DRAFT Report on the Cable-CDFW 1.0 Model and the Calculation of Spawning Potential Ratio

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INTRODUCTION

The California spiny lobster (*Panulirus interruptus*) Fisheries Management Plan (FMP) utilizes the Cable Model to calculate spawning potential ratio (SPR), one of the three threshold reference points prescribed by the Harvest Control Rule (HCR). SPR serves as an indicator of the reproductive potential of the stock by comparing the number of eggs produced under current conditions relative to a theoretical unfished state. CDFW would have a duty to investigate the status of the fishery whenever the SPR of the stock falls below that of the average SPR during the reference period between 2000 and 2010, when the fishery was deemed stable and productive by the stock assessment (Neilson 2011).

The model was originally developed by Dr. Richard Parrish under contract with the South Bay Cable Liaison Committee (Parrish 2013), and it subsequently underwent revision through collaboration with California Department of Fish and Wildlife (CDFW) staff and CDFW contractors as a part of FMP development. Dr. Parrish aided CDFW in recent months with some refinements of the model as it underwent ongoing improvement and revision (Parrish 2014). In particular, Dr. Parrish created better alternatives to the von Bertalanffy curves that have been used in the earlier iterations of the model to estimate lobster growth. CDFW has expanded upon Dr. Parrish's work and modified the model independently to improve its ability to provide a SPR reference point under the FMP harvest control rule (CDFW 2015). The new version of the model contains a new set of growth curves and the corresponding adjustments to size, age, and season at initial time-step of the model. The model was also stream-lined with the removal of features that do not have direct relevance to the management needs of the fishery as outlined by the FMP.

The model calculates the SPR of the lobster stock by simulating the life history of a single 1000-individual cohort. In addition to SPR, the model also estimates the yield in weight per recruit (YPR) and instantaneous fishing mortality (F), as well as incorporating the effects of Marine Protected Areas (MPAs), which prohibit the take of lobster within their boundaries. This model allows CDFW to estimate and evaluate the effects that varying degrees of fishing pressure and MPA protection might have on the SPR and YPR of the lobster stock.

This report describes the structure, parameters, and the principal mathematical relationships in the model and should be accompanied by the EXCEL spreadsheet (Cable-CDFW 1.0). Implications for the use of SPR as a biological reference point within the FMP are discussed. Other management implications and directions for future research suggested by the model are also presented.

METHODS AND PARAMETERS

The Cable Model is an EXCEL spreadsheet model that calculates the yield of 1000 age-1 lobster recruits over a 30 year lifespan. The model relies upon the estimates of the average size of commercially caught lobster derived from fisheries-dependent data (CDFW Daily Lobster Logs) to infer fishing pressure and generate outputs.   It can assess the entire population or individual regions by inputting the appropriate average size estimates. It does not include a stock-recruitment relationship, so can't directly address reproductive overfishing. However, egg production per-recruit associated with a range of fishery conditions can be assessed. Growth, fecundity, and mortality rates are calculated using the best currently available data. Attempts have been made to parameterize these relationships for the entire Southern California Bight (SCB) but some estimates are regionally specific where data is limited.

The population model begins on row 40 of the "MODEL" worksheet. Input parameters are shown in the rows above 40 and may be changed there by the user. Parameter names are shaded yellow and values are orange. Descriptions of those parameters are provided in the "Parameters" worksheet. The model proceeds by 3-month time steps.

An initial 500 male and 500 female recruits grow and die according to a series of size-specific rates described by equations in each spreadsheet column to supply the number of males and females present at the next time step proceeding down the spreadsheet rows. Descriptions of those equations are provided in the "Column Descriptions" worksheet. Egg production occurs in the 2nd quarter and fishing in the 4th and 1st quarters. This seasonality, the current carapace size limit of 82.5 mm, and an estimate of the percentage of available lobster habitat in MPAs are the aspects of the current management regime included in the model. The fishing mortality rates (F) and harvest rates are estimated by calculating the average weights in the landings during the 2000-01 to 2011-12 lobster seasons. The model user iteratively adjusts F as an input parameter until the correct average size within the catch of simulated lobsters matches fisheries-dependent estimates.

The principle mathematical steps used to calculate the number of lobsters occurring in each time step, the commercial fishery catch, and egg production include:

1. Age-length (growth)

2. Weight
3. Vulnerability to traps
4. Instantaneous fishing mortality
5. Natural mortality
6. Fishing mortality not recorded due to ghost fishing and handling
7. Lobster habitat in MPAs and survival of lobsters inside and outside MPAs
8. Migration and movement rates of lobsters into and out of MPAs.
9. Catch and landings
10. The length-maturity relationship of females
11. The length-fecundity relationship of females

The form of the relationships, their purposes, and the sources of their data inputs are outlined below. Associated parameters are described on the Excel worksheet titled: Parameters.

1. Age-length (growth):

Direct measurements of crustacean growth are rare because an individual's shell, the only hard structure which might be used for aging, is shed periodically. Indirect estimation of growth with age can be performed through tag-recapture data. Three tag-recapture studies of *P. interruptus* were available to us for growth estimation at the time of this work. Newly settled and larger juvenile spiny lobsters from Santa Catalina Island were surveyed on SCUBA, tagged, and studied in the laboratory by Engle (1979). Tag-recapture studies of adult *P. interruptus* using commercial traps have been performed in the San Diego region by Hovel et al. (unpublished data) and at sites around the northern Channel Islands by Kay (2011). A summary of the raw data for each these three studies is provided below (Table 1).

The raw growth increment data was filtered in several ways to eliminate data inappropriate for extrapolation to annual growth. First, for individuals that were recaptured and measured multiple times, only the sizes and time at liberty for the initial capture and last recapture event were used. Second, only measurements from individuals that experienced a sufficient time at liberty and were at large through summer-fall between captures were included to ensure that a molt occurred between the first and second size measurements.

Engle (1979) showed that juvenile *P. interruptus* molt an average of nine times per year. Frequency of molting and the amount of growth per molt varies with temperature. To ensure that several juvenile molts representing a range of growth per molt values were used in extrapolation of growth to one year, we included growth increments over 150 days at liberty and greater. We did not restrict the juvenile time at liberty to a particular time of year. Lobsters are thought to molt once per year following sexual maturity and the molting season spans July through November with most lobsters molting in September (Mitchell et al. 1969). Reliable estimates of size at sexual maturity are not available. We therefore assumed any lobster greater than 50 mm CL could be sexually mature and restricted the Hovel and Kay datasets to measurements occurring over 200 or more days at liberty that must span this molting period. These treated data and their associated annual growth are presented in Figure 1.

We combined raw and untransformed data from all three studies and examined the differences in male and female growth over all sizes. Annual growth for males and females were not significantly different for sizes below 82.5 mm CL. Because of this similarity we chose to model growth for the sexes combined from the size at the first January post-settlement (17.2 mm CL) up to legal size at 82.5 mm. For this 17.2-82.5 mm CL size range, SigmaPlot was used to test the fit of several equations described by (Rogers-Bennett et al. 2003) as well as other equations suitable for modeling growth. We examined von Bertalanffy, Ricker, logistic dose-response, and Gaussian 3-parameter and 4-parameter models. A Gaussian 4-paramter model with the equation $f = y0 + a * e^{(-0.5((x-x0)/b)^2)}$ where f = annual CL increase and x = initial CL, resulted in the most appropriate fit (Figure 5, Table 2).

For individuals greater than 82.5 mm, male *P. interruptus* grew significantly faster on an annual basis (Kruskal-Wallis, *p< 0.001, df= 1, H= 164.42, n(females)= 389, n(males)= 182)* (Figure 2) and variability in their growth was higher. Males show a "hump" shaped distribution, whereas females show a gradual decline in growth. For individuals >60 mm CL, a separate Gaussian 4-parameter model was fit to males (Figure 3, Table 2) and an exponential decay equation was fit to females (Figure 4, Table 2). Although these curves were constructed using individuals 60mm CL and up, they were used in the model for individuals greater than 82.5 mm CL (Figure 3, 4).

These growth equations are used in the model column C to calculate an individual's size at age by adding the calculated annual growth to an initial size in the row above. The model is initialized in January or quarter one. Peak settlement of *P. interruptus* is thought to be August and the average size of field collected young of the year in January was 17.2 mm CL (Engle 1979). We therefore used an initial age of 1.42 years and initial size of 17.2 mm for males and females. Because the model proceeds in 3-month time steps, one quarter of the calculated annual growth was added to the previous size in each step.

2. Weight

Length is converted to weight using a power function ($Wt = a * Lt^b$) and was parameterized for males and females separately using data from CDFW Sport Creel Census data collected in 1992 and 2007.

