at each site were related to different habitat variables, and no single variable or combination of variables reliably predicted the odds of finding lobsters across the entire study region. The first four principal component axes of the PCA explained 56% of the variation in habitat parameters across sites (**Figure 21**). PC1 represented deep sites with high cobble and understory algae cover, but low cover of *E. menziesii*; PC2 represented sites with high-relief boulder fields and low cover of flat rock; PC3 corresponded to sites with high red algae and *C. osmundacea* cover and little sand; and PC4 represented sites with high kelp density and low *E. arboria* cover (**Appendix B**). Sites differed qualitatively in benthic substrate. In general (going from south to north), reefs surveyed at Cabrillo had high cobble and high understory algae cover; South La Jolla reefs were typically either cobble patches with high understory algae cover, or boulder fields; reefs surveyed at Swami's mainly consisted of flat rock with high cover of *M. pyrifera*; and reefs at Laguna were generally either high-relief boulder fields with high *E. menziesii* cover, or sand flats.

Figure 21. Principal component analysis (PCA) of the five substrate and ten vegetation variables measured on dive surveys conducted across the study region: PC1 vs. PC2 (A) and PC3 vs. PC4 (B). Lines indicate the eigenvector scores for variables that strongly contributed to each principal component (PC). PC1: depth (DEP), cobble cover (COB), *Laminaria farlowii* (LAM), *Egregia menziesii* (EGR), and coralline algae (COR). PC2: relief (REL), flat rock (FLA), and boulder cover (BOUL). PC3: sand (SAN), *Cystoseira osmundacea* (CYS), and other red algae (OR). PC4: *Macrocystis pyrifera* (KELP) and *Eisenia arboria* (EIS).



At the regional level, the odds of encountering lobsters were not strongly predicted by any logistic regression model. However, at Cabrillo and South La Jolla, the odds of finding lobsters increased with increasing values of PC4, i.e., on reefs with low cover of large kelps (*M. pyrifera* and *E. arboria*) (**Table 7**). In contrast, at Swami's, greater amounts of low-relief flat rock, *C. osmundacea*, and red algae increased the odds of finding lobsters. Although not statistically significant, the model that best described the data for Laguna indicated that the odds of finding lobsters were highest where cover of *E. menziesii*, kelp, and *E. arboria* were high.

Table 7. Results of best fitting models in forward stepwise logistic regressions on principal component (PC) factor loading scores for lobsters found on surveys at each MPA. Variables that entered into the model at $P < 0.1$ are in bold. Odds ratio is the change in the odds of finding lobsters given a unit change in the PC loading scores. Numbers in parentheses are lower and upper Wald confidence limits.

Source	**df**	**Parameter**	**P**	**Odds ratio**
Cabrillo				
Intercept	1	0.72	**0.06**	
PC4	1	1.24	**0.09**	3.44 (0.82, 14.5)
South La Jolla				
Intercept	1	1.68	**0.006**	
PC4	1	2.1	**0.046**	8.14 (1.04, 63.8)
Swami's				
Intercept	1	0.89	0.11	
PC2	1	-1.78	**0.038**	0.17 (0.03, 0.90)
PC3	1	0.82	0.1	2.3 (0.8, 6.2)
Laguna				
Intercept	1	0.8	0.11	
PC1	1	-0.52	0.33	0.6 (0.21, 1.7)
PC4	1	-0.35	0.37	0.70 (0.32, 1.5)

Previous research conducted within and around the South La Jolla SMR in San Diego suggested that *P. interruptus* has a high affinity for rocky reefs with dense stands of algae, including *E. menziesii*, *C. osmundacea*, turf-forming red algae, and articulated coralline algae (Parnell et al. 2006). Within that same area, Withy-Allen and Hovel (2013) found that the odds of finding lobsters were highest in areas of high boulder cover. Our results, however, suggest that lobster-habitat associations are not consistent across the South Coast Region, and that one of the main drivers of lobster habitat use is the local availability of substrate and vegetation. For example, reefs surveyed at Swami's consisted mainly of flat rock substrate with turf algae, and as a result, the odds of finding lobsters increased with greater amounts of low-relief substrate. In contrast, high-relief boulder fields with high giant kelp cover dominated reefs surveyed at Laguna, which may have contributed to an increase in the odds of finding lobsters in areas of dense *M. pyrifera* or *E. menziesii* cover, although this trend was not statistically significant. Reefs surveyed at Cabrillo and South La Jolla typically contained suitable lobster habitat, but results of logistic regressions indicated that the absence of *M. pyrifera* was the primary variable predicting lobster presence. One explanation for these results is that many species of fish, including some common lobster predators (e.g., California sheephead *Semicossyphus pulcher* and kelp bass *Paralabrax clathratus*), are abundant on rocky reefs with dense kelp canopies and understory algal beds. Another research group engaged in MPA monitoring (Vantuna Research Group, Occidental College, CA) recorded the highest levels of predatory fish biomass (California sheephead, kelp bass, and black sea bass *Stereolepis gigas*) at Cabrillo and South La Jolla during our sampling seasons. It is therefore possible that lobsters shelter in areas of low kelp cover at these MPAs to reduce the risk of detection by diurnal predators.

Social behavior. At the regional level, small groups of ≤ 4 lobsters were common, with a median group size of two lobsters and a maximum group size of 53 lobsters. Although most shelters contained a single lobster, this accounted for only 33% of the total number of lobsters observed; in contrast, 67% of all lobsters encountered within the study region were found in aggregations of ≥ 2 lobsters (**Figure 22**). Regionally, group size distribution rejected the truncated Poisson model (df = 4, $\chi^2 = 83.22$, $P < 0.001$), as we observed twice as many single lobsters and three

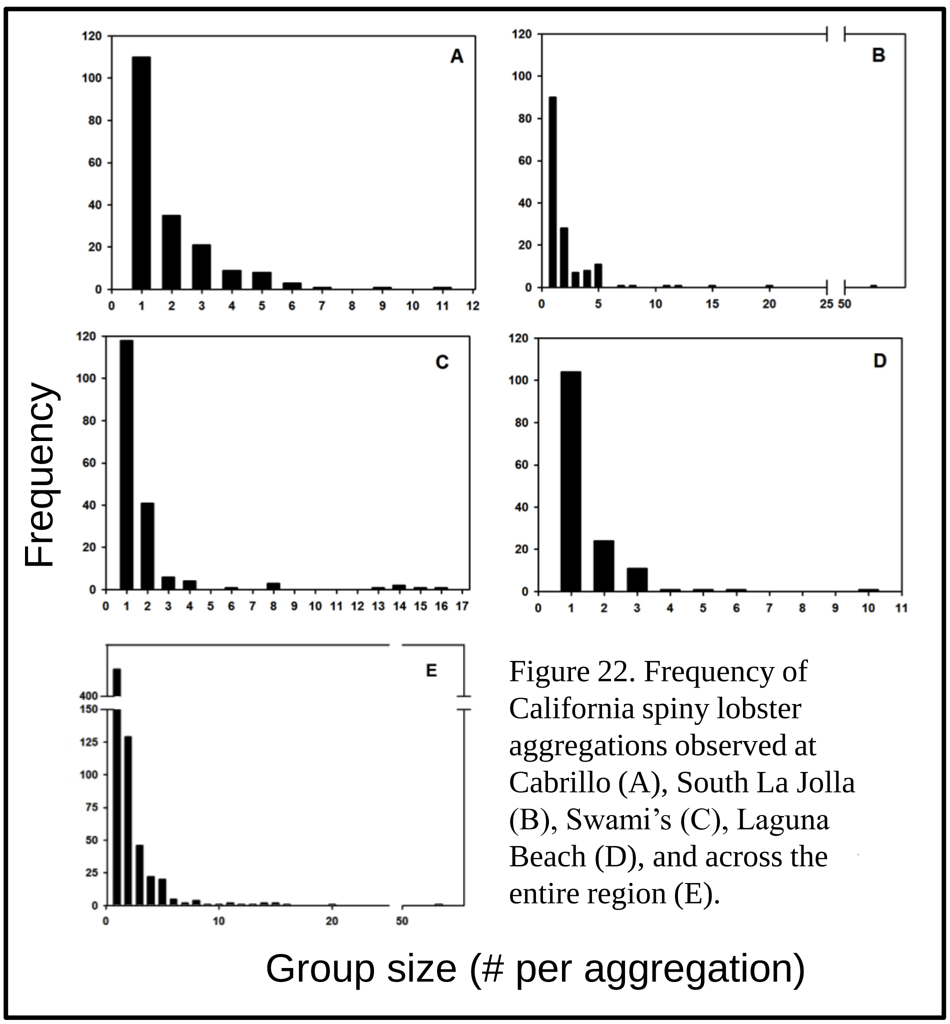


Figure 22. Frequency of California spiny lobster aggregations observed at Cabrillo (A), South La Jolla (B), Swami's (C), Laguna Beach (D), and across the entire region (E).

times as many aggregations ≥ 5 lobsters than expected by chance. Comparing sites, we found differences in group size distribution only between South La Jolla and Swami's (KS *D* statistic = 0.22, $P = 0.002$): we observed more single lobsters at Swami's compared to South La Jolla, and twice as many large aggregations (≥ 5 lobsters) at South La Jolla compared to Swami's. Within sites, similar to the regional level, single lobsters and aggregations ≥ 5 lobsters were more common than expected by chance at Cabrillo, South La Jolla, and Swami's (Cabrillo: df = 4, $\chi^2 = 16.00$, $P = 0.003$; South La Jolla: df = 4, $\chi^2 = 44.58$, $P < 0.001$; Swami's: df = 4, $\chi^2 = 26.60$, $P < 0.001$). Laguna was the only site where group size distribution did not reject the truncated Poisson model (df = 3, $\chi^2 = 3.56$, $P = 0.313$).

