Management strategy evaluation: Recreational Red Abalone Management Strategy Integration

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Section 1. Introduction

When data limitations preclude quantitative stock assessment as the basis for management decisions, management strategies rely instead on simpler indicators derived from monitoring data that can be used to inform decision-making (Prince et al. 2008, Butterworth et al. 2010, Dowling et al. 2015). Design of a data-limited management strategy for northern California's recreational red abalone fishery was initiated by two recent scientific proposals by the California Department of Fish and Wildlife (CDFW) and The Nature Conservancy (TNC) (OST 2018). A variety of considerations were addressed in these proposals, but a need for further refinements was stressed by a team of peer reviewers and by the California Fish and Game Commission (CFGC 2018, OST 2018). Peer review urged integration of indicators from the two separate proposals as well as a focus on developing rebuilding criteria. The Commission recommended integrating aspects of both proposals through the use of simulation modeling, emphasized developing an allowance of a de minimis fishery during rebuilding, and required engagement with stakeholders.

This report describes simulation modeling that was used to evaluate rebuilding strategies for red abalone. The development of these rebuilding strategies was carried out through discussions with the Project Team and Administrative Team. Among the diverse array of topics discussed by the Project Team, their views have influenced management strategy design in terms of the need for multiple indicators, designs that emphasize opportunities for fishing, the need for frequent decision-making (i.e., annual application of management strategy), and enabling citizen scientists to continue to engage in data collection.

Through feedback from the Project Team and the peer review process, a variety of challenges related to data quantity and data quality were identified that constrained rebuilding strategy design in some important ways. First, fine-scale spatial stock structure of red abalone is at odds with feasible scales of data collection. This constraint on data quantity requires a rebuilding strategy that is designed to recognize site-specific signals about resource changes, while also attempting to guide decision-making at much larger spatial scales. Second, each of several data streams that have been identified (e.g., density, length frequencies distributions, kelp abundance, sea urchin density, ocean temperature, body condition) emphasizes a unique aspect of the biological and ecological condition of red abalone, thus requiring consideration of how multiple indicators can function cohesively to support scientifically sound management decisions (OST 2018). Third, and perhaps most challenging, is the various ways that each data stream is limited in its information content. Information content is a key consideration, as even in instances where fisheries are considered to be data-rich, in actuality, these same fisheries can be information-poor in terms of data reliability for supporting decision-making (Magnusson and Hilborn 2007, Carruthers et al. 2014, Dowling et al. 2015, Harford and Babcock 2016). For red abalone density surveys, the precision with which this quantity can be estimated has been called into question, and directly reflects its information content (OST 2014). For length frequency distributions, sampling precision appears adequate; however, information content reflects the uncertain reliability of life history information used in analyzing this data stream and a persistent information lag between changes to spawning condition and subsequent detection of this change (Bellquist n.d., Prince 2016, OST 2018). For ecological or environmental indicators, despite the intuitive nature of these indicators, implicit mechanistic linkages between red abalone biology and environmental conditions are typically difficult to verify, and more broadly, simulation testing of other fisheries has failed to demonstrate improved management performance through inclusion of such indicators in harvest control rules, except when mechanistic relationships are clearly understood (A’mar et al. 2010, Punt et al. 2014).

Given the above stated design constraints, the Project Team identified a rebuilding framework that would consist of two parts (see Section 2). In summary, Part A reflects a Project Team recommendation to require examination of the state of the northern California ocean environment and the productivity of red abalone for exceptional circumstances or emergency circumstances. Part A provides an opportunity to consider whether exceptional circumstances are occurring in a variety of indicators (e.g., kelp abundance, sea urchin density, ocean temperature, body condition, gonad condition). If exceptional circumstances are deemed to be occurring and may impede initiation or continuation of a fishery, then direction is sought from the Commission and/or CDFW. Where no exceptional circumstances are found, Part B follows. Part B is an indicator-based approach (i.e., indicators considered were derived from density and length frequency data streams) where each indicator contributes to annual decision-making. As a separate analysis, the Project Team also asked for an examination of whether a low sampling intensity monitoring program could assist in the development of a separate management strategy for Humboldt and Del Norte counties (a preliminary exploration of this issue is provided in Section 4).