3. Vulnerability to traps

Vulnerability describes gear selectivity with the current legal trap configuration. Young lobsters are invulnerable to traps because they are small enough to walk out of escape vents. They quickly reach 100% vulnerability to traps as they grow. Vulnerability is then dampened by a subtracting factor representing the exclusion of larger lobster too big to enter traps. Parameters were informed by comparisons of size frequency distributions of *P. interruptus* caught in traps with and without escape ports (Kay 2011). Additionally, the simulated percent of sub-legal individuals in the cumulative cohort catch was fitted to the percentage of sublegals reported on CDFW commercial fishing logs by adjusting vulnerability equation parameters.

4. Instantaneous fishing mortality

Fishing effort varies across the season as the availability of legal-sized individuals declines. The iteratively adjusted F input parameter is multiplied by the size-based vulnerability and adjusted by either the Foct or Fjan parameter to estimate instantaneous fishing mortality. Those parameters simulate differences in landings at the beginning and end of the fishing season based on fishery-dependent data. Fishing mortality is zero during the second and third quarters of the year when the fishery is closed.

5. Natural mortality

Natural mortality is based on Kay (2011). Kay used the length frequency data collected in the interior of Northern Channel Island MPAs to estimate natural mortality using the linearized catch curve method originally described by Sparre and Venema (1998). This method first parameterizes a von Bertalanffy growth equation based on mark recapture growth increment data. Kay used only female growth because of the high variability in his male growth data which prevented reliable estimation of maximum size (L_∞). The inverse von Bertalanffy equation is then used to calculate age of lobsters in discrete size classes and an estimated amount of time lobsters spend in each age class, which is then used in further steps of the linearized catch curve analysis. Given that von Bertalanffy has a poor fit with lobster growth, future work should explore using the new growth curve derived in this report to re-estimate natural mortality.

6. Fishing mortality not recorded due to ghost fishing and handling mortality

There are additional sources of mortality associated with fishing apart from direct take of lobsters. *Panulirus interruptus* smaller than the legal size but large enough to be captured in traps are brought to the surface, handled, and thrown back into the water. These individuals suffer some rate of mortality due to injury during the process and increased susceptibility to predators while returning to appropriate habitat (handling mortality). Unrecorded mortality can also occur when lost traps continue to trap for a period of time until the destruction clips fully disintegrate (ghost fishing).

The model includes an equation for fishing mortality that is not recorded (FNR) that scales F with a parameter for handling mortality and two parameters for ghost fishing. This is then included as an additional source of mortality in the survival equations applied to lobsters in the IN and Open regions. The two parameters that describe ghost fishing are the rate of trap loss (Tloss) and the fishing rate of those traps (Ghost). Reliable data on these processes is not available and therefore these parameters have been set to zero. The functionality for estimating their effects has been retained in the event these data become available. The model does not currently incorporate a function to account for poaching.

7. Application of MPA protection to survival

The model accounts for the effect of MPAs by modifying the survivorship of all the members of a model cohort based on their projected location. Survivorship of *P.*

interruptus in the interior of MPAs is calculated as an exponential function of the natural mortality rate. No fishing mortality is applied because these individuals are assumed to be fully protected from fishing. Individuals in the MPA and within 0.75 miles of a boundary were given a fishing mortality equal to 20% of the value in the open area on top of natural mortality to account for nightly foraging movements that might bring them across the boundary and thus make them vulnerable to fishing (see below). *Panulirus interruptus* outside of MPAs survive according to their combined natural mortality, full recorded and unrecorded fishing mortality rates.

8. Lobster habitat in MPAs, migration and movement rates

The Northern Channel Islands was one of the first regions to implement a network of MPAs in California. Since then a statewide coastal MPA network was completed in 2012. The percentage of *P. interruptus* habitat inside MPAs in southern California is not clearly known as there are gaps in the benthic habitat data for rocky intertidal and shallow kelp forest habitats. The local impacts of MPAs on *P. interruptus* will depend on MPA size and the local mix of habitat types. In the absence of complete habitat data for the entire region, it was estimated that 14.6% of *P. interruptus* habitat across the region is within MPAs. This estimate utilized the most recent GIS analyses of the percentage of rocky substratum covered by MPAs.

The model treats every MPA in the SCB as the same size and distributed equally along the coast. Assuming regular spacing of MPAs along the coastline, and an average MPA width alongshore of 3 miles, an average of 17.55 miles of coastline open to lobster fishing is calculated to exist between each MPA. In order to pursue a more realistic spatial representation of existing MPAs, CDFW would need to develop an individual-based model capable of simulating more complex movement patterns and other spatial dynamics.

Movement rates of *P. interruptus* across MPA boundaries are not well established. Tag-recapture data collected by Lindberg (1955) estimated an average movement of 0.75 miles in 3 months with 2% of the population moving each 3 months. In addition, Lindberg (1955) suggested that the nightly foraging distance of *P. interruptus* was about 0.25 miles. Each 3-mile MPA was divided into two regions: 1) the edge of the MPA within 0.75 miles of a border with open fishing grounds (IN) and 2) the interior of the MPA greater than 0.75 miles from the border (IN-IN) (Figure 6). Therefore it was assumed that 2% of the *P. interruptus* within a 0.75 mile section of MPA will move into or out of that section at each 3-month time step, resulting in a 1% migration rate in each of two directions alongshore (Mig_{out} parameter). Similarly, 1% of *P. interruptus* in the IN-IN region will migrate to the IN region in either direction. Migration rates into MPAs from open fishing grounds were calculated by estimating the proportion of *P. interruptus* that would occur in the 0.75-mile wide strip of fished area that is adjacent to MPAs, then assuming 1% of those will migrate in the direction of the MPA (to the IN region) on both sides of the MPA at each time step. This results in a migration rate into MPAs from fished regions of 0.09 (mig_{in} parameter).

The number of *P. interruptus* occurring in each region (IN-IN, IN, and Open) at each time step is a function of their survival and immigration and emigration rates. On the first time step the number of the 500 individuals of each sex is distributed to each region according to the percent of available habitat each region represents.

9. Catch and Landings

Catch is calculated for both the IN and Open regions separately using the numbers of individuals present in those regions. The catch equation is applied above the legal size limit:

$$\text{Catch} = (F/Z)(N_t)(1-e^{-Z})$$

Where N_t = the number of *P. interruptus* in that time step and Z = Total mortality (F+M+FNR). A separate catch equation is applied to lobsters below the size limit:

$$\text{Catch} = N_t(-F(1+M/2).$$

This equation accounts for replacement of sublegals after they are caught.

Because there is a size limit and catch below the size limit isn't retained, catch and landings are not equal. An additional column in the model calculates landings as the catch in IN and Open regions when above the legal size and zero when below.

10. Length-Maturity of Females

The proportion of sexually mature females at each time step is described by the equation:

$$\text{Maturity} = 1/(1 + e(^{23.49 - 0.304*CL}))$$

Where CL = carapace length. This equation was parameterized by data collected at the Northern Channel Islands (Kay 2011).

11. Length-Fecundity of Females

Improving estimates of fecundity at size is a key research priority. Currently data are available from four female *P. interruptus* collected by Allen (1916) and 12 by Lindberg (1955). The following equation was derived from those data sets:

$$\text{Fecundity} = (0.9197*CL^{2.7})*\text{Maturity}.$$

<u>Model Output</u>

The three primary outputs of the model are instantaneous fishing mortality (F), yield per recruit (YPR), and spawning potential ratio (SPR). Simple equations in the columns of the population model that follow catch are used to total both the number and the weight of landed and unlanded males, females, and both sexes as well as the number of eggs produced by females. Sums from those columns generate key outputs to cells F7 to F13. Additional outputs are found in cells O14 to O27.

While F is an output of the model, it functions like an input parameter. This is because F is iteratively found by adjusting it until the known average weight of *P. interruptus* in the catch from fishery-dependent data matches the average weight in the catch (AveWt) of simulated *P. interruptus*. This simulated average weight is calculated by dividing the total weight caught in all model time steps by the total number. The yield per 1000 recruits (YPR) is simply the total weight in the catch in all time steps.

Calculation of SPR requires two model runs because it represents a ratio of the number of eggs produced in two alternate scenarios. For the purposes of the FMP, we calculate a ratio relating the current conditions of the fishery to the number of eggs that would theoretically be produced with no fishing mortality and no habitat protected by MPAs. Other alternate scenarios could be compared in this way (*e.g.,* equal fishing mortality and different percent of habitat within MPAs).