Many aquatic and terrestrial species exhibit gregarious behavior as an antipredator strategy because grouping with conspecifics may confuse predators via overstimulation, reducing the likelihood that any member of a group will be the target of a predatory attack. California spiny lobsters in aggregations may benefit from enhanced group defense mechanisms, including the cooperative use of antennae to ward of predators. Although lobsters generally exhibited gregarious behavior across the region, there were some differences among sites. For example, the abundance of flat rocks with deep ledges may have promoted communal sheltering over asocial behavior at some sites (e.g., Cabrillo and Swami's), whereas an abundance of stacked boulders and crevice shelters may have resulted in more solitary behavior at others (e.g., Laguna). Cabrillo had the highest mean lobster density and the highest level of predatory fish biomass recorded by the Vantuna Research Group, and 70% of all lobsters > 5.0 cm CL were gregarious within shelters at Cabrillo, with aggregations ≥ 5 lobsters more common than expected by chance. In contrast, at Laguna where lobster density was moderate and predatory fish biomass was low, only 50% of all lobsters > 5.0 cm CL were gregarious within shelters, and large aggregations were not common.

Though organismal abundance is the focus of most MPA monitoring, behavior is important to quantify as well. Gregariousness is used by lobsters as an antipredator strategy, and the level of gregariousness may change as MPAs age due to increasing lobster density, or as a response to increasing predator density. In contrast, if lobster mean size increases in MPAs, more lobsters may obtain a size refuge from predators, and the propensity for lobsters to form groups in shelters may decrease. These factors may be particularly important to evaluate for juvenile lobsters that are much more vulnerable to predators, as juveniles often are found in dens with large lobsters, which improves their odds of survival (Harrington 2014). We suggest that behaviors such as shelter use and the propensity for lobsters to be outside of shelter during the day be recorded as part of future monitoring efforts for California spiny lobsters.

Habitat mapping. The shelf supporting the La Jolla kelp forest (**Figure 23**) is composed of two large ridges oriented cross-shore, bisected by a drainage valley in the middle portion of the forest. The ridges exhibit complex bedding and compressional fracturing at multiple angles and scales that present spiny lobsters with an abundance of shelter habitat. The best predictors of lobster density included maximum curvature at the 50 m scale (the maximum observed curvature at a point in any direction), bottom depth, and minimum and cross-sectional curvature at the 10 m scale (minimum curvature is the curvature observed at a point that is orthogonal to the direction of maximum curvature; cross-sectional curvature is the curvature observed orthogonal to the direction of the maximum gradient, caused by features such as gulleys created by streams during times of lower sea level). We combined mapped benthic features with lobster counts from transects to generate predictive maps of lobster habitat. The maps were developed by using lobster counts at the sites and then using the random forest approach to compare lobster density (the dependent variable) to the bottom features derived from the acoustic map (the independent variables). Random forest techniques identify which derived bottom features are significantly related to lobster densities and those relationships are then used to calculate (predict) lobster density (a proxy of good habitat) over the entire forest.

Two versions of modeled spatial lobster occupancy were calculated. The first model included depth and several terrain features while the second version of the model utilized the same terrain features as the first model, but did not include depth. The random forest model that included depth (**Figure 24**) exhibited strong depth dependence with the greatest predicted lobster densities in shallow water. The partial dependence of lobster density on depth indicates a steep decline in lobster abundance between 12 and 18 meters depth. The

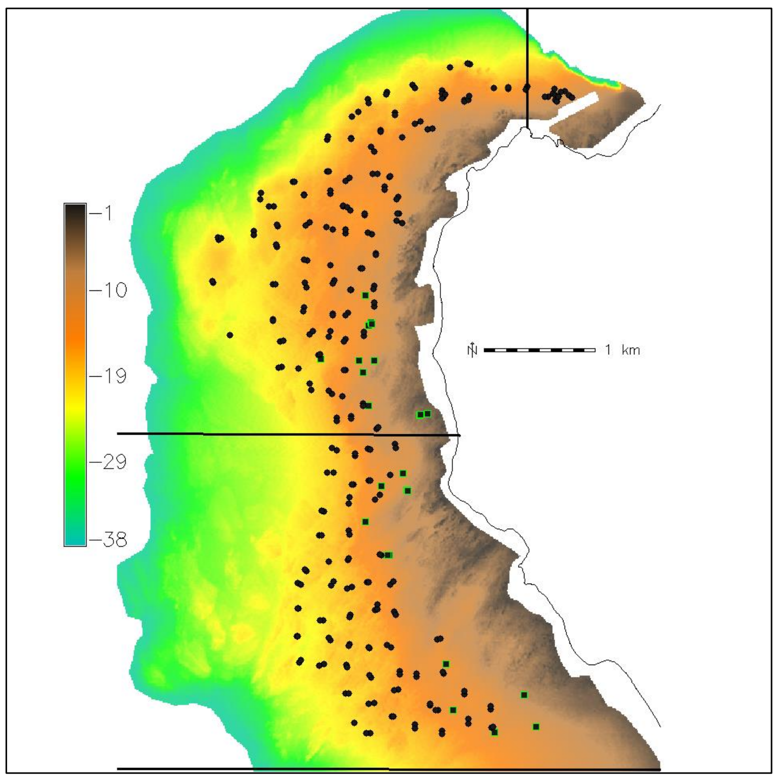


Figure 23. Bathymetry of the La Jolla kelp forest with locations of band transects. Solid circles indicate transects from earlier surveys (Parnell, 2002-2004) and black squares with green edges indicate transects conducted as part of the current study. Legend units are meters. Black lines indicate edges of the South La Jolla SMR and the Matlahyual SMR.

second random forest model (without depth) indicated abundant habitat deeper than 18 meters, based solely on bottom shape morphometrics (**Figure 25**). This result indicates that the deeper habitats are underutilized by spiny lobsters, even in the presence of greater fishing effort targeting the shallower portions of the shelf. This suggests that while spiny lobsters are observed at deeper depths (as deep as 75 m: Parnell, pers. obs.) off southern California, their occupancy

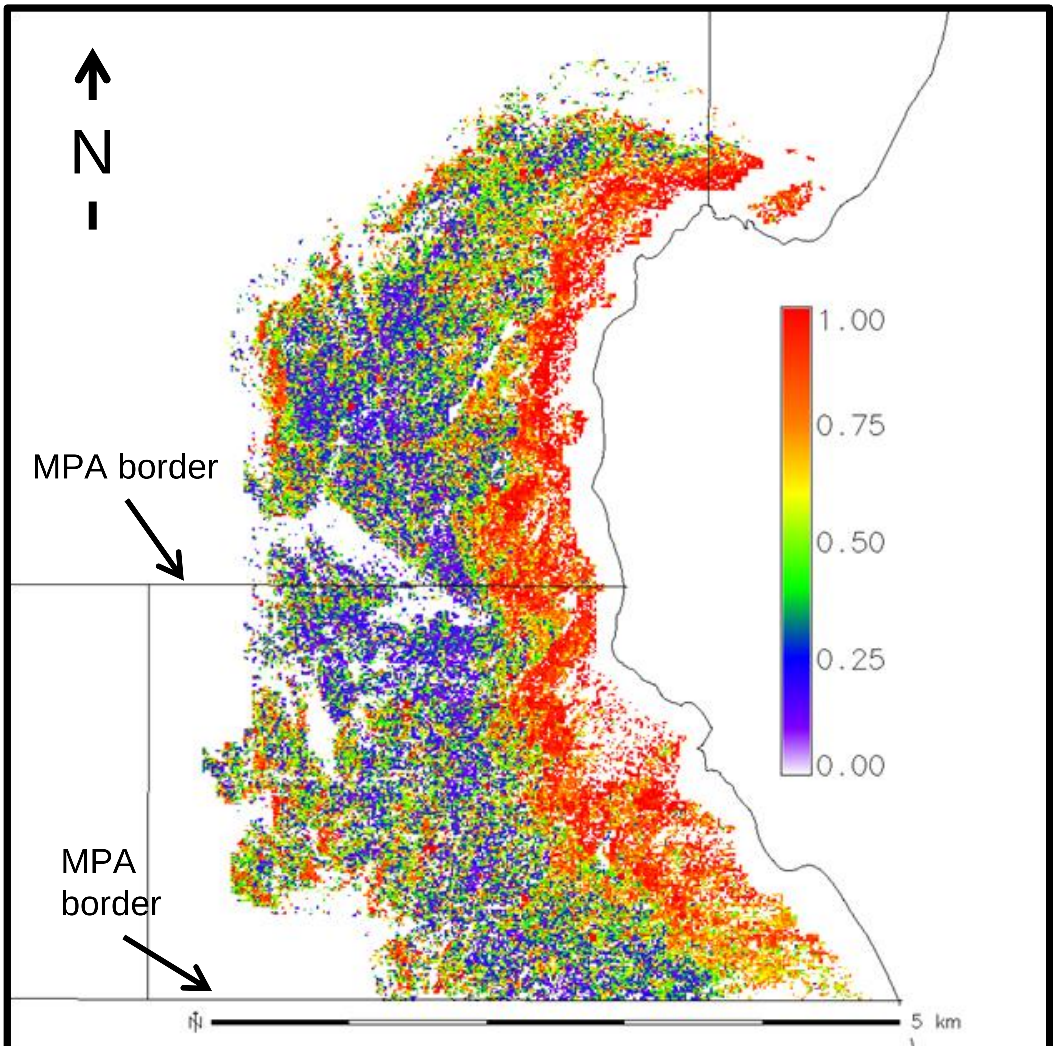


Figure 24. Spatial distribution of relative expected spiny lobsters density as a function of bottom terrain features. Predictions were based on a random forest analysis of acoustically-derived terrain features and depth with intensive in situ estimates of lobster density derived from in situ SCUBA-based band transect surveys. Red areas indicate maximum abundance, and purple areas indicate minimal abundance. The northern and southern borders of the South La Jolla SMR are shown.