Simulation testing of rebuilding strategies was carried out through management strategy evaluation (MSE; Smith et al. 1999, Butterworth 2007, Rademeyer et al. 2007, Punt et al. 2016). MSE is used to simulate the connections between field sampling, method of indicator calculation (i.e., data analysis), and decision-making via a harvest control rule (HCR). An HCR is used to interpret indicator values according to pre-stated criteria, which produces a recommended management action. Part B is an indicator-based HCR. Given the questions faced about data quantity and quality for managing the red abalone fishery, MSE was used to understand how existing sampling designs can support resource management. The objectives of the MSE were threefold. First, MSE supported a process of characterizing uncertainty in red abalone productivity and in the current state of resource depletion through alternative parameterizations of population dynamics models. Second, MSE supported development and refinement of rebuilding strategy options by requiring explicit representation of Peer Review guidance and Project Team ideas as HCRs. Third, MSE was used to provide guidance on selecting among several rebuilding strategy options by presenting expected outcomes in terms of trade-offs between catches and the provision of protection of abalone abundance. Collectively, these objectives were intended to support the Commission's recommendation to integrate two previous management strategies through a stakeholder-led engagement process.

Section 2: Two-zone rebuilding strategy

Outlook on rebuilding strategy design

The proposed two-zone rebuilding strategy is developed according to the two-part rebuilding framework outlined in the introduction, where Part A serves as an exceptional circumstances provision and Part B involves the application of an indicator-based HCR. Part A provides an opportunity to consider whether exceptional circumstances are occurring in a variety of indicators (e.g., kelp abundance, sea urchin density, ocean temperature, body condition, gonad condition). Where no exceptional circumstances are found, Part B follows. Part B is a two-indicator approach (i.e., indicators derived from density and length frequency data streams).

Part B is implemented using what is known as a ‘traffic light method’ and provides a unified framework within which challenges related to data quantity and data quality are addressed (Fig. 2.1; Caddy 2002). Under the indicator approach, indicators derived from density and length frequency data streams are assigned a color category that is determined by comparing the indicator value against pre-agreed reference points. Red indicates a dangerous condition, far from enabling open fishery status. Yellow reflects unsatisfactory conditions, occurring during transition from red to green. Green reflects satisfactory conditions aligned with enabling open fishery status. Having assigned color categories to both indicators, an HCR in the form of a set of decision trees is then used to interpret indicator color combinations and produce a recommended management action.

The traffic light method enables a coarse characterization of a defined geographic region according to the measurement of prevailing conditions (via indicators), which is consistent with the need to guide decision-making at spatial scales larger than the specific sites that are subject to field sampling. The traffic light method enables multiple indicators to inform decision-making, each according to the biological or ecological qualities to which the indicator is most responsive. Finally, the traffic light method establishes a harvest control rule that integrates indicators into decision-making according to their known information limitations. The traffic light method has been implemented in various forms (Caddy 1999, 2015, Caddy et al. 2005), and offers several benefits in addressing the management circumstances facing red abalone. It simplifies data into a set of value judgements, presented in an understandable form, and enables uncertainty in indicators to be embraced while providing a basis for coarse adjustment to management status (Mangel and Levin 2005, Caddy 2015).

A detailed description of the entire management strategy follows. The reader is encouraged to examine the management strategy in the order it is presented, concluding with the technical summary of how indicators are calculated. Then, given an understanding of indicator calculations, work backwards and re-visit the other components of the strategy to understand how data quality and quantity influence the defined structure of the management strategy.

Rebuilding strategy

Fishing Zones

The management strategy relies on the concept of management according to fishing zones, which are geographic areas of the coastline comprising several of the formerly defined abalone report card sites. This strategy is designed to unify regulatory decisions and enforcement (notwithstanding marine protected area sites). Zoning is also designed to rely on established sampling programs and to help to ensure a pragmatic approach to coordination of data collection and application of indicators and corresponding reference points.

Through consultation with the Project Team, requests were made to consider up to four zones (i.e., separate zones for Marin, Sonoma, Mendocino, and Humboldt + Del Norte counties, and combinations thereof), as well as requests to consider report card site-specific management strategies. The use of site-specific management strategies was not further considered in this report for the following reasons. While it is plausible that a set of criteria could be constructed for implementing de minimis fishery triggers at various report card sites, it is unclear whether shifting of resources towards continual monitoring of sites where a de minimis fishery is operating while also attempting to ensure that coast-wide monitoring coverage is a tractable option. Secondarily, consideration should be given as to whether serial depletion could be more problematic when fishing is concentrated at only a few sites, relative to the dispersion of catches across many sites (Post 2013).

Now shifting focus to fishing zones encompassing several report card sites, data limitations constrain how fishing zones can be currently delineated. The use of multiple indicators presents a complex challenge for treating the combined Humboldt and Del Norte counties as a unique fishing zone because there is no historical baseline sampling on which to gauge the suitability of density reference points. In the absence of a historical baseline, the Project Team considered measuring a contemporary density baseline through a concerted sampling effort to occur in the near future (prior to implementation of any management strategy). This idea was met by some opposition from the Project Team. An additional challenge with using a contemporary baseline lies in understanding whether this baseline is a suitable target or limit reference point. Such a baseline could be conservatively regarded as a limit reference point (where the management objective is to keep density above this density limit); however, it is uncertain whether this baseline might even be too low to ensure fishery sustainability. Furthermore, it is unclear whether sufficient length frequency data could be collected from the combined Humboldt and Del Norte counties to support use of this information.