To produce SPR, first set model parameters values to the base state representing the ratio denominator. To produce an unfished state with no MPAs, F and MPAS in cells B5 and B7 should be set to 0.0001 because the model can't accommodate zero. Size limit can be left at the current value of 82.5. The spreadsheet will calculate outputs to cells F7-F13 and P14-P27. The user must then copy the values (not formulas!) within cells O14-O22 and O27 over to cells P14-P22 and P27 shaded in green. This then provides the necessary information for cell G12 to produce an SPR value and cells Q15-Q21 to compare several types of cohort biomass under a fished scenario to the simulated unfished biomass.

Several graphical outputs are produced on the spreadsheet to the right of the population model; four 3-dimensional plots and three 2-dimensional graphs. The first 3-D plot and all of the 2-D plots require the user to copy base run output values to new cells. Copy the values from cells:

1. BA73 to BA72
2. BB101-BV101 to cells BB102-BV102 shaded in green
3. BY101-CT101 to cells BY102-CT102 shaded in green
4. CX101-DR101 to cells CX102-DR102 shaded in green

Each of the 3-D plots is constructed using a different 2-way table. The 2-way tables each contain a key output from the current model run in the top left cell. Variable fishing conditions such as fishing mortality and size limits run to the right and down from that top left cell. The interior of the matrix represents output calculations under each combination of conditions.

The first plot illustrates how percent of maximum YPR varies with fishing mortality and size limit. The 2-way table informing this plot begins at cell BA78 which contains the total yield output of the current model run. The formula in cell BA73 identifies the maximum value in that matrix or the maximum total yield that can be produced under this range of mortality and size limit under current model run conditions. Another matrix above, beginning in cell BA45 converts the yield values below from units of kilograms to pounds and calculates a percent relative to the maximum yield that could be produced under base model run conditions.

The second 3-D plot illustrates change in SPR with variable fishing mortality and size limit. The 2-way table for this plot is based on total fecundity output. The matrix above converts each total fecundity value to an SPR relative to the maximum possible fecundity found in cell BY42.

The third 3-D plot illustrates the change in average weight of lobsters in the catch with variable fishing mortality and size limit. The 2-way table calculates an average weight under each scenario and the matrix above it converts those weights from kilograms to pounds. The final 3-D plot illustrates the change in SPR with variable fishing mortality and percent of habitat in MPAs. No further conversion is necessary.

Each of three 2-D plots located below the 2-way tables plots a model output against variable fishing mortality on the x-axis. The two data series represent the base and current model runs which represent current MPA coverage and no MPAs.

RESULTS

Primary Model Output

The SCB-wide average weight of *P. interruptus* in the catch for the 2000-2012 fishing seasons was 1.57 lbs, which corresponds to an instantaneous fishing mortality (F) of 0.66. As Figure 7 illustrates, F is fitted by the model to average size, and regulation of fishing effort can be used to balance against a different size limit to maintain a desired average size. There are apparent differences in the average weights of the catch in the northern region of the SCB including the mainland north of Palos Verdes and the northern Channel Islands and the southern region of the SCB including the mainland south of Palos Verdes and Santa Catalina and San Clemente Islands. Higher average weight in the north results in a lower estimate of F and vice versa for the south (Figure 8).

Different rates of F also interact with size limit to result in variation in YPR and SPR. Yield increases rapidly as F increases from zero while the increase in yield with decreasing size limit is more gradual (Figure 9). At the current size limit, the statewide fishery as well as both the northern and southern regions, are achieving 60-70% of the maximum possible yield under a range of F from 0 to 2. Only a scenario of F=2 and size limit at 65mm CL can achieve 90-100% of maximum yield, in part because the base comparison is a scenario without MPAs. At lower size limits SPR decreases rapidly as F increases from zero then declines gradually (Figure 10). At higher size limits SPR only declines gradually across a wide range of values for F. At the current size limit, SPR declines rapidly with increasing F but cannot pass below approximately 30% within the range of F values examined.

The impact of MPAs on the relationship between average weight in the catch and F is illustrated in Figure 8. As expected, the average weight of individuals in the catch at very low values of F is very similar between the current condition of 14.6% of *P. interruptus* habitat within MPAs and a no MPA scenario. As F increases, the difference in average weight between these scenarios is modest. This may be a combined result of *P. interruptus* within MPAs not achieving drastically larger size than those outside MPAs, and a lack of spill-over. Further sensitivity analysis on the impacts of model parameters for movement rate would be useful for investigating this dynamic.

The presence of MPAs has a demonstrable impact on model estimates of YPR and SPR. YPR is reduced under current MPA coverage conditions similarly across estimates for F at the northern, southern and SCB-wide levels (Figure 11). Current MPA coverage also provides a similar increase in SPR of approximately eight percentage points across all current estimates for average weight in the catch (Figure 12). Interestingly, increasing the percentage of habitat covered within MPAs up to 27% results in only modest increase in SPR of about 10 percentage points (Figure 13).

Model Limitations

The model estimates of F and their corresponding impacts on YPR and SPR are sensitive to the average weight of individuals in the catch, particularly at smaller average weight values. Therefore when the average weight is relatively high, incremental change in average weight leads to small change in F. When average weight is low, small change in average weight leads to large change in F. This effect can be seen in the shape of the curves in Figure 7. This is of concern because as average weight is reduced by increasing F, the accuracy of our fishery-dependent estimates of average weight becomes increasingly important. Small chance variation in average weight estimates may lead to substantially different management conclusions and it may be harder to detect incremental changes in population dynamics resulting from management action. CDFW is proposing new reporting requirements on landing receipts and at-sea logs in the regulatory package associated with the FMP. These will greatly improve the accuracy of our estimates of average weight of individuals in the catch.

The relationship between average weight and F under the current size limit and MPA coverage conditions asymptotes at approximately 1.45 lbs (Figure 8). Values of F below 1.45 cannot be estimated by the model. However, based on CDFW creel survey data, the average weight of *P. interruptus* just above legal size is 1.3 lbs. Therefore a catch level that would drive the average size of a landed individual down to right at or above this figure should be possible in the actual fishery. However, the model cannot currently simulate such a scenario. For now, the smallest average weight estimated has been 1.53 pounds, which is still above the model's weight limitation.

This model is also limited by the fact that it applies the same treatment to every member of a cohort, even though different individuals would encounter different experience in the real world resulting in plasticity of traits. This limitation is particularly obvious in the growth part of the model which applies the same growth equation to every individual in a cohort, resulting in the same length increase for every individual and a stepped rather than continuous growth pattern. This stepped growth pattern produces an issue with knife-edge selection in other model functions based on size. For example, much of the catch is at a size just above the legal size of 82.5 mm CL. However, in the model, sizes progress from 81.9 mm in quarter 1 to 82.7 in quarter 2, jumping over legal size to a size above legal in a quarter of no fishing. These individuals will not be subject to harvest until they reach 84.7 mm CL in quarter 4. For this reason we chose to allow growth in every model quarter rather than programming growth only during the summer quarter when molting and growth actually takes place. This results in a more continuous growth pattern but does not fully alleviate this modeling artifact.

Several model equations are parameterized using limited and/or regionally-specific data that may not reflect spatial variation across the fishery. Natural mortality estimates are based on a von Bertalanffy growth model and work needs to be done to adjust this to CDFW's improved growth model as mentioned above in the methods section. Vulnerability parameters could be improved using data on trap density, size frequency data from transect surveys, and spatially co-located data on size frequency in commercial traps. Fecundity and size at sexual maturity are also key data needs.

Finally, the Cable model is an equilibrium model that assumes constant recruitment and therefore is unable to capture stock-recruitment dynamics.

Sensitivity Analysis

Lobster growth has commonly been described using a von Bertalanffy model (Hall & Chubb 2001, Hobday & Punt 2007, Chavez & Gorostieta 2010, Nielson 2011) and earlier versions of the Cable model included von Bertalanffy growth using parameters derived by other studies (Parrish 2013, 2014). Upon further examination of raw growth data from tag-recapture studies, von Bertalanffy was found to produce a poor fit (Figure 14). CDFW staff acquired more raw growth data and developed a new growth model as described in the methods above. Model runs using these two growth models differ in several important outputs (Table 3). The age of legal sized individuals using von Bertalanffy growth is approximately half of what it is calculated to be using CDFW growth. This short time to the fishery results in fewer spawning seasons before F is applied and therefore much smaller SPR. Survival to the fishery is also higher because individuals have not been subject to natural mortality for as many years. Finally, the values of F associated with average weight are higher under von Bertalanffy growth and this also likely contributes to the decreased SPR (Figure 15).