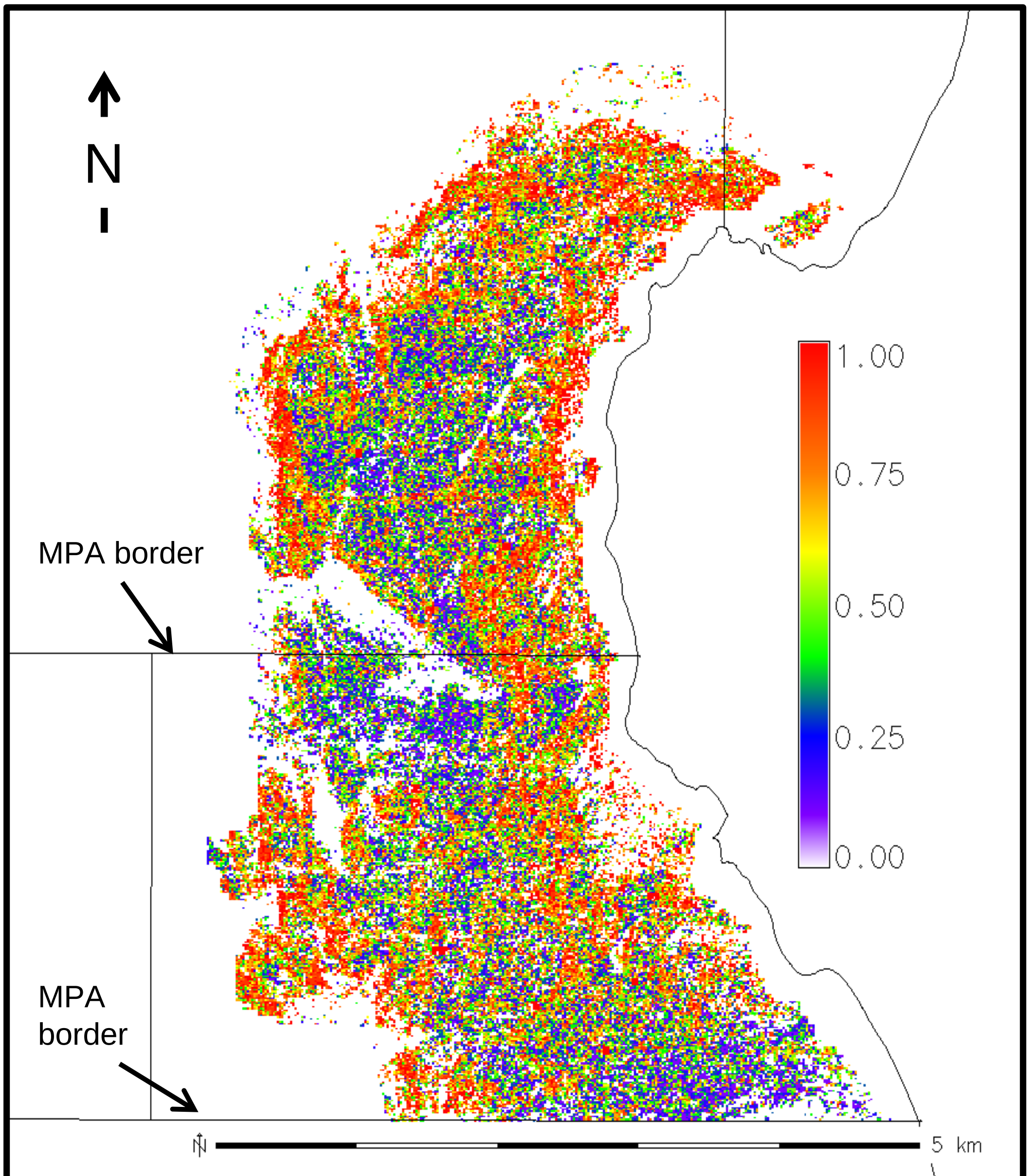


Figure 25. Spatial distribution of relative expected spiny lobsters density as a function of bottom terrain features. Predictions were based on a random forest analysis of acoustically-derived terrain features with intensive in situ estimates of lobster density derived from in situ SCUBA-based band transect surveys. **Depth was not included as a predictor in this version of the model.** Red areas indicate maximum abundance, and purple areas indicate minimal abundance. The northern and southern borders of the South La Jolla SMR are shown.

of similarly bottom-structured habitats at the deeper depths of the acoustic study (35 m) is depth limited. This strongly suggests that bottom structure as a factor for lobster occupancy is subsumed by other factors at depths > ~20 m or that bottom structure interacts differently with other such factors at different depths. These factors include but are not limited to the provision of food, temperature, differential lobster predator densities with depth, and differential depth distributions of potential biogenic shelters such as algae or surfgrass. It should be noted that human exploitation effort, perhaps the greatest source of adult spiny lobster mortality, is focused in shallow water yet the shallow distribution of spiny lobster persists indicating that at least one these other factors is apparently very important relative to bottom structure.

Summary for lobster surveys and habitat mapping

From the lobster surveys and habitat mapping, we found that:

1. There are differences in lobster density (over hard bottom habitat) between inside and outside of MPA borders for some MPAs. Cabrillo had a higher density of lobsters inside the MPA compared to outside, likely due to abundant surfgrass and cobble habitat close to shore at that MPA. At Swami's, and to a lesser extent South La Jolla, lobster density was higher outside the MPA than inside, also likely due to habitat distribution.
2. Lobsters use a variety of habitat types, and the odds of finding lobsters were correlated with different habitat types at different sites.
3. Lobsters may be found in groups or may be solitary when inhabiting daytime shelters. Though most lobsters were found in groups of 2 -5 lobsters, solitary lobsters were more common than expected by chance, as were large groups of more than 5 lobsters.
4. Lobster distribution in La Jolla is heavily skewed toward shallower habitats, despite the presence of apparently suitable habitat in deeper water and despite the fact that fishing pressure is highest in shallow water.

Short-term changes in lobster fishing

Initial changes in catch and effort for commercial lobster fishing

The purpose of this section is to characterize MPA effects by tracking changes in fishing location, effort, and success rates of fishermen. Lobsters are fished along the entire coast south of Point Conception and at all the Channel Islands. The fisheries involved include both recreational and commercial fishermen, with approximately 30,000 and 150 participants, respectively. Prior to the MPAs, commercial fishermen were already excluded from fishing in bays (including all of Santa Monica Bay), and the front side of Santa Catalina Island. These area closures for the commercial fishery were left intact, and after the 2012 MPA implementation, approximately 14.6% of the California bight (based on habitat estimates) is now closed to all lobster fishing (CA Department of Fish and Wildlife). Fishermen that had fished previously in areas that now are closed were required to move to new locations if they wanted to continue fishing. This was not a straightforward option for commercial fishermen, however. For the last 100 years, most if not all available fishing grounds were occupied by commercial fishermen. Although the boundaries between individual fishing grounds were not rigid, and overlap did occur, moving out of MPAs, no matter the distance, meant moving into an area already being fished by one or more fishermen. Moving was also restricted in some sense by fuel costs, both from home to the dock or launch ramp, and from there to the actual fishing grounds. Because of this, most commercial fishermen displaced by the MPAs were expected to move to areas adjacent to the MPAs. This would save on fuel costs, the fisherman would be more familiar with the available lobster habitat than if he moved to a more remote location, and he would still be fishing around the same fishermen (acclimated to his presence) as before.

Recreational fishermen confronted with an MPA where they used to fish may have had to shift as well but there was less affinity for an individual area overall. Individual fishermen might fish the same location but on any given day, the people fishing that location would change. The recreational fishery also included shore-based fishing via hoop nets from piers and jetties, by hand while diving from any beach access point, or from pleasure craft and kayaks. The CPFV fleet also offers hoopnetting trips which generally visit areas in proximity to their docks. Recreational fishers have more flexibility in how and where to catch lobsters, and are not under pressure to actually succeed at catching them. Because of this, there are no clear expectations of where a displaced recreational fisherman might move, nor an identifiable group that could be associated with a location year after year.

Because of site affinity relative to the commercial fishery, the analysis will focus on the commercial fishery only. The analysis will also be based on CDFW logbook data which contains location data in the form of fishing blocks and local landmarks. However, fishing blocks are limited to a resolution of 10 by 10 nautical miles, and landmarks are subject to a lack of specificity. For instance, block 860 encompasses the Point Loma peninsula, Mission Bay, parts of La Jolla, and parts of Coronado (**Appendix C**). Within this block, fishermen have specified the closest landmark as the entire Point Loma peninsula, while others might specify a specific location on the Point Loma peninsula (e.g. "green tank") for the same location.

Block Numbers and MPAs

Each of the 5 MPAs targeted for this study is enclosed within one or two CDFW fishing blocks (**Table 8**). One fishing block, 860, contains 2 of the targeted MPAs: Cabrillo and South La Jolla. Maps of MPAs and fishing blocks are shown in **Appendix C**.

Table 8. Association of MPAs and commercial lobster fishing blocks in Southern California.

MPA	Resident Fishing Block	Adjacent Fishing Blocks
Cabrillo SMR	860	842
South La Jolla SMR	860	878, 877
Swami's SMCA	821	801, 822, 842
Laguna Beach SMR	737	738, 757, 756
Point Vicente SMCA	720	719

Commercial Logbook Datasets

Datasets examined include commercial logbooks for the season immediately prior to MPA implementation (2010-11) and immediately after (2012-13). MPAs went into effect halfway through the 2011-12 season on January 1, 2012. For this analysis, therefore, the 2011-12 season dataset was split into pre- and post-implementation datasets. Because fishing effort drastically decreases in winter each year, during the 2011-2012 season MPA establishment coincided with a normal decrease in fishing effort. *Therefore the best comparison of pre vs. post-MPA implementation is between the 2010 – 2011 season and the 2012 – 2013 season*. Logbooks record daily activity of individual fishermen and include the location fished, number of traps pulled, and the number of lobsters landed.

Approximately 15,000 trap strings are pulled across the bight each season, with most (around 80%) occurring in the first half of the season. Each trap string can contain from 1 to about 300 traps although the majority have less than 100 traps. The median number of traps per string over the last 10 years is around 50.

Analyses

Logbook information for each fishing block associated with the five target MPAs was extracted and summarized by location and season. The data were then sorted by block, in north to south order, and by season. This provided a means to quickly determine if the number of fishermen, strings pulled, total traps pulled, and lobster landed changed from before MPA implementation to after. North to south ordering of the blocks allowed a simple analysis of whether fishermen were displaced from their normal fishing areas by the MPAs, whether they continued to fish, and whether they move up or down the coast.

Because the Laguna Beach SMR and SMCA fill the majority of a single fishing block (737), an attempt was made to track the logbook locations of individual fishermen before and after MPA implementation. Instead of relying on the fishing block numbers, this analysis used landmark data from the commercial logbooks. This was not attempted at the other sites.

Results: Point Vicente SMCA.