But the idea of maintaining Humboldt and Del Norte counties as separate from Mendocino county, and likewise separating Marin county from Sonoma county, should not be readily dismissed. Natural heterogeneity in ecological characteristics within a zone will negatively affect the ability for the management strategy to correctly guide regulatory adjustments. This problem is acute for the use of density as an indicator. Density reference points are chosen based on several criteria (described later) and are compared to historical densities to ensure that they are chosen sensibly. But because historical sampling has occurred in California only as far north as Glass Beach, near Fort Bragg, it is currently unclear how to specify such reference points for Humboldt and Del Norte counties. These circumstances suggest two alternative zoning options as it relates to Humboldt and Del Norte counties. The first alternative is that a special initiative could be carried out to produce an appropriate sampling design for a separate fishing zone consisting of Humboldt and Del Norte counties. The second alternative is that a lack of data on which to base decision-making does not necessarily preclude the specification of Humboldt and Del Norte counties as a separate zone, where a highly limited fishery could occur with a catch limit equivalent to biological sampling needs for research or other management purposes. Neither of these two alternatives are further developed in this Section, instead a two-zone approach is examined in detail.

For the purpose of testing via management strategy evaluation (MSE), two fishing zones are defined:

- **Mendocino, Humboldt and del Norte counties.**
- **Marin and Sonoma counties.**

The most pressing constraint leading to this zone configuration is reliance on established sampling programs. The two-zone design attempts to reconcile site-specific signals of resource change and utilize these signals in guiding decision-making at much larger spatial scales.

Management status definitions

The rebuilding strategy proposed here is used to determine when changes to the management status of each zone should take place via an indicator-based HCR. Differences between each management status reflect the degree of access restriction in the form of total allowable catch (TAC). There are three types of management status: closed, de minimis fishery, open fishery. The management status of closed has no access; a TAC of zero. The management status of de minimis fishery ranges between a small level of take that has no effect on recovery to a TAC level that is anticipated to have a minimal effect on the recovery of the resource. The lowest level of de minimis TAC allows a fishery for abalone but requires presenting abalone to CDFW to collect data first before abalone are retained by the fisher. The term ‘open fishery’ is used to signal the end of the rebuilding period.

Allocation of individual take limits (ITLs)

An allocation program for individual take limits (ITLs) must be developed to annually distribute any specified TAC. Allocation to individuals and/or user groups is not covered here, although Project Team discussions have highlighted the desire to allocate any TAC among subsistence and recreational uses. Once allocation is determined, the proposed strategy relies on the assumption that dispersal of fishing across several sites within a zone will occur (notwithstanding marine protected areas or any other closed sites). Thus, allocation of TACs among individuals should not restrict where harvest occurs, except that it occurs within the defined fishing zone and no catches within MPAs or other closed sites. This criterion is intended to disperse the effects of fishing across the entire zone, at least to the extent possible given user preferences.

Additional and existing regulations

This rebuilding strategy is expected to function in conjunction with other existing regulations. Those existing regulations include at least the following: 7-inch size limit; report cards that establish individual take limits (ITLs) and require documentation of prescribed data (date of effort, catch, location, etc.); ban on scuba; no taking abalone for someone else; no high grading, taking a larger abalone and putting a smaller one back; no co-mingling abalone with another fisher; uniform start time for fishery; and other existing CDFW regulations.

Rebuilding strategy details

The rebuilding strategy is applied in two parts, with each part being applied annually. Part A addresses exceptional circumstances and has conditions that must be satisfied before moving to Part B. Part B determines management status via an indicator-based harvest control rule. Parts A and B are applied to each zone separately in the following order: Apply Part A. If no exceptional circumstances are triggered, then apply Part B to determine management status and to determine the type of fishery and its corresponding TAC.

Part B of the rebuilding strategy is based on a set of decision trees that delineate how data-driven triggers enable transitions between closed, de minimis, and open status. The decision tree is always applied separately to each zone, thus, each zone can have a different management status from its neighboring zone at any given time. Each time the decision tree is used to determine current status, it is possible that the current status may differ from the previous status. Change in status is limited to one step in the positive direction (i.e., from closed to de minimis and from de minimis to open, but no jump from closed to open), but multiple steps can be taken in the negative direction, as necessary. This restriction is codified into the decision trees; no additional steps are necessary to execute this condition.