It is important to note that while SPR values calculated using von Bertalanffy growth are much lower than those using CDFW growth, the relative difference in SPR between the reference years and most recent fishing season are very similar, suggesting that the results are robust when interpreted this way. The fishing seasons between 2001-02 and 2010-11 were defined as a reference period due to relatively high, stable catch (see management implications below). The SPR calculated based on average weight in the catch over that time period and using MPA coverage of only 4.6%, reflective of the channel island MPAs present at that time, serves as a threshold reference point in the *P. interruptus* FMP. Model runs using von Bertalanffy and CDFW growth, both show that SPR is currently above the threshold by two and one percentage points, respectively.

An additional sensitivity analysis between applying lobster growth only once per year after individuals reach maturity and once every quarter over the entire lifespan shows very little difference in terms of outputs (Table 3). Current and threshold SPR are equal. However, values of F associated with average weight are slightly higher under annual growth than quarterly growth (Figure 15). By applying quarterly growth even after lobsters have matured, the model is able to accommodate a smaller average size. This is what would be expected as since by dividing growth into smaller increments, the first time step where *P. interruptus* become legal and harvestable would be closer to the 82.5 mm CL harvestable threshold. This in turn results in a smaller size for the absolute smallest lobsters that can be harvested in the model. An overall smaller size then leads to a smaller value where the F vs. average size curves asymptote, and allows the model to project a meaningful F down to a smaller average size.

Other sensitivity analyses that CDFW recognizes as valuable but have not yet been completed include vulnerability, fecundity, age at maturity, and migration rates.

MANAGEMENT IMPLICATIONS

The current SPR calculation of 41% produced by Cable-CDFW 1.0 shows that we are close to the SPR threshold of 40%. The FMP designates the HCR threshold as SPR for the reference period and not a specific number (CDFW 2015). Thus adjustments to the Cable-CDFW 1.0 model may be made to improve SPR output for both current and reference (threshold) conditions without triggering the HCR threshold.

Although crossing this threshold does not require any immediate regulatory action, it requires that we further investigate the potential causes and if deemed necessary, provide a management response. While the Catch, CPUE and SPR reference points were chosen to identify very specific fishery issues that may signal trouble in the fishery, the HCR Matrix is designed to assess these measures collectively (CDFW 2015, Table 4-2).

If SPR and CPUE (CDFW 2015, Figure 4-7) continue to decrease, we will likely arrive at Scenario 7 within the HCR Matrix within the next couple of years, which states that the stock may be “overfished” and/or subject to “probable overfishing” (CDFW 2015, 4-2).

Preliminary analysis conducted by CDFW suggests that the likely cause for the current decreasing trend in CPUE is related to the recent increase in effort, measured by the total trap pulls recorded on commercial fishing logs (CDFW 2015, Figure 2-4). The decreasing trend in SPR (Table 4) may be attributed to increasing effort as well, since the average size of *P. interruptus* landed in the commercial fishery has trended downward since the 2000-2001 fishing season. The implementing regulations of the FMP would require recording landing receipt numbers on commercial fishing logs and vice versa as well as the number of landed individuals on the landing receipts. This will greatly improve our estimates of average size of individuals in the catch, one of the key parameters used in the model. In addition, implementation of the proposed trap limit program proposed by the Lobster Advisory Committee may help alleviate overall fishery effort, although it should be noted that the intent of this proposed regulation is primarily related to gear reduction.

The new growth curves developed by CDFW staff have led to much higher SPR values than the threshold values calculated for other lobster fisheries (reviewed in CDFW 2015). The higher value can be attributed in part to the effects of MPAs, however, even if MPAs are discounted, the model still cannot produce an SPR value lower than 30% (Figure 11). This discrepancy could have been caused by unresolved uncertainties concerning the model's inputs and structure. Specifically, the lack of data on *P. interruptus* fecundity likely plays a part in the model's SPR projection.

Since most fishery managers calculate their respective SPR values differently, comparison between SPR values computed by different teams using different assumptions and methodology is inherently problematic. SPR can be referring to "spawn-per-recruit" for some fishery managers and "spawning potential ratio" to others (Mace & Sissenwine 1993, Hall & Chubb 2001). Even among the managers who use spawning potential ratio as their reference points, some calculate baseline condition using model projections of a theoretical unfished state while others derive baseline conditions with real-life unfished populations in remote locations (Bohnsack et al. 1990). Among the managers who calculate baseline using model projections, some account for density-dependent population factors while others do not (Hall & Chubb 2001, Puga et al. 2005).

CDFW's immediate policy goal for *P. interruptus* management is not to achieve the most accurate SPR value that can be achieved with modern sampling and computing techniques. Rather, CDFW management, in collaboration with various stakeholders including fishermen groups, has decided to set the SPR threshold at the value during the reference period of the 2001-02 to 2010-11 fishing seasons. Values derived by other management teams can provide crucial references for CDFW's parameters and methodologies, but the primary management goal here is to ensure consistency between the SPR values calculated for the reference period and the most recent year.

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Table 1: Summary of *Panulirus interruptus* mark and recapture data for Engle (1979), Hovel (unpublished data), and Kay (2011) data sets used in growth estimates.

Source	Sex	n	Initial CL size range (mm)
Engle	F	125	9.55-43.05
	M	115	10.05-40.85
Hovel	F	171	55.00-86.00
	M	266	51.00-101.00
Kay	F	520	64.00-143.00
	M	254	69.00-146.00

Table 2: Selected equations and parameter values and R-squared values for *Panulirus interruptus* growth.

Sex and Size Class	Equation	Parameters	R-squared
Male + Female, Initial size 0-82.5 mm	$F=y_0+a*e^{(-0.5*((x-x0)/b)\text{^}2)}$	a=31.96, b=12.22, x_0=21.63, y_0=3.22	0.808
Female 60-150 mm	$F=a*e^{(-b*x)}$	a=8.37, b=0.01	0.073
Male 60-150mm	$F=y_0+a*e^{(-0.5*((x-x0)/b)\text{^}2)}$	a=4.78, b=18.57, x_0=112.37, y_0=2.59	0.272

Table 3: Results of sensitivity analyses comparing quarterly with annual growth using the CDFW growth curve, and a von Bertalanffy growth curves using annual growth.

Growth Model	CDFW		von Bertalanffy
Growth Schedule	*Quarterly*	*Annual*	*Annual*
SPR Threshold	40%	44%	18%
SPR Current	41%	44%	20%
Age to legal male	12.7	12.7	6.4
Age to legal female	12.7	12.7	6.9
Max size for male	150.4	151.0	142.9
Max size for female	114.9	115.4	124.2
% survival to legal	6.6%	6.7%	27.9%

Table 4: SPR of the SCB *Panulirus interruptus* stock over time based on the average weight of a landed lobster.

***% of habitat protected by MPAs is increased from 4.5% to 14.6% for the 2011-12 fishing season**

Fishing Season	Average Weight (lbs)	SPR
2000-01	1.59	42%
2001-02	1.62	44%
2002-03	1.59	42%
2003-04	1.58	41%
2004-05	1.57	40%
2005-06	1.53	38%
2006-07	1.56	40%
2007-08	1.54	38%
2008-09	1.56	40%
2009-10	1.57	40%
2010-11	1.53	38%
2011-12	1.53	41%*