The Point Vicente SMCA is centered inside fishing block 720 (**Appendix C**) and forms an arc around the end of Palos Verdes Peninsula. A short distance north of the SMCA at Rocky Point the fishing block enters the Santa Monica Bay Commercial Fishing Closure which is closed to lobster fishing. To the east, Abalone Cove SMCA shares a boundary with the Point Vicente SMCA. After implementation of the MPAs, therefore, fishing block 720 only allows lobster fishing between the SMCA and Santa Monica Bay closure and east of Abalone Cove SMCA extending towards San Pedro in fishing block 719. Outside of the Los Angeles/Long Beach Harbors, fishing block 719 is open to commercial lobster fishing. Launch ramps and marinas can be found at Kings Harbor in Redondo Beach or inside the breakwater at the Los Angeles/Long Beach Harbors and Alamitos Bay. Point Vicente is located approximately halfway between these locations.

After the Point Vicente MPA became operational, the number of fishermen along the Palos Verdes/Long Beach coast dropped from 33 total to 22 (**Table 9**) and, since blocks 720 and 719 contain the entire Palos Verdes coastline fishable by commercial fishermen, the missing 11 fishermen either left the area entirely, or quit fishing for lobster. The majority of trap strings also shifted to block 719, adjacent to the MPA's resident block, 720; prior to the MPAs trap strings were more evenly distributed. Despite the drop in trap strings, the number of trap pulls and catch actually increased. The amount of lobster landed in block 719 in 2012-13 exceeded the combined catch in blocks 719 and 720 in 2010-11. Even with the reduced take in block 720 from the MPA, the general area enjoyed elevated catches, although CPUE of legal size lobsters dropped slightly from 0.37 to 0.34 lobsters per trap pull.

Table 9. Summary of fishing effort and catch associated with the Point Vicente SMCA. Values from the resident fishing block of the MPA (720) are marked in red. Block 719 covers portions of Palos Verde Peninsula and extends across Long Beach to approximately Los Alamitos. Blocks immediately to the north of fishing block 720 lie within the existing Santa Monica Bay Commercial Closure area and were not available for displaced fishermen. Note that the 2011-12 post-MPA period coincides with a decline in fishing effort that typically occurs in winter; declines in catch in 2011-12 (post-MPA) should not be interpreted solely as an effect of the MPA.

Fishing Block	**2010-11**	**2011-12 Pre-MPA**	**2011-12 Post-MPA**	**2012-13**
# Fishermen				
720	12	12	9	5
719	21	19	15	17
Total	***33***	***31***	***24***	***22***
# Trap Strings Pulled				
720	644	565	214	341
719	722	439	395	908
Total	***1,366***	***1,004***	***609***	***1,249***
# Trap Pulls				
720	31,938	40,034	13,898	17,925
719	57,071	40,547	29,975	87,214
Total	***89,009***	***80,581***	***43,873***	***105,139***
# Lobster Landed				
720	11,027	23,767	3,023	7,561
719	22,340	15,907	9,022	27,662
Total	***33,367***	***39,674***	***12,045***	***35,223***

Results: Laguna Beach SMR

The Laguna Beach SMR lies wholly inside fishing block 737 (**Appendix C**). Just to the south and sharing a border with the SMR is the Laguna Beach SMCA which also lies completely inside fishing block 737; the SMCA's southern boundary is the fishing block's southern boundary as well. Commercial lobster fishing is prohibited in both, and together these fill virtually the entire block. To the north and south of the Laguna Beach MPAs, and sharing a boundary, are SMCAs which do allow commercial fishing: the Crystal Cove and Dana Point SMCAs, respectively. Crystal Cove SMCA fills the remaining portion of fishing block 737 and extends into fishing block 738. From Laguna Beach, the Dana Point SMCA ends at the Dana Point Harbor breakwater. Dana Point Harbor, itself, lies outside the SMCA. The Dana Point SMCA lies entirely in fishing block 757 which extends south to approximately Capistrano Beach. South of this, fishing block 756 covers San Clemente to the northern part of Camp

Pendleton. Launch Ramp or marina access is either from Dana Point Harbor (south) or Newport Harbor (north) and the Laguna Beach SMR lies approximately halfway in between. Along this portion of the coast, fishing occurs primarily from Corona Del Mar/Newport Beach in the north to San Onofre/Camp Pendleton in the south and, while most fishermen are fairly localized in

Table 10. Summary of fishing effort and catch associated with the Laguna Beach SMR and Laguna Beach SMCA. Values from the resident fishing block of the MPA (737) are marked in red. Block 738 lies north of Laguna Beach and extends to Huntington Beach. Blocks 757 and 756 are to the south and together cover the coast from south Laguna Beach to San Onofre. Marina and launch access are at Newport Bay (block 738) to the north, and at Dana Point Harbor (block 757) to the south. Note that the 2011-12 post-MPA period coincides with a decline in fishing effort that typically occurs in winter; declines in catch in 2011-12 (post-MPA) should not be interpreted solely as an effect of the MPA.

Fishing Block	**2010-11**	**2011-12 Pre-MPA**	**2011-12 Post-MPA**	**2012-13**
# Fishermen				
738	7	11	9	7
737	12	16	5	7
757	21	22	13	22
756	15	15	9	16
Total	***55***	***64***	***36***	***52***
# Trap Strings Pulled				
738	344	284	214	386
737	489	361	57	104
757	726	568	257	686
756	631	475	267	792
Total	***2,190***	***1,688***	***795***	***1,968***
# Trap Pulls				
738	23,953	20,518	9,050	28,600
737	30,291	24,935	4,177	5,985
757	48,795	41,566	18,049	53,435
756	57,375	45,158	21,262	76,241
Total	***160,414***	***132,177***	***52,538***	***164,261***
# Lobster Landed				
738	8,399	8,061	2,322	12,179
737	12,511	11,213	282	3,278
757	23,589	14,775	2,475	18,276
756	20,844	18,325	4,640	26,307
Total	***65,343***	***52,374***	***9,719***	***60,040***

their trapping, historically it would not be unusual to see fishermen working the entire range (pre-MPA) over the course of several days to a week.

Like the Point Vicente SMCA, the resident block (737) for the Laguna Beach SMR/SMCA experienced a drop in the number of fishermen operating, and the number of trap strings pulled, in the block (**Table 10**). The combined number of fishermen in all 4 fishing blocks was lower in 2012-13 than in 2010-11 and, similar to the Point Vicente SMCA, the missing 5 fishermen either left the area entirely or quit fishing. Continuing the parallels with Point Vicente SMCA, trap pulls and landed catch increased. However the post-MPA CPUE of legal size lobsters dropped slightly from 0.41 to 0.37 lobsters per trap pull.

The Laguna Beach individual fishing history (**Table 11**) demonstrates displacement as well. In 2010-11, this individual fished primarily from Dana Point, north to Crystal Cove. In the lead up to MPA implementation, more areas around Laguna Beach were visited and fishing expanded to both the north (Arch Rock) as well as the south. Once implementation of the MPAs was complete, however, fishing contracted and the northern locations were completely missing. South Laguna Beach, previously the southernmost point fished in blocks 738 and 737, became the northern most point fished. The individual, post-MPA has now expanded to the south as far as San Clemente.

Results: Swami's SMCA

The coastal portions of the Swami's SMCA suitable for lobster fishing are located in block 821 (**Appendix C**). The SMCA shares the southern boundary with the block and extends about 40% of the way up the block's coastline. A portion of the SMCA, offshore, also lies in fishing block 822 but is generally too deep for lobster fishing and all occurrences of block 822 in the commercial logbooks refer to the corner of the block that meets land at Carlsbad. North of fishing block 822, fishing block 801 contains the remainder of the San Diego County coastline, including Oceanside and Camp Pendleton. Immediately south of the Swami's SMCA, fishing block 842 extends to La Jolla. Block 842 is also the long-time location, in the south, of the La Jolla Reserve, now expanded and called the Matlahuayl SMR. Combined with the adjacent San Diego-Scripps SMCA, lobster fishing in block 842 is restricted to the northern half, and a small sliver at the southern edge adjacent to Scripps Park. Marina and boat launch access is south in Mission Bay (block 860, not shown) or Oceanside (block 801) to the north. Both locations involve a long cruise to the Swami's area. However, the landmark Encinitas in block 821 is well represented in the historical logbook record.

Between 2010-11 and 2012-13, the number of fishermen in the area around Swami's did not change significantly, nor did they fish more trap strings (**Table 12**). However, the number of trap pulls increased about 8% while the landed catch declined 13%. Overall, the CPUE dropped from 0.61 legal size lobsters per trap pull (the highest of the five MPA regions examined here) to 0.49 lobsters per trap pull.

Table 11. Example of the changes in fishing landmarks over time from before MPA implementation, to after (yellow). Landmarks were used at least once during the associated seasons and were either specific locations (e.g., Heisler Park), a range of coastline (e.g. Dana Point to Salt Creek), or a general area (e.g., South Laguna Beach). Landmark names originated with the fishermen. Landmarks are roughly ordered from North to South within each fishing block. Dana Point, the primary access for this area, is situated approximately in the middle of the coastal range of these four fishing blocks.

Block	2010	2011a	2011b	2012
738		Arch Rock		
737	Crystal Cove Laguna Beach South Laguna Beach	Aliso Beach Sewer Pipe Crystal Cove Heisler Park Laguna Beach South Laguna Beach	South Laguna Beach	South Laguna Beach
757	Dana Point to South Laguna Beach Whistle Buoy 2SJR to Three Arch Bay Salt Creek Dana Point to Salt Creek San Juan Rocks to Salt Creek Whistle Buoy 2SJR to Salt Creek Whistle Buoy 2SJR San Juan Rocks Dana Point Dana Point Jetty Doheny State Beach	Salt Creek Dana Strand Beach to Salt Creek San Juan Rocks to Salt Creek San Juan Rocks Dana Point Wall to San Juan Rocks Dana Strand Beach Dana Point Wall Dana Point West Jetty Dana Point Pipe Doheny State Beach to West Jetty Doheny State Beach	Salt Creek San Juan Rocks to Salt Creek San Juan Rocks Dana Point Wall to San Juan Rocks Dana Point West Jetty Dana Point Pipe Doheny State Beach to West Jetty Doheny State Beach	Salt Creek Dana Point Harbor to Salt Creek Dana Point Doheny State Beach Dana Point to Dana Point Pipe Dana Point to Poche County Beach
756		Wheeler North Artificial Reef		Camp Pendleton Dana Point Harbor to North Beach Dana Point Harbor to Poche County Beach Dana Point Harbor to San Juan Capistrano Dana Point Harbor to Seal Rock Dana Point Harbor to West Reef Poche County Beach San Clemente Pier to San Onofre San Onofre to Poche County Beach San Onofre to Seal Rock Seal Rock to San Onofre Trestles to Poche County Beach

Table 12. Summary of fishing effort and catch associated with Swami's SMCA (block 821, marked in red). Blocks 801 and 822, to the north, extend from Carlsbad to San Clemente. The Oceanside marinas and launch ramps are located in block 801. Block 842 is to the south extending to La Jolla. The closest access point to the south is in Mission Bay (past block 842 in block 860). Note that the 2011-12 post-MPA period coincides with a decline in fishing effort that typically occurs in winter; declines in catch in 2011-12 (post-MPA) should not be interpreted solely as an effect of the MPA.