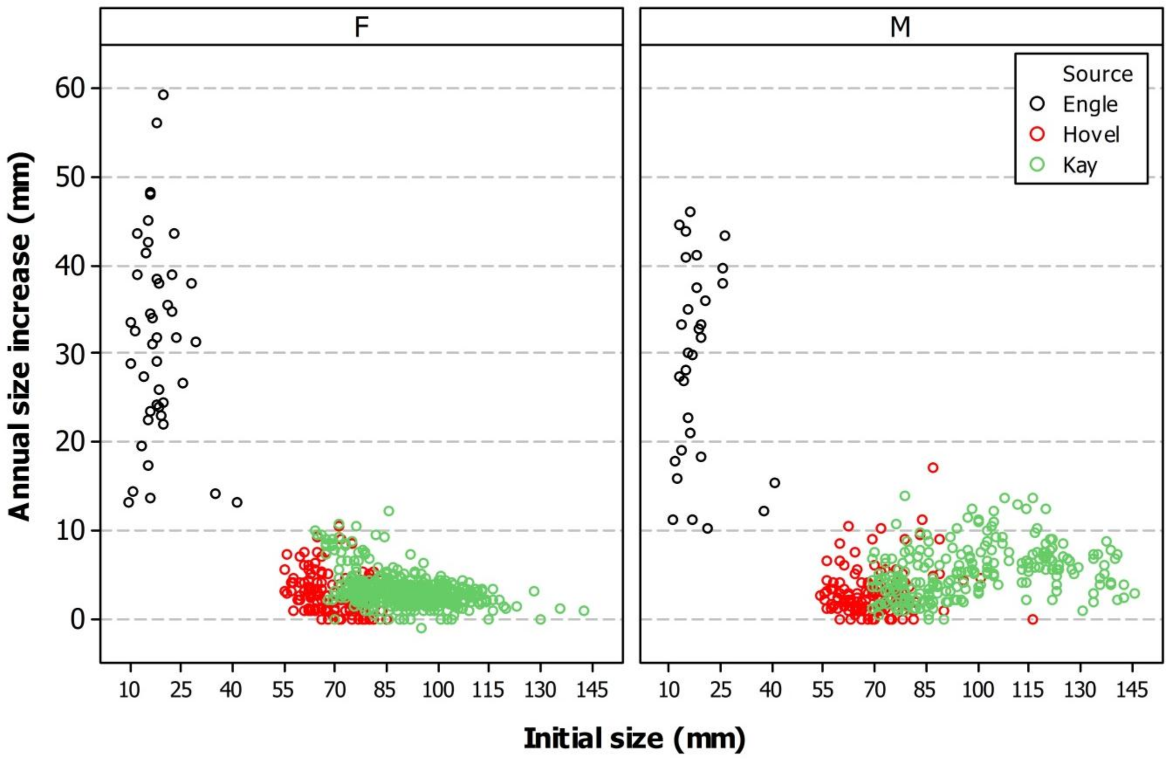


Figure 1: Treated data used in growth curve analysis comparing Initial size (mm) CL vs. Annual increase in size (mm) for Females (F) and Males (M).

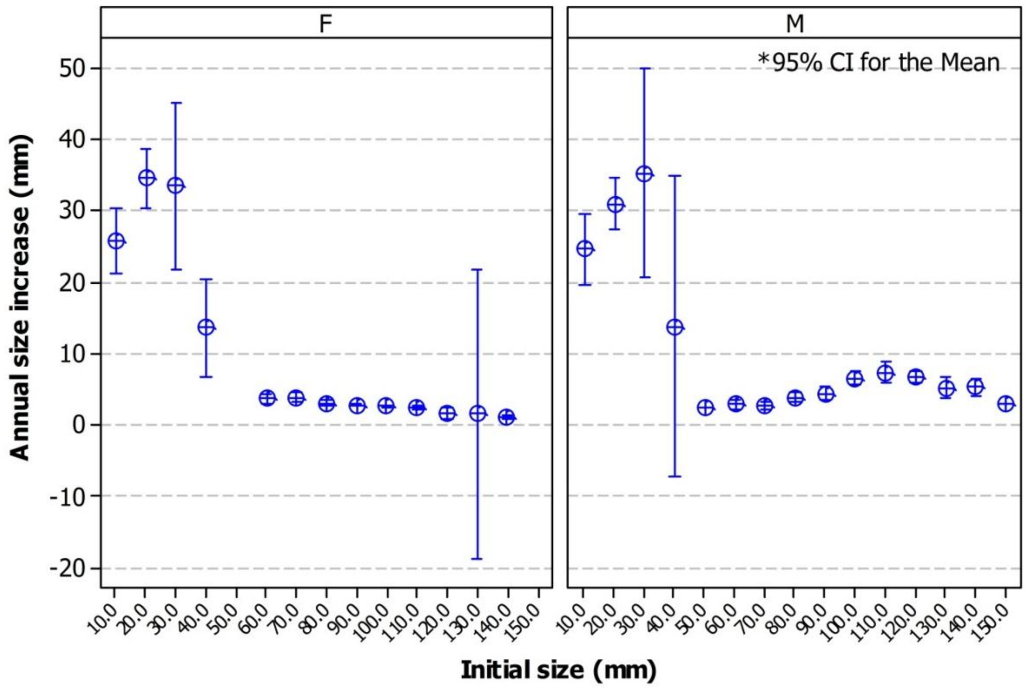


Figure 2: Comparison of male and female mean annual growth within 5 mm initial size bins.

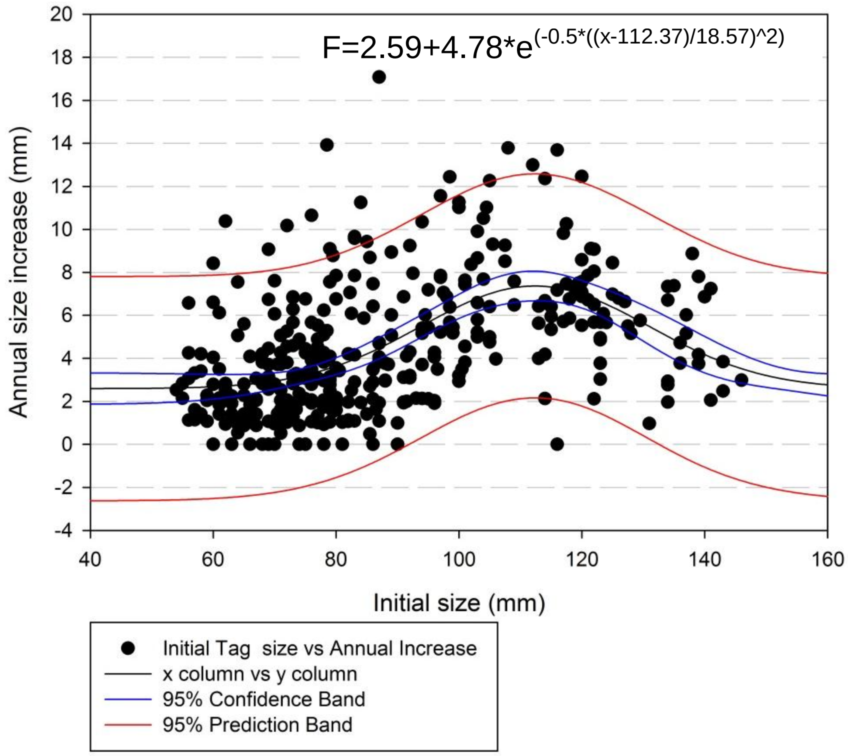


Figure 3: Male Gaussian 4-parameter curve fit to annual growth for initial sizes greater than 60 mm CL.

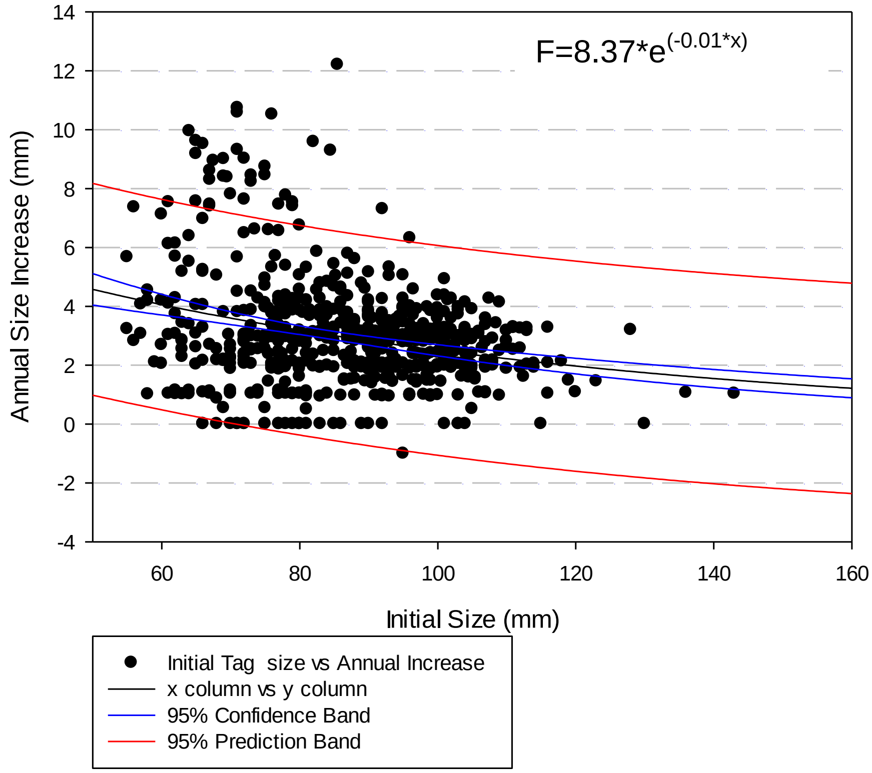


Figure 4: Female exponential decay curve fit to annual growth for initial sizes greater than 60 mm CL.

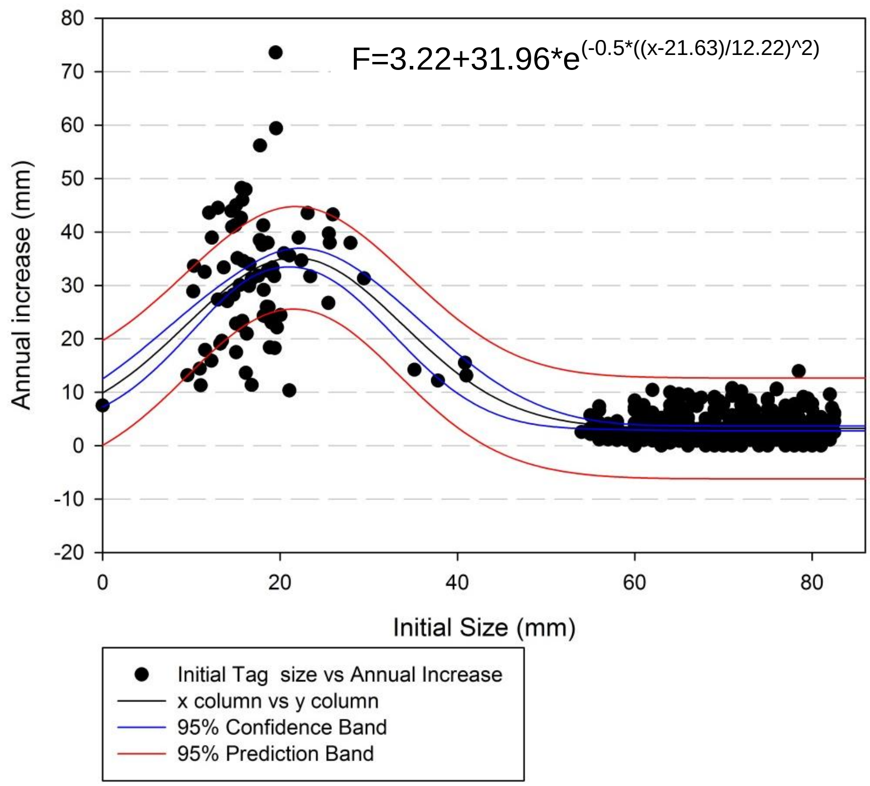


Figure 5: Male and female combined Gaussian 4-parameter curve fit to annual growth for initial sizes from 0-82.5 mm CL.

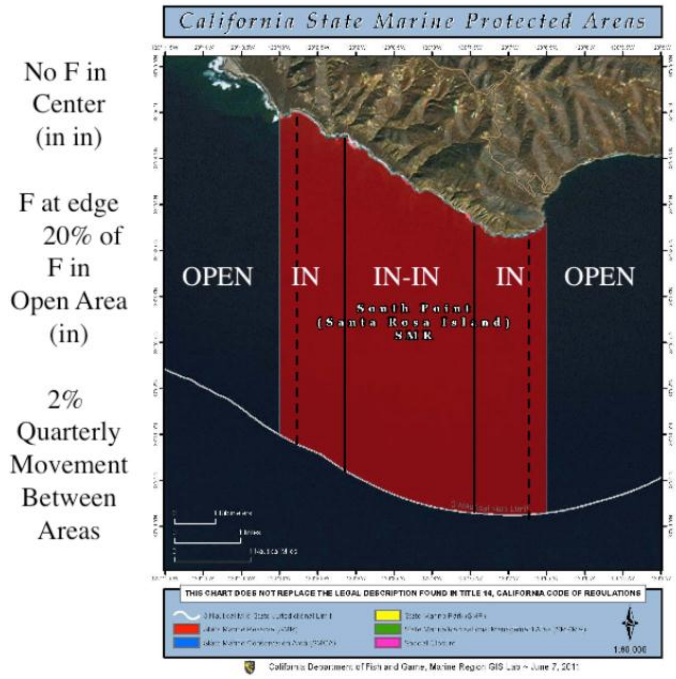


Figure 6: Division of coastal lobster habitat into areas unprotected by MPAs (OPEN) and within MPA interior (IN-IN) and MPA edge (IN) habitat (Figure taken from Parrish, 2014).

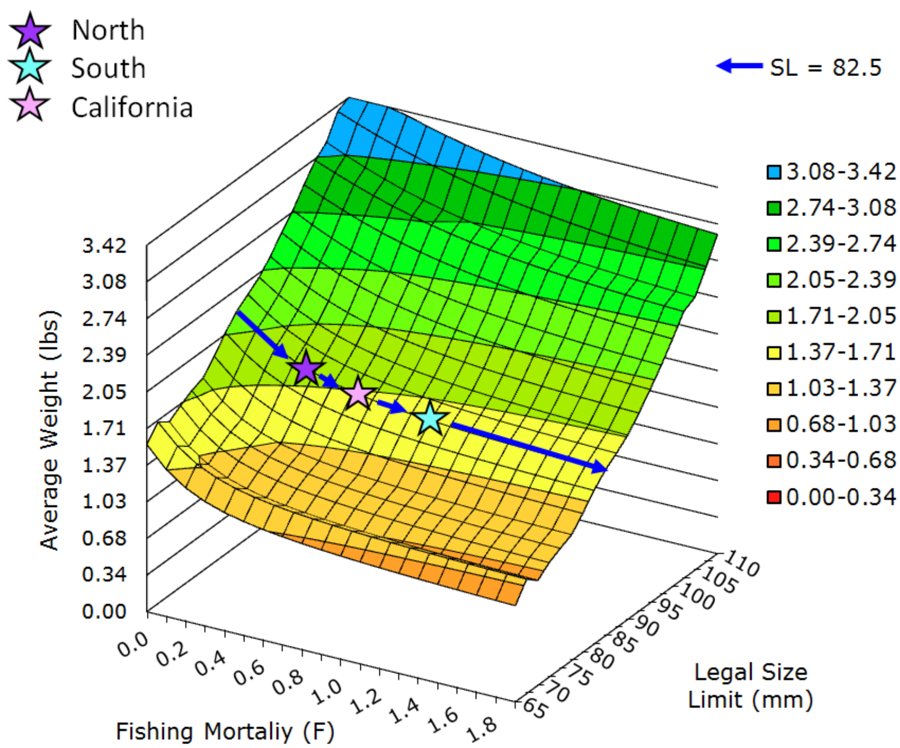


Figure 7: Response in average weight of lobsters in the catch to variation in fishing mortality and legal size.

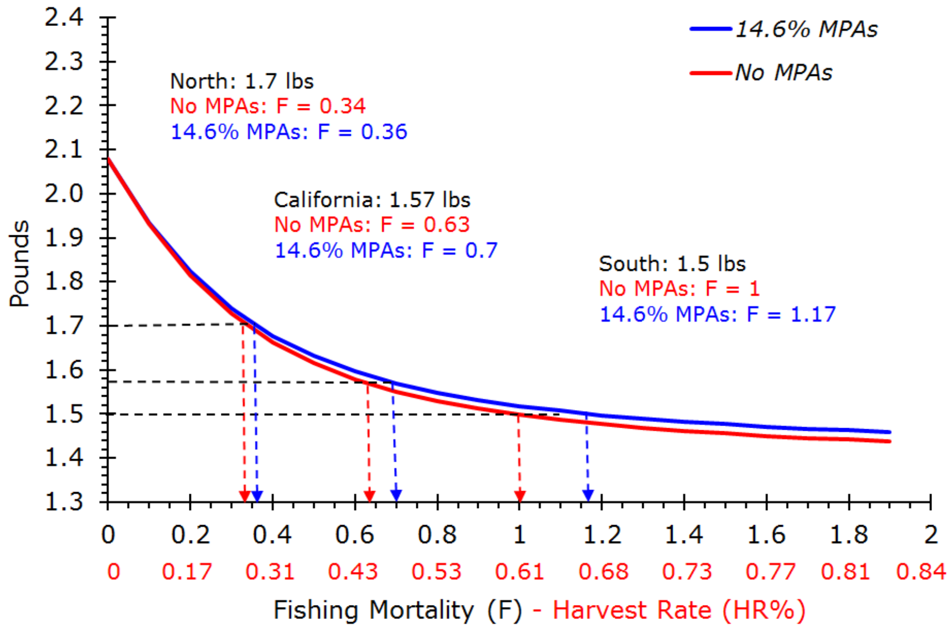


Figure 8: Relationship of average weight in the catch with instantaneous fishing mortality (F) with current MPA coverage (blue) and no MPAs (red).