Fishing Block	**2010-11**	**2011-12 Pre-MPA**	**2011-12 Post-MPA**	**2012-13**
# Fishermen				
801	4	4	4	5
822	8	9	5	7
821	9	14	9	8
842	14	16	10	13
Total	***35***	***43***	***28***	***33***
# Trap Strings Pulled				
801	94	104	51	193
822	136	150	73	341
821	637	565	214	299
842	556	525	189	604
Total	***1,423***	***1,344***	***527***	***1,437***
# Trap Pulls				
801	4,959	5,516	3,180	12,124
822	7,268	7,712	3,940	17,925
821	36,135	40,034	13,898	20,339
842	23,954	21,694	5,354	27,718
Total	***72,316***	***74,956***	***26,372***	***78,106***
# Lobster Landed				
801	2,800	3,662	1,156	5,629
822	3,383	5,034	1,149	7,561
821	21,366	23,767	3,023	9,090
842	16,581	14,721	1,722	16,046
Total	***44,130***	***47,184***	***7,050***	***38,326***

Results: Fishing Block 860

Fishing block 860 contains 2 new MPAs: The South La Jolla SMR, and the Cabrillo SMR (**Appendix C**). Both SMRs prohibit lobster fishing in areas that historically allowed it. Fishing block 860 has for decades recorded the highest catch of any block in the southern California bight, regularly accounting for 15-20% of the entire bight's lobster catch, and some of its highest effort. The block is also recognized as a location that favors smaller lobster; approximately 70% of the commercial catch is discarded each season as shorts (lobsters smaller than legal size). Launch ramps and marinas for block 860 are located at both Mission Bay, and inside San Diego Bay. Mission Bay is closer to South La Jolla SMR but either Bay can be used to access block 860.

South La Jolla SMR. South La Jolla SMR is located at the northern end of block 860 (**Appendix C**), approximately 2 miles south along the coast from the Matlahuayl SMR (in fishing block 842), and extends down almost to Mission Beach. The South La Jolla SMCA is located adjacent to the offshore end of the SMR and extends into fishing block 861, but is generally too deep for lobster fishing and absent from the logbook record. Open coast with rich lobster habitat extends south to the Cabrillo SMR located at the southern end of block 860.

Cabrillo SMR. Cabrillo SMR is a small MPA (**Appendix C**) that primarily includes a portion of Point Loma contained in the Cabrillo National Monument in fishing block 860. Fishing block 878 includes the extreme tip of Point Loma near the lighthouse, which was fished for lobster prior to inclusion in the Cabrillo SMR. The east side of Point Loma, also in block 860 forms the western side of the entrance channel to San Diego Bay and commercial lobster fishing is not allowed. Because of its size, displacement north by implementation of the Cabrillo SMR would only add a few minutes motoring time coming from San Diego Bay, or shorten the distance the same amount coming from Mission Bay. There is limited commercial fishing in the southern portion of block 860 along Coronado and fishing grounds farther south than this are generally along Imperial Beach near the Mexican border in block 877.

Unlike the other blocks examined, block 860 and its neighbors experienced relatively little change between 2010-11 and 2012-13 in trap pulls and landed catch (**Table 13**). However, there was a 10% drop in fishermen active in the blocks, and they set 10% more trap strings (2010-11 vs. 2012-13). Trap pulls and landed catch, combined across all the blocks, remained at similar levels, and CPUE measured 0.51 lobsters per trap pull (0.54 prior to the MPAs), the highest of all the blocks examined.

Table 13. Summary of fishing effort and catch associated with Block 860, which contains two target MPAs: South La Jolla SMR, and Cabrillo SMR (the southern half of Cabrillo SMR is actually located in fishing block 878). Block 860 also includes the access points at Mission Bay, and northern San Diego Bay. Block 877 extends south into Mexico, while block 842 covers the San Diego coast from La Jolla to Encinitas. The Matlahuayl SMR and San Diego-Scripps SMCA are located at the southern end of block 842. Dash marks signify data excluded for legal reasons. Note that the 2011-12 post-MPA period coincides with a decline in fishing effort that typically occurs in winter; declines in catch in 2011-12 (post-MPA) should not be interpreted solely as an effect of the MPA.

Fishing Block	**2010-11**	**2011-12 Pre-MPA**	**2011-12 Post-MPA**	**2012-13**
# Fishermen				
842	14	16	10	13
860	42	44	33	38
878	-	-	-	-
877	5	4	-	5
Total	***61***	***64***	***43***	***56***
# Trap Strings Pulled				
842	556	525	189	604
860	3,333	2,646	958	3,579
878	41	2	28	40
877	100	57	13	162
Total	***4,030***	***3,230***	***1,188***	***4,385***
# Trap Pulls				
842	23,954	21,694	5,354	27,718
860	196,386	168,761	44,608	21,0317
878	3,341	227	1,948	3,594
877	9,747	4,877	1,200	10,603
Total	***233,428***	***195,559***	***53,110***	***252,232***
# Lobster Landed				
842	16,581	14,721	1,722	16,046
860	100,113	87,315	12,993	107,074
878	1,924	32	736	1,390
877	7,556	3,708	544	6,640
Total	***126,174***	***105,776***	***15,995***	***131,150***

Generally, evidence exists to show that fishermen continued to fish their usual locations where MPAs would soon be located up to their implementation on January 1, 2012. In some cases (e.g., Swami's SMCA), fishing increased in the 3 months immediately prior to an MPA's establishment. The level of fishing in blocks containing an MPA in 2012-13 (post-MPA) returned to 2010-11 (pre-MPA) levels if those blocks could absorb the displaced fishermen. Where the blocks could not absorb the displaced, fishing effort dropped substantially. For instance, Point Vicente SMCA and Laguna Beach SMR/SMCA essentially filled their associated blocks, increasing the probability that fishermen would have to move to neighboring blocks to continue fishing the area. The number of fishermen fishing these MPAs in 2012-13 was approximately half the numbers from 2010-11. After implementation of the MPAs these two blocks experienced reduced levels of effort and catch at the same time that adjacent blocks increased effort and catch.

Overall, fishermen adapted to the presence of the MPAs and, where possible, moved to adjacent fishing grounds. On a bight-wide scale, the MPAs did not appear to impact the level of catch, and while some fishermen may have been impacted, the level of catch and effort does not appear to be significantly different than in previous seasons. In 2010, 939,485 traps were pulled and 450,549 lobsters landed (landed CPUE of 0.48). In 2012, effort increased to 1,131,700 traps pulled, but landings increased as well to 565, 118 (for an increased CPUE of 0.50). It should be noted that this analysis includes only one year of data for post-MPA implementation; future monitoring of CPUE, incorporating longer time periods, may yield alternative conclusions.

Short-term distribution of commercial fishing effort in La Jolla

We estimated the spatial distribution of commercial lobster fishing as per Parnell et al. (2007), which involves noting the location of lobster buoys marking individual lobster traps used by commercial fishermen. We did this in particular to gauge the intensity of edge fishing on the borders of the South La Jolla SMR. One possible result of implementation of MPAs is "fishing the line" in which many traps (and associated buoys) are placed along the MPA border to capture large lobsters spilling over from MPAs, as is the case for the Matlahuayl MPA in La Jolla, a long-established MPA. Though we do not necessarily expect an immediate shift in fishing effort to the border of the MPA (in part because MPAs need many years before effects on fishery populations may take effect), we performed a short survey on 6 October 2012, within three days of the opening of the first lobster season after protection went into effect, to get baseline information on this behavior for comparison to future years. Traps were counted while navigating tracklines based on a 250m grid pattern developed using Grass GIS. The map and tracklines were then transferred to a PC equipped with navigational software (Fugawi ENC, http://www.fugawi.com/web/products/fugawi_marine_enc-in.htm) and interfaced to a GPS (Hemisphere V110). The survey area included all of La Jolla from the lowest intertidal to the 35 m contour.

The northern and southern edges of the South La Jolla SMR were fished extensively (**Figure 26**). The survey was conducted only at the beginning of the season, but frequent later visits conducted for other research during the two lobster seasons since the South La Jolla SMR establishment indicate this pattern of edge fishing to be robust throughout the lobster season (Parnell, pers. obs.). The density of traps near these edges during the 2006/2007 season (see Parnell et al., 2007), well before MPA establishment, was much less. Overall, lobster trapping effort throughout La Jolla on the opening week of the 2006/2007 season declined from 3,333 traps to 2,256 traps during the first week of the 2012/2013 season when the South La Jolla SMR was in effect. While the overall number of traps declined due to the protected area, lobster trap densities in the area still open to fishing in La Jolla increased by ~37%, because ~48% of the lobster fishing grounds off La Jolla were lost to the South La Jolla SMR.