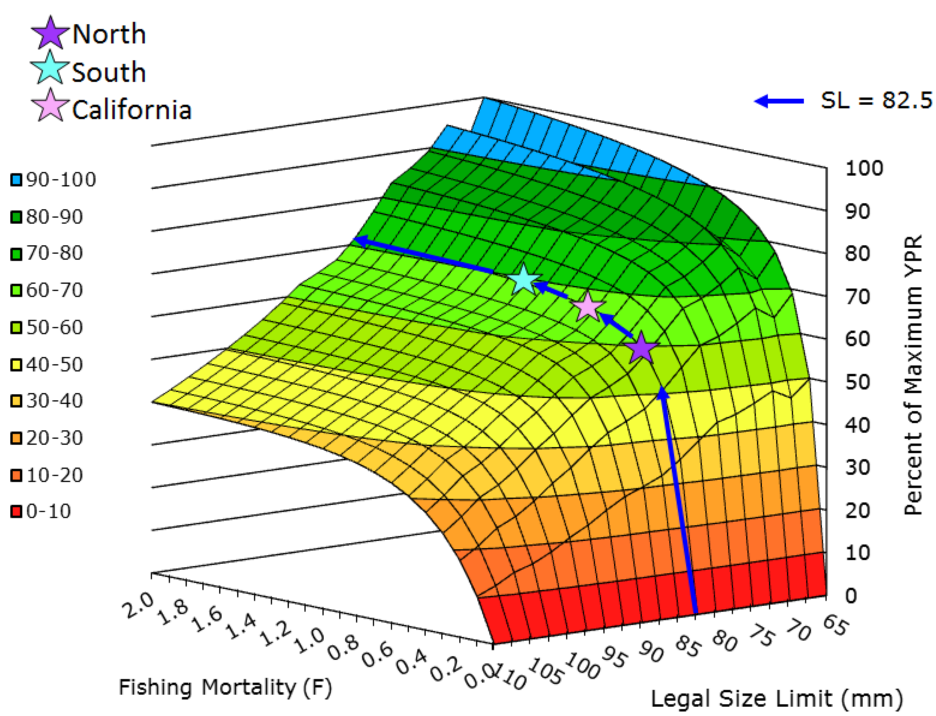


Figure 9: Response in the percent of maximum yield from 1000 lobster recruits to variation in fishing mortality and legal size. Maximum yield is calculated based on a scenario of no MPAs and current yield uses current MPA coverage (14.6%).

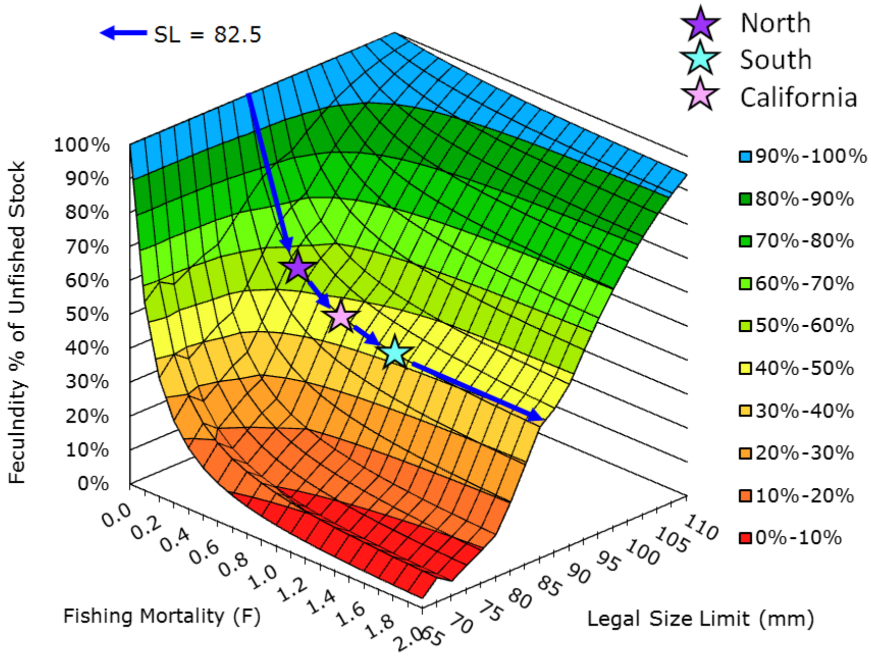


Figure 10: Response in spawning potential ratio (SPR) to variation in fishing mortality and legal size limit. Egg production under current harvest rates and MPA coverage is related to theoretical egg production in an unfished state with no MPAs.

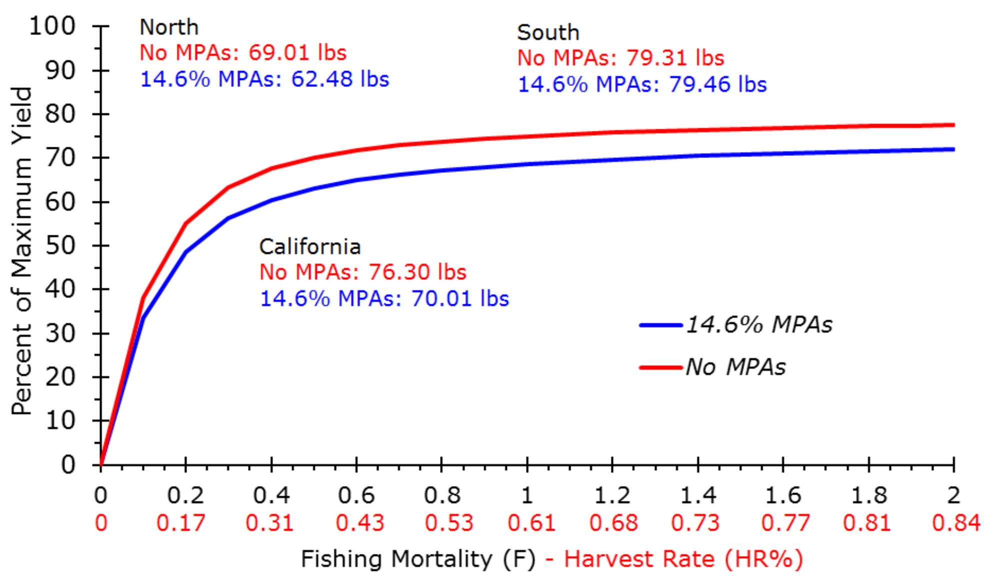


Figure 11: Relationship of percent of the maximum yield from a simulated population with instantaneous fishing mortality (F) with current MPA coverage (blue) and no MPAs (red).

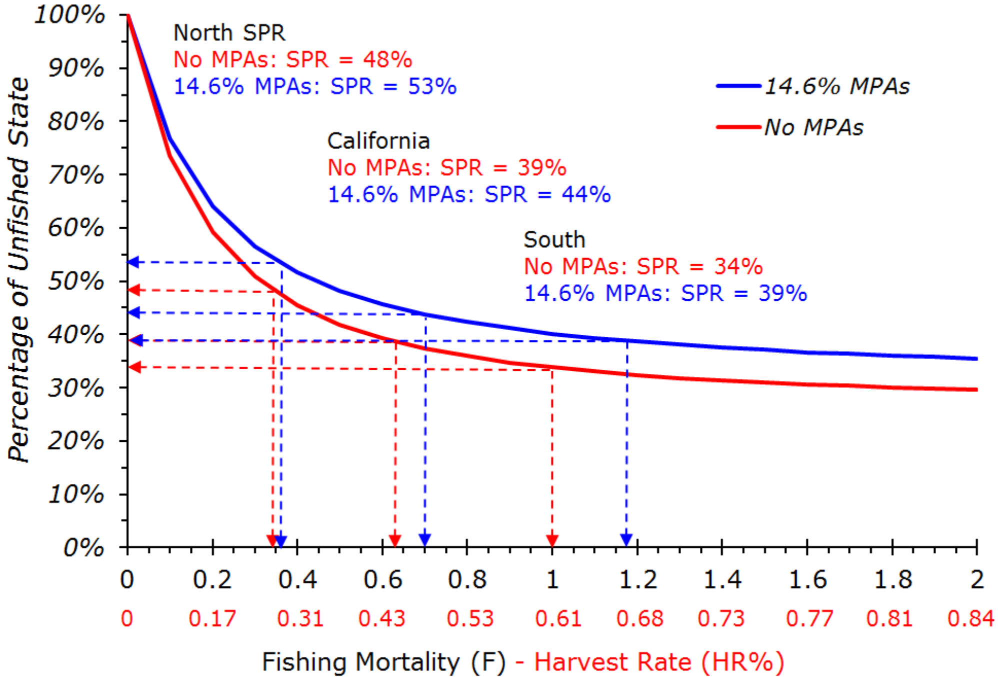


Figure 12: Relationship of spawning potential ratio (SPR) with instantaneous fishing mortality (F) with current MPA coverage (blue) and no MPAs (red).

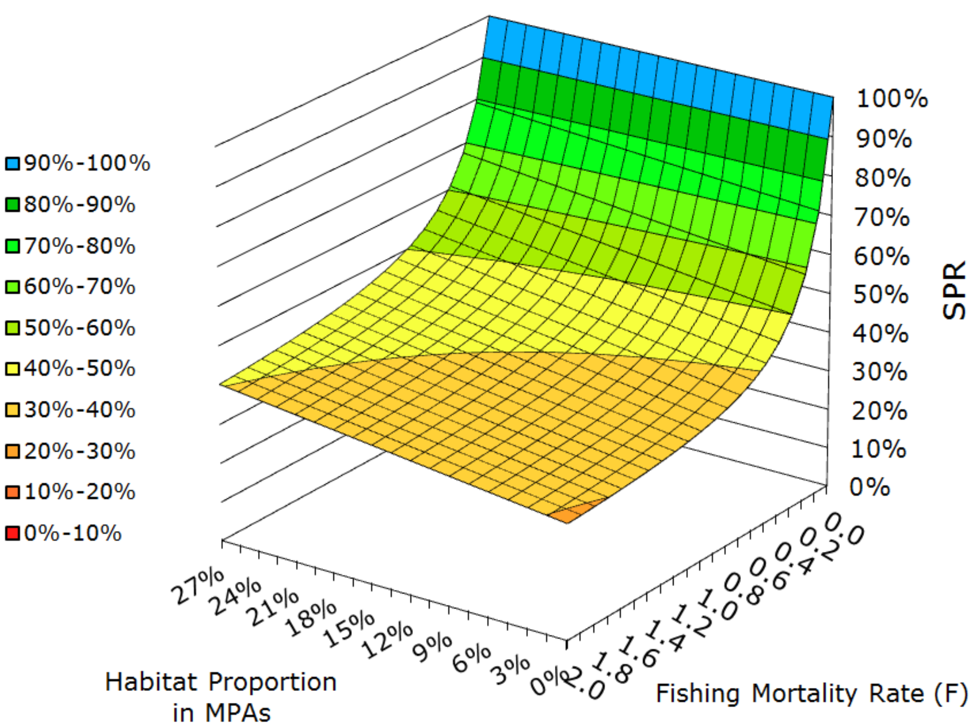
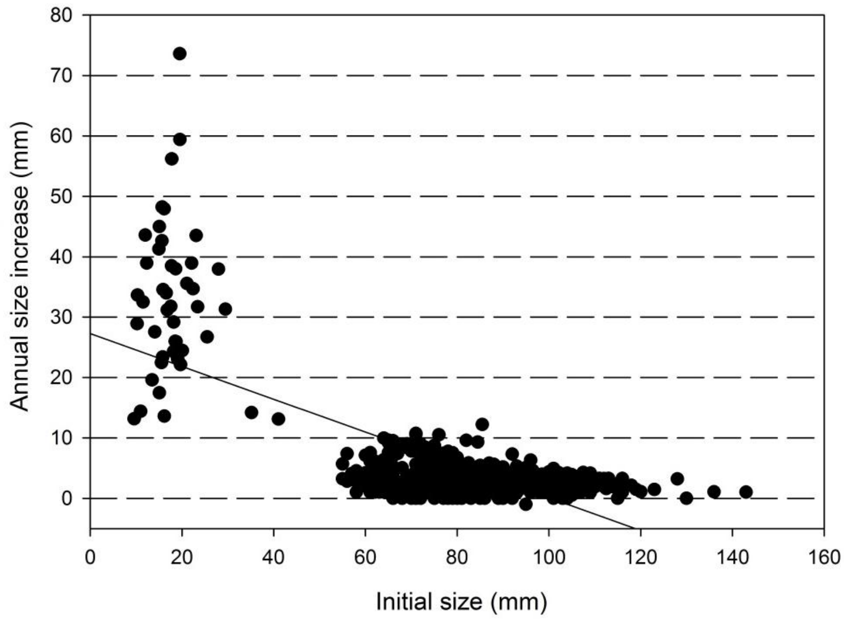


Figure 13: Response in spawning potential ratio (SPR) to varying instantaneous fishing mortality and proportion of *Panulirus interruptus* habitat within marine protected areas (MPAs).

a)



b)

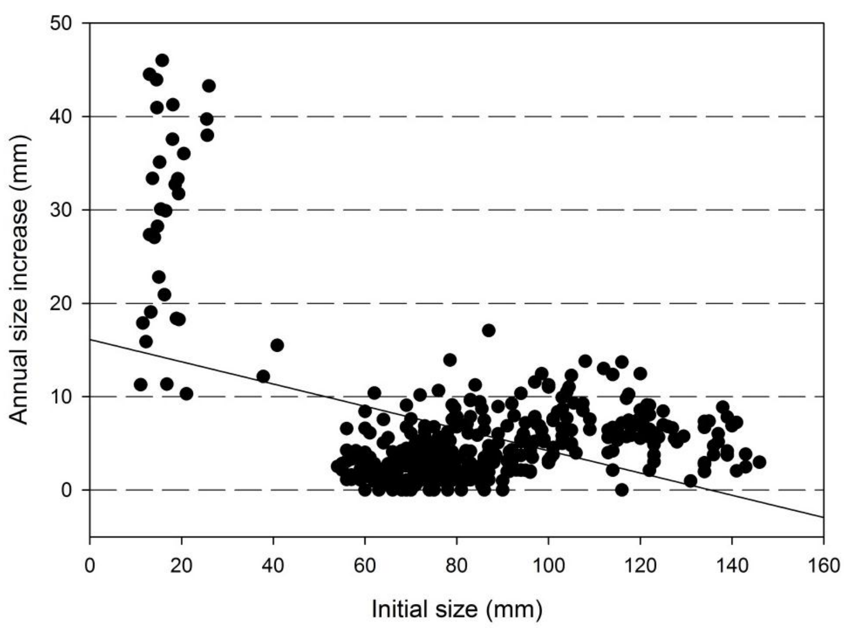


Figure 14: Von Bertalanffy growth model (f = J∞ (1-e^{-K})- Jt (1-e-$^{K)}$) fit to annual growth with initial size over the entire size range for a) females and b) males.

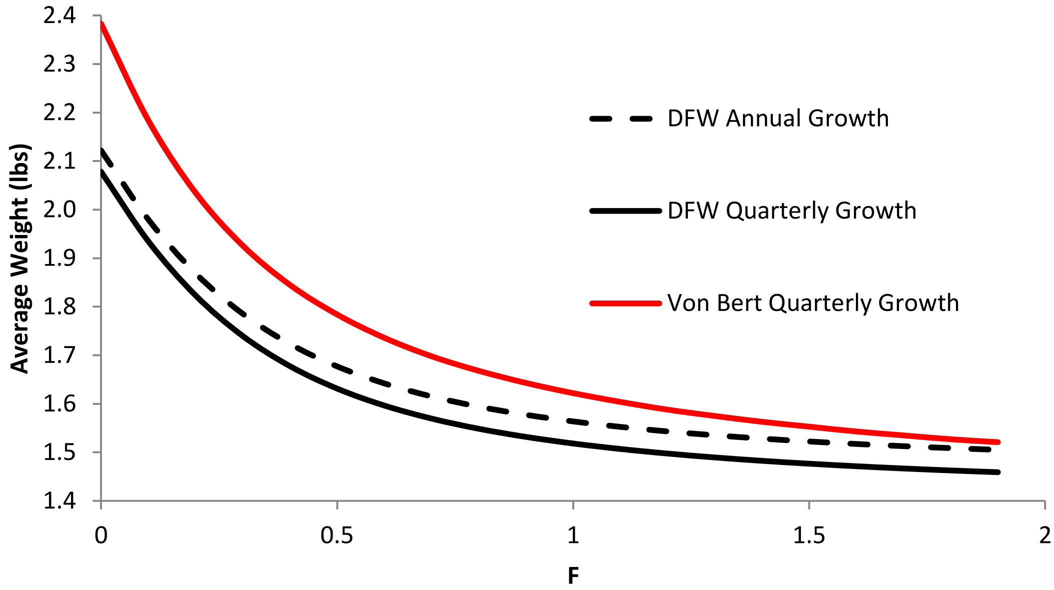


Figure 15: Relationship between average weight in the catch and instantaneous fishing mortality (F) with different growth models and schedules: quarterly von Bertalanffy (red solid), quarterly growth based on curves developed by CDFW (black solid), and annual growth based on CDFW curves (black dashed).