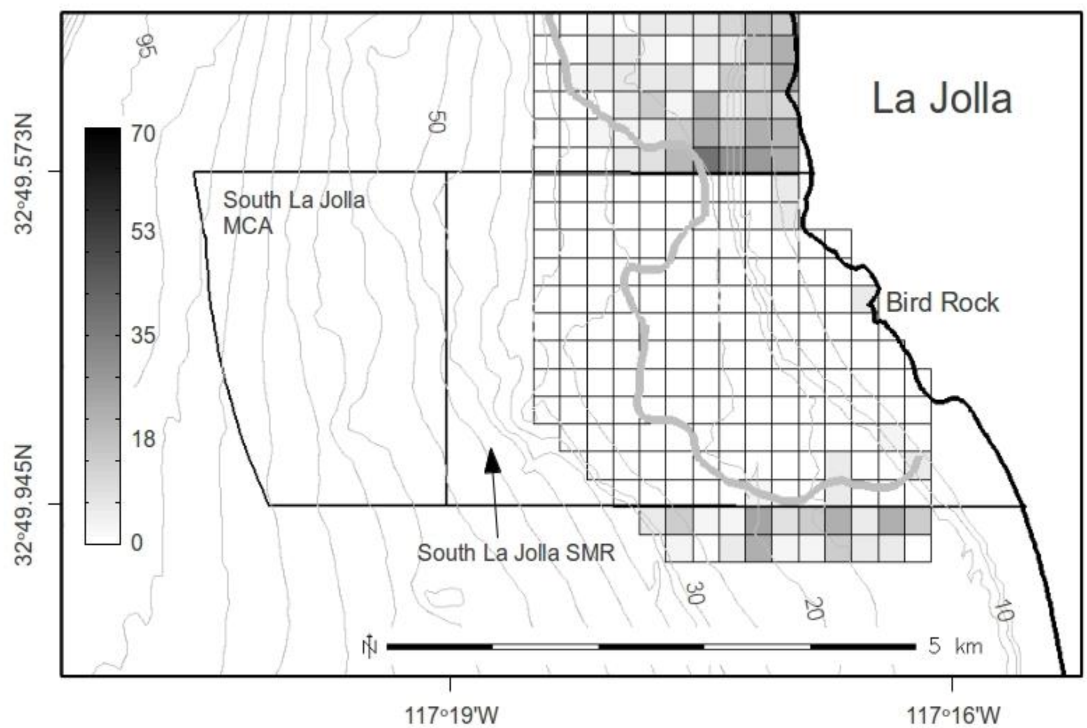


Figure 26. Distribution of commercial lobster fishing effort (trap float density) on 6 October 2012, the first week of the commercial lobster fishing season, estimated from counts conducted from a small vessel. Shading indicates number of traps observed in each box. Grid dimensions are 250m on each side.

Summary for short-term changes in lobster fishing

Our analysis of short-term changes revealed that:

1. Regionally, CPUE did not fall after MPA establishment. Fishermen moved to adjacent fishing grounds where possible (particularly in the San Diego area).
2. The establishment of the South La Jolla SMR corresponded to a decline in the number of lobster traps fished and an increase in the density of traps in areas still open to fishing.

Deviations from original work plan

The following is an explanation of how and why our research deviated from our original work plan in some instances.

1. *We did not conduct surveys in the Matlahuayl SMR in La Jolla as planned.*

Extensive surveys in this long-standing MPA have been conducted and are presented in numerous publications (e.g., Parnell et al. 2006, Withy-Allen and Hovel 2013). We decided a better use of our time and resources was to sample more extensively in the other, newly established MPAs, including the South La Jolla SMR, which is nearly adjacent to the Matlahuayl SMR (raising questions of independence between any surveys conducted in the two MPAs). We also note that the small Matlahuayl SMR is extremely popular with swimmers, kayakers, and divers, making it difficult and potentially dangerous to deploy and sample research traps in this MPA.

2. *Benthic habitat mapping was conducted by boat rather than by using Cobra-Tac diver held acoustic bathymetric and navigation ADCP as planned.*

We tested the Cobra-Tac system, and unfortunately found that navigation error was greater than initially specified by the manufacturer (RDI Instruments) resulting in too much error to be useful even at small spatial scales. The single beam vessel mounted acoustic system was used instead which enabled resolving bathymetric features at a spatial scale of ~10 m. The vessel mounted system also enabled surveying of the entire kelp forest rather than several smaller areas that would have been possible with the diver held Cobra-Tac.

3. *We did not measure the dimensions of shelters used by lobsters as planned.*

This is partially true; we did measure the height of shelters used by lobsters, and the type of shelters they occupied, in our 2013 benthic surveys. However, our analysis of shelter scaling, performed for a master's thesis associated with this research, revealed wide variability in shelter use and limited utility in assessing the size of shelters used by solitary lobsters. Instead, we found much stronger and interesting patterns in the number of lobsters occupying shelters, which we cover in this report.

4. *We did not estimate population size at each site using mark-recapture equations.*

We did in fact use the Schnabel equation (see Odemar 1975) to estimate population size based on the mark-recapture data from each site. However, we chose not to include these estimates in our final report for a few reasons. First, it was difficult to accurately estimate the area over which lobsters were sampled at each site, and sampling areas necessarily differed among sites in correspondence with the different sizes of MPAs.

Moreover, the true areas over which lobsters may be sampled likely are dependent on bottom topography and benthic habitat characteristics, which are site-specific. An estimate of population size should correspond to an area over which the population can be found, and this technique may be more applicable to discrete sampling areas such as a lake, cove, or isolated reef. Second, our strategy of sampling for lobsters in the proximity of MPA borders, to measure spillover, means that we cannot report on estimated population size within MPAs at each site. Rather, our SCUBA-based transect surveys are better indications of lobster abundance within the MPAs.

Conclusions, recommendations, and research partnerships

California spiny lobsters are a valuable resource, but heavily fished commercially and recreationally. The State of California recently conducted the first stock assessment for this species (Neilson 2011), and presently is engaged in developing a fishery management plan to help prevent (and if necessary, respond to) reductions in catch. Though South Coast MPAs were not designed specifically to protect spiny lobsters, one of their potential benefits is enhanced abundance and size of this heavily harvested species. MPAs have been used in many places throughout the world to enhance spiny lobster populations and to maintain fisheries via the creation of source populations and spillover, and results from other locations indicate that spiny lobster populations can respond relatively quickly to protection within MPAs, and enhance fisheries in nearby waters (e.g., Kelly and MacDiarmid 2003, Goñi et al. 2006). This includes California spiny lobsters, whose populations may rapidly rise within MPAs after establishment (Iacchei et al. 2005, Kay et al. 2012). However, their long larval durations, small home ranges, and strong dependence on benthic habitat (particularly during nocturnal foraging when they may spill over MPA boundaries) create uncertainty regarding the degree to which an MPA or network of MPAs may result in larger lobster populations, particularly at regional spatial scales. For instance, spiny lobster mean size typically increases within MPAs as MPAs age, which results in greater egg production. However, larvae reside in planktonic waters for 8 – 10 months and may be carried great distances from their source, creating uncertainty as to whether more productive lobster populations within MPAs will result in enhanced population growth on a regional scale. Thus, additional MPA monitoring is critical for determining whether potential benefits of MPAs for lobsters and fisheries are realized at regional scales, or only at local scales. Such analyses should be accompanied by a detailed assessment of fishing pressure and changes to the fishery to enable a determination of the relative effects of harvest vs. protection in MPAs on lobster populations.

Our study established baseline levels of spiny lobster abundance, size frequency, growth, and behavior that we hope will be useful in future monitoring for this species, as well as in current efforts to assess and model lobster populations. Overall, we found gradients in abundance, size, and growth with latitude that correspond to overall fishery trends in the region. The highest lobster yield comes from the San Diego area, where we found lobster abundance (CPUE) to be substantially higher than in sites farther north. This corresponds to historical high fishing effort in San Diego County as well as to the high landings consistently seen in this region (Figure 6). Trends in abundance accompanied latitudinal trends in lobster body size and growth, which were highest in the northern sites that we studied (in particular, Laguna Beach). Trapping indicated that, at the outset of these MPAs (established in January 2012), there is little difference in lobster populations inside vs. outside of each MPA. SCUBA surveys indicated a somewhat different pattern (higher densities inside vs. outside of the Cabrillo MPA, but higher densities outside vs. inside at Swami's), but we note that trapping and SCUBA surveys measure different aspects of lobster abundance. The higher density of lobsters outside or inside of MPAs is a product of where lobster habitat is located, or where lobster prey or predators are located, or (most likely) some combination of these factors. Data from SCUBA surveys should be interpreted as a measure of lobster abundance over a relatively narrow range of habitat types, which we targeted primarily to establish lobster-habitat associations. In contrast, the best measure of differences among sites and region-wide trends in lobster abundance are data from trapping.

The analysis of lobster-habitat associations, and our predictive model of lobster habitat provided two key findings that should be considered in future monitoring and conservation: (i) lobsters are not consistently associated with only one habitat type, and (ii) lobsters may not occupy suitable habitats (in particular, in deeper water) for reasons we do not yet understand. Finally, the expanded sampling of the lobster population for monitoring has provided more accurate estimates of the sizes and maturities of lobsters than previously available, and will allow CDFW to bring all its currently models into conformance with each other.

We instituted a collaborative fisheries research (CFR) program, similar to that used by Kay et al. (2012), to survey each MPA for lobster abundance, size distribution, and movement (spillover). There were two key reasons to structuring our research in this framework:

1. it allowed us to implement a variety of monitoring tools. Building a strong team of researchers from academia and industry, with different expertise, allowed us to focus on several different components of monitoring which contributed different but complementary information. *We strongly recommend that future monitoring also involve a combination of techniques and analyses*, including boat-based trapping (which can survey a substantial fraction of the lobster population and provide the best estimates of trends in population size and lobster body size) and SCUBA-based surveys (which can establish lobster-habitat associations and assess behavioral shifts). Though these tools should form the backbone of a comprehensive monitoring program, modern technological tools will be very useful additions. This includes habitat mapping at high resolutions, particularly in shallow water, and assessments of lobster movement, home range size, and spillover using acoustic tracking.
2. CFR promotes buy-in from the fishing community that monitoring is being done correctly and that the data accurately reflect population trends of fishery species. CFR involves a collaboration between fishers, scientists, and others to collect data on fishery species, and show great promise for unbiased assessments of how populations change through time because fisher knowledge and experience is combined with scientific rigor. *The contributions of the fishing community, in terms of local*

ecological knowledge (LEK), were invaluable in our research and can contribute substantially to future monitoring efforts (see also Kay et al. 2012).

Our goal was to go beyond a collaboration between fishers and scientists and involve the public in our research. We therefore established a strong corps of volunteers we could rely on to assist with lobster tagging. Through the San Diego Oceans Foundation, we reached out to over 20,000 southern Californian residents within the SDOF database to recruit volunteers for this project. With the help of the SDOF staff and program interns, we received hundreds of volunteer applications. Volunteers were interviewed individually, and then were required to read a volunteer manual, upon which they were tested before being allowed to go to sea. Once trained, volunteers helped the lobster fishermen and scientists capture and record data. SDOF also created and maintained a website for fishers to use to report tagged lobsters they have caught. This program was designed to supplement our own recapture data on tagged lobsters with reports from commercial and recreational fishers on the size and location of any tagged lobster captured in commercial traps, hoop nets, or by hand. We advertised this program over the internet, and in person through meetings with lobster fishers and via word-of-mouth. Anyone who captured a tagged lobster was able to enter relevant information on a website specifically designed for this purpose (www.taggedlobster.com), or call the San Diego Oceans Foundation with the information. This information was used to help establish the baseline estimates of movement presented in this report, though it represents a small fraction of lobsters analyzed compared to our own recapture efforts (which were specifically targeted at the consistent locations and focused inside MPAs).

Lastly, future monitoring for California spiny lobsters may be integrated with other forms of monitoring. Lobsters are heavily habitat-dependent, suggesting that detailed maps of benthic habitats can be used in conjunction with information on lobster density to create maps of suitable lobster habitat and to identify hotspots for abundance, growth, and catch. This could be done using our predictive habitat mapping as a template, and might be particularly valuable to assess potential changes to lobster populations in the face of climate change. Lobsters also strongly interact with other fauna and flora in their communities. A useful integration could involve testing for correlations (positive or inverse) between lobster density and the density of urchins, algae, and potential lobster predators (large fishes). Visual surveys could be combined with more integrative techniques such as stable isotope analysis to develop a more comprehensive picture of the role that lobsters play in maintaining healthy coastal ecosystems.

References cited

Bivand, R. 2007. Using the {R}--{GRASS} Interface: Current Status. OSGeo Journal, 1, pp. 36-38.

Follesa, M.C., D. Cuccu, R. Cannas, A. Sabatini, A.M. Deiana, and A. Cau. 2009. Movement patterns of the spiny lobster *Palinurus elephas* (Fabricius, 1787) from a central western Mediterranean protected area. Scientia Marina 73: 499-506.

Frisch, A. J. 2007. Short- and long-term movements of painted lobster (*Panulirus versicolor*) on a coral reef at Northwest Island, Australia. Coral Reefs 26: 311–317.

Goforth, H., and S. U'Ren. 1980. A survey of the spiny lobster (*Panulirus interruptus*) population in San Diego Bay, California. Technical report 542, Naval Ocean Systems Center, San Diego, CA.

Goni, R., A. Quetglas, and O. Renones. 2006. Spillover of spiny lobsters *Palinuris elephas* from a marine reserve to an adjoining fishery. Mar Ecol Prog Ser 308: 207–219.

Harrington, A.M. 2014. Impacts of shelter scaling and group composition on the relative survival of subadult California spiny lobster (*Panulirus interruptus*). MS Thesis, Department of Biology, San Diego State University.

Hovel, K.A. and D. Neilson. 2011. Movement and population size of spiny lobsters in San Diego Bay. Final report to the Unified Port District of San Diego. 30 pp.

Iacchei, M., Robinson, P., and K.A. Miller. 2005. Direct impacts of commercial and recreational fishing on spiny lobster, *Panulirus interruptus*, populations at Santa Catalina Island, California, United States. NZ J Mar Freshw Res 39: 1201–1214.

Kay, M.C., H.S. Lenihan, C.M Guenther, J.R. Wilson, C.J. Miller, and S.W. Shrout. 2012. Collaborative assessment of California spiny lobster population and fishery responses to a marine reserve network. Ecological Applications 22: 322-335.

Kelly, S. and A.B. MacDiarmid. 2003. Movement patterns of mature spiny lobsters, *Jasus edwardsii*, from a marine reserve. NZ J Mar Freshw Res 37: 149-158.

Lindberg, R.G. 1955. Growth, population dynamics and field behavior of the spiny lobster, *Panulirus interruptus*. Univ Cal Publ Zool 59:157-247.

Mitchell, C.T., C.H. Turner, and A.R. Strachan. 1969. Observations on the biology and behavior of the California spiny lobster, *Panulirus interruptus* (Randall). California Department of Fish and Wildlife 55: 121-131.

Mitasova, H. and L. Mitas. 1993. Interpolation by regularized spline with Tension: I. Theory and Implementation. Math. Geol. 25:641-655.

Mitasova, H., Mitas, L., Brown, W., Gerdes, D., Kosinovsky, I. and T. Baker. 1995. Modeling spatially and temporally distributed phenomenon: New methods and tools for GRASS GIS. Int. J. Of GIS, Special issue on Integrating GIS and Environmental modeling 9(4):433-446.

Neilson, D.J. 2011. Assessment of the California Spiny Lobster (*Panulirus interruptus*). Final, post technical review, report submitted to and approved by the California Fish and Game Commission. 138p.

Odemar, M.W., R.R. Bell, C.W. Haugen, and R.A. Hardy. 1975. Report on California spiny lobster, *Panulirus interruptus* (Randall) research with recommendations for management. Report to the State of California Resources Agency, Department of Fish and Wildlife. 98 pp.

Parnell, P.E., Dayton P.K., Lennert-Cody C.E., Rasmussen L.L., and J.J. Leichter. 2006. Marine reserve design: optimal size, habitats, species affinities, diversity, and ocean microclimate. Ecological Applications 16: 945-962.

Parnell P.E., Dayton, P.K., and M. Francesca. 2007. Spatial and temporal patterns of lobster trap fishing: a survey of fishing effort and habitat structure. Bulletin of the Southern California Academy of Sciences 106:27-37.

Robles, C.D., Sweetnam, D., and J. Eminike. 1990. Lobster predation on mussels: shore-level differences in prey vulnerability and predator preference. Ecology 71: 1564–1577.

Withy-Allen, K.R. and K.A. Hovel. 2013. California spiny lobster (*Panulirus interruptus*) movement behaviour and habitat use: implications for the effectiveness of marine protected areas. NZ J Mar Freshw Res 64: 359-371.

Appendices

Appendix A. Number of lobster trapping days in 2011, 2012, and 2013 for each site. An equal number of traps were fished inside on outside of MPAs on each day at each site. Tally of trapping days does not include the day on which traps were deployed but not fished. Note that we conducted the trap comparison study in South La Jolla in July 2013, resulting in a high number of trapping days for that month.

		Number of trapping days				
Year	**Month**	Cabrillo	South La Jolla	Swami's	Laguna	Vicente
2011	Sep	2	2	0	2	0
	May	2	2	2	0	2
	June	2	2	2	4	2
2012	July	2	2	2	2	0
	August	2	2	2	4	2
	Sep	0	0	0	0	2
	May	0	0	0	0	0
	June	0	0	2	2	0
2013	July	2	8	0	2	2
	August	0	0	2	0	0
	Sep	0	0	0	0	0
	TOTAL	**12**	**18**	**12**	**16**	**10**

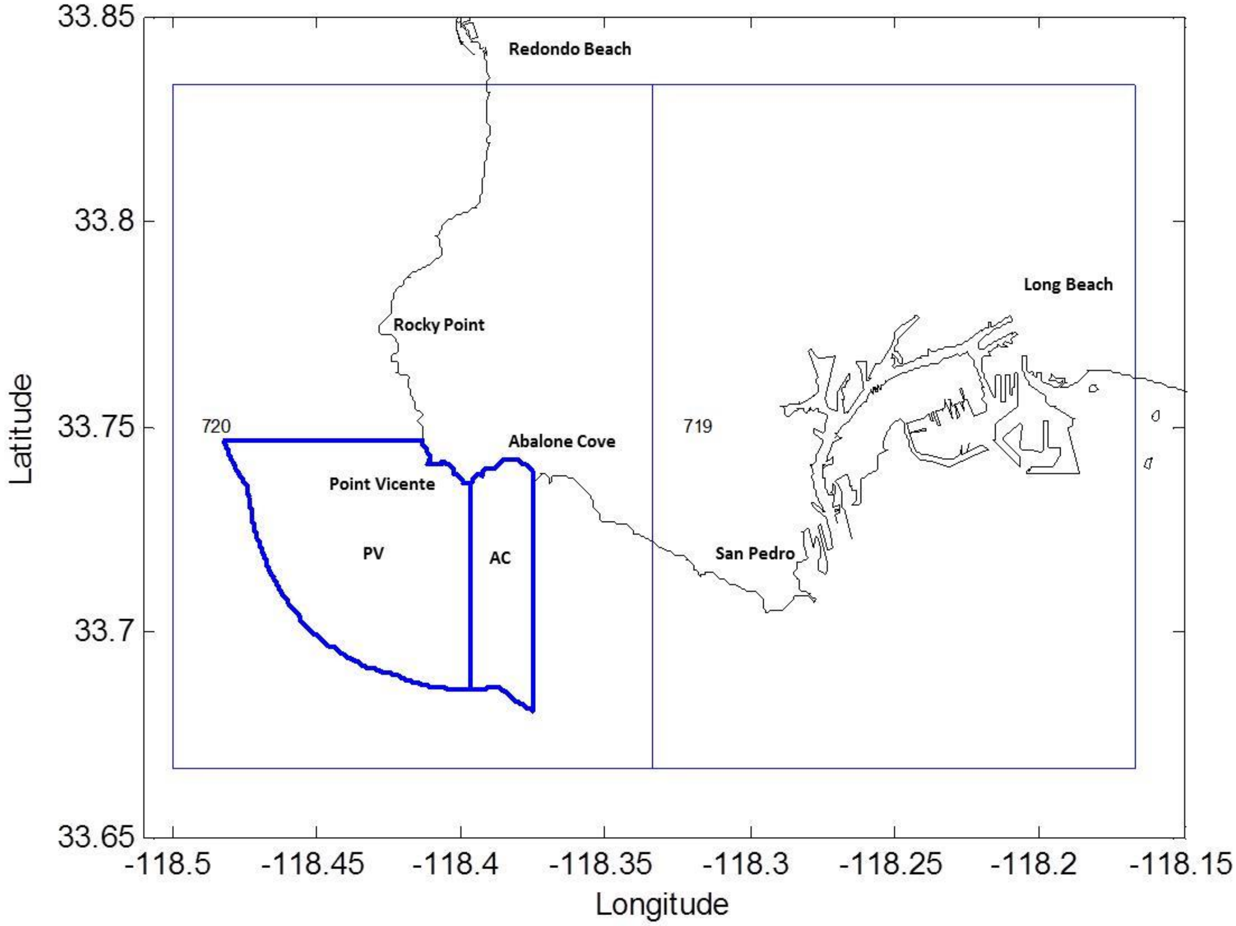
Appendix B**.** Eigenvector loading scores for each habitat variable in the first four principal components (PCs) of the principal component analysis (PCA) used in Part 2 (SCUBA-based lobster surveys). Variables that strongly contributed to each PC and are in bold. Parentheses indicate the scale used to quantify each variable.

Variable	PC1	PC2	PC3	PC4
Depth (m)	**0.79**	-0.23	0.03	0.15
Relief (cm)	0.05	**0.58**	0.00	-0.47
Flat rock (%)	0.17	**-0.82**	0.39	-0.20
Cobble (%)	**0.60**	0.38	-0.13	-0.03
Boulder (%)	-0.01	**0.82**	0.23	-0.22
Sand (%)	-0.43	0.18	**-0.57**	0.41
Kelp density (# per m^2)	0.12	0.10	0.00	**-0.75**
Pterygophora californica (%)	**0.59**	-0.25	0.28	0.31
Laminaria farlowii (%)	**0.64**	0.18	0.29	0.33
Eisenia arboria (%)	-0.14	0.07	0.07	**-0.66**
Egregia menziesii (%)	**-0.65**	0.12	0.11	0.04
Cystoseira osmundacea (%)	-0.10	0.19	**0.79**	0.21
Plocamium cartilagineum (%)	0.14	0.00	0.31	0.26
Other red algae (%)	-0.05	-0.07	**0.62**	-0.13
Coralline algae (%)	**0.61**	0.10	0.07	-0.19
Surfgrass (%)	-0.39	0.20	-0.42	0.23

Appendix C. Maps showing the correspondence of commercial lobster fishing blocks (numbers within rectangles on each map) to each of the five South Coast MPAs surveyed in the study.

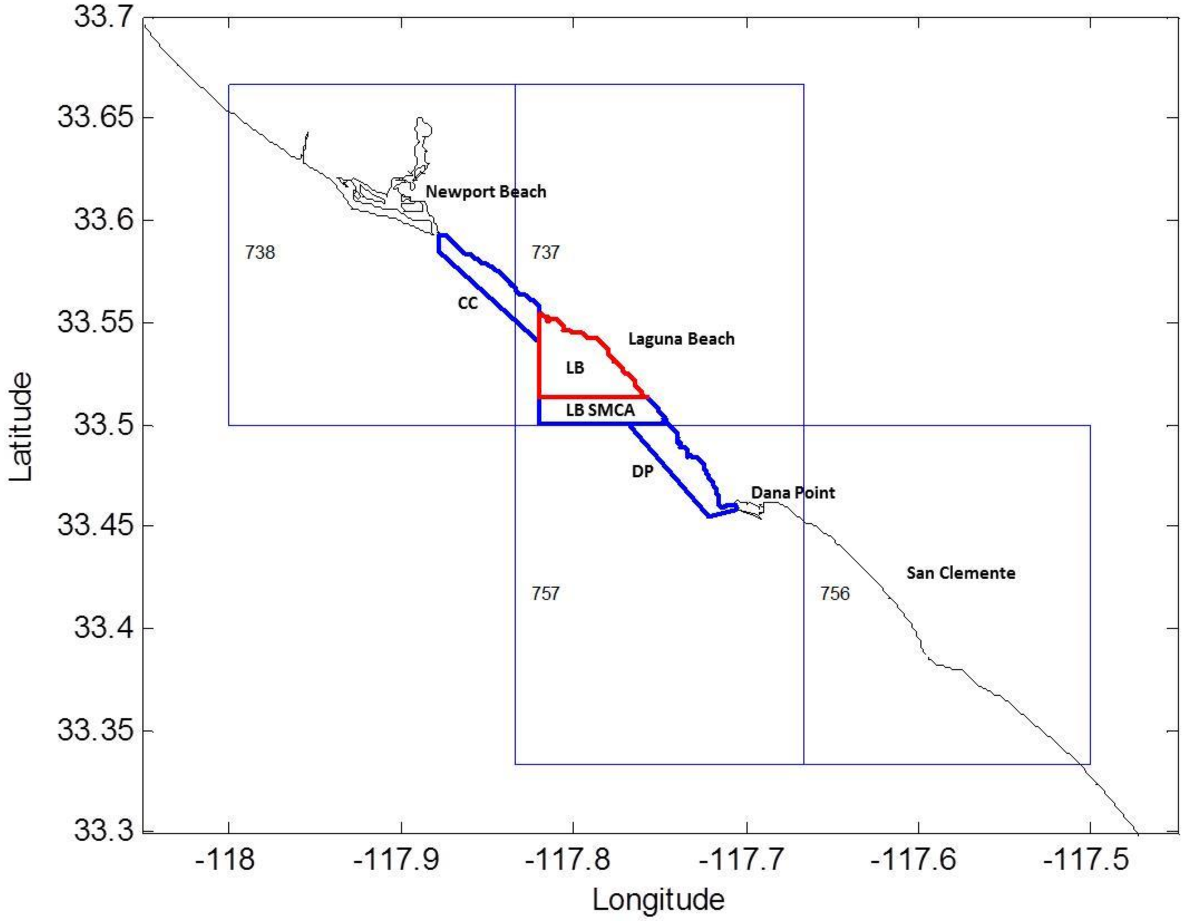
1. Pt. Vicente SMCA

Point Vicente SMCA (Vicente), Abalone Cove SMCA (AC), and associate CDFW Fishing Blocks. The Santa Monica Bay Commercial Closure begins at Rocky Point and includes the entire Santa Monica Bay. Commercial lobster fishing is not allowed inside the closure.



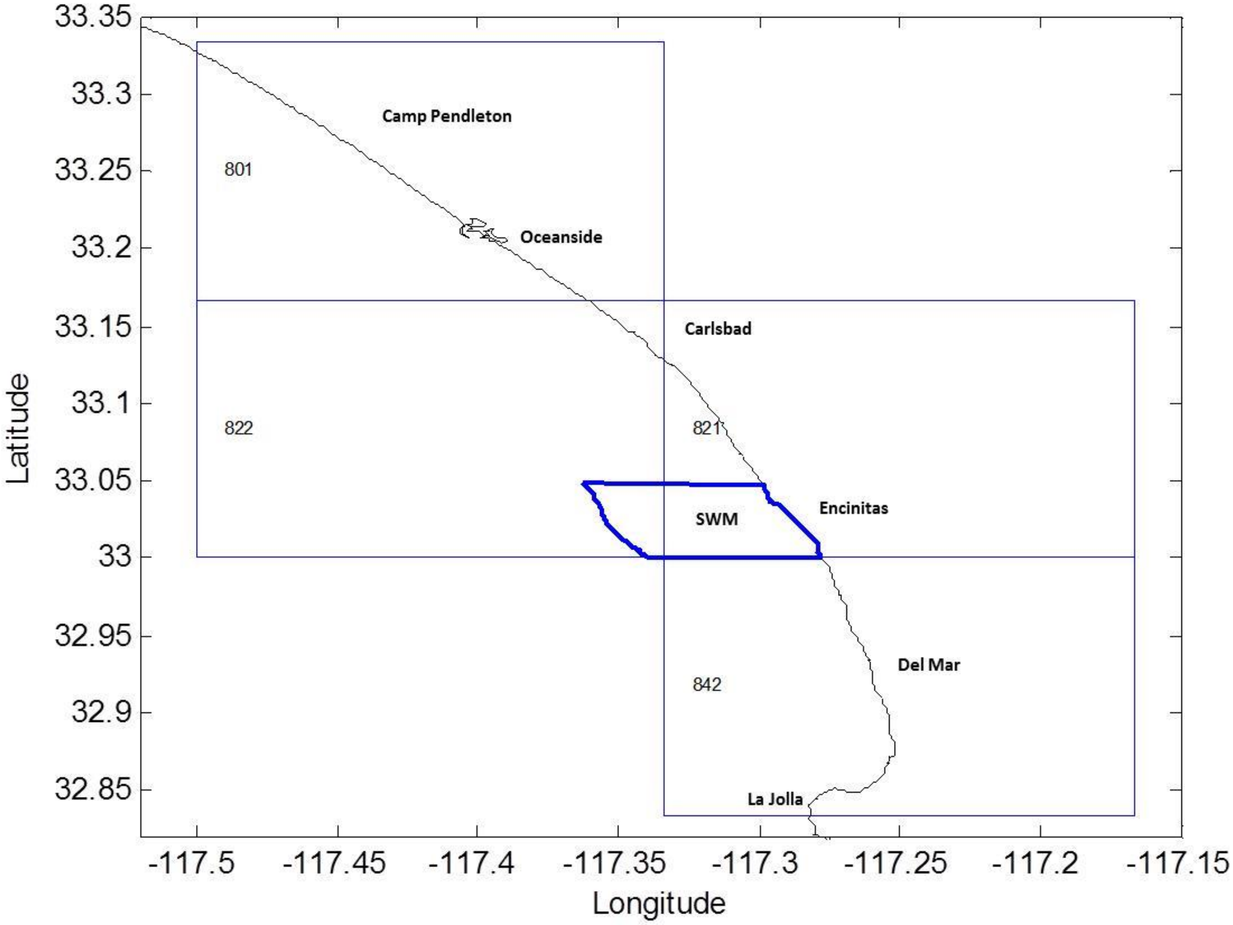
2. Laguna Beach SMR

Laguna Beach SMR (Laguna), Laguna Beach SMCA (Laguna SMCA), Crystal Cove SMCA (CC), Dana Point SMCA (DP), and associated CDFW Fishing Blocks. Fishing block south of 738 is too deep for lobster fishing and was excluded from the analysis.



3. Swami's SMCA

Swami's SMCA (Swami's) with associated CDFW fishing blocks. Block to the south of 802 is too deep for lobster fishing and was left out of analysis.



4. South La Jolla SMCA and Cabrillo SMR (Fishing Block 860)

South La Jolla SMR (South La Jolla), Cabrillo SMR (Cabrillo), and associated CDFW Fishing Blocks. The Matlahuayl SMR and San Diego – Scripps SMCA (M/SD) were not included in the analysis but represent another closure in the general area. Block 877 and 878 extend into Mexico although the lobster fishery stops at the US-Mexico border.