The proposed rebuilding strategy is designed to be applied annually. This condition has implications both in terms of timely reactivity to population changes, but also to observation-error-driven oscillation between management status, cautious but timely transitions between management status, and administrative considerations. Given a decision interval of one year, the management strategy is applied as follows. When an updated management status is to be applied in year *y*, data analysis and decision-making occur in year *y-1*, and data analysis relies on field sampling in years *y-2, y-3, y-4.* The condition of a one-year time-lag between data analysis and implementing a decision the following year was specified as a precaution to enable various entities time to carry out analysis and decision-making processes. This time lag can be removed from the management strategy if more rapid decision-making appears feasible. The need to utilize field sampling in years *y-2*, *y-3, y-4* reflected the desirability to have obtained sufficient geographic sampling coverage to most reliably characterize the fishing zone as a whole. This means that recursive annual decision-making relies on a 3-year moving window of field sampling.

Part A: exceptional circumstances

Through discussions with the Project Team, Part A was identified as a necessary precursor that examines the state of the northern California environment and the productivity of red abalone. This step was developed by the Project Team as both an ecological safe-guard and as an opportunity to consider whether exceptional circumstances are occurring in a variety of indicators (e.g., kelp abundance, sea urchin density, ocean temperature, body condition, gonad condition). Where such exceptional circumstances protocols are used in other fisheries, responses to exceptional circumstances tend to either trigger a formal review of the management strategy or trigger an ad hoc management adjustment in the current decision interval (Butterworth 2008, Carruthers and Hordyk 2018). The Project Team's comments appeared to align with the latter circumstance, requiring Commission direction and potential temporary adjustments to regulations.

A set of rules for what constitutes exceptional circumstances is not explicitly defined here, nor are justifications for triggering this condition, nor the protocol or advisory process involving Commission decision-making. Part A, as described here, should be regarded as reflective of discussions held by the Project Team regarding the essential nature of such a protocol and the potential utility of such a protocol to incorporate a variety of environmental and red abalone productivity indicators into a more holistic decision-making framework. This protocol may also be useful for responding to conditions under which the decision trees (i.e., harvest control rule) have been identified as not providing robust performance; which may be identified or revealed by management strategy evaluation (MSE). Thus, a HCR can be implemented under the principle motivation of establishing consistent decision-making, within the broader context of an FMP that also acknowledges the need for occasional reliance on ad hoc regulatory adjustments (Butterworth 2008, Carruthers and Hordyk 2018).

Several environmental and productivity indicators identified prior to the peer review are:

- Ocean Temperature
- Canopy-Forming Kelp Abundance
- Sea Urchin Density
- Body condition and gonad condition (productivity)

Some additional indicators identified by the Project Team are:

- Sea star presence/density
- Acidification, pH
- Oxygen saturation
- Harmful algal blooms
- Disease
- Pacific Decadal Oscillation

The Project Team noted that exceptional circumstances based on indicators described above may not always require Commission direction, but in some circumstances indicators may instead trigger the collection of additional or more up-to-date abalone data, including density and length frequency distribution data. Such a protocol would allow more up-to-date information to be used in Part B. Thus, as circumstances dictate, reliance on the 3-year moving window of field sampling can be limited, instead using up-to-date information gathering that is triggered under an exceptional circumstances protocol.

Part B: Traffic light decision trees

Part B relies on the use of two data streams: density and length frequency distributions. Initial project Team discussions centered around the use of density, length frequency distributions, and productivity indicators (i.e., either gonad index or body condition). The productivity indicator(s) have been shifted to Part A. Part B begins by guiding the selection of the correct decision tree to be applied based on the management status in the previous decision interval. The correct decision tree to follow is determined by the previous management status (i.e., the management status in the previous decision interval).

- If the previous management status is closed, proceed to tree #1 (Fig. 2.2)
- If the previous management status is de minimis, proceed to tree #2 (Fig. 2.3)

- If the previous management status is open, proceed to tree #3 (Fig. 2.4)

In any instance where insufficient density or length frequency distribution data are available to proceed to a decision tree, then an interim decision is to be made at the discretion of the Commission.

When following a path through a decision tree, pay special attention to the text on the left side of the tree. This text will state which indicator to apply at each node. Pay special attention to the text pertaining to the density indicator(s). Do not jump ahead in following a path through the decision tree. It may appear that some pathways are repetitive or redundant, but this is not the case and each decision tree is designed to cover most eventualities.

Indicators used in each decision tree are presented according to their color category. Assignment of a color category to an indicator is determined through the analysis of the various data streams, and comparison of indicator values to pre-agreed quantitative reference points. In the case of spawning potential ratio (SPR), categories are assigned relative to a limit reference point. In the case of density, a more involved approach is used that requires specification of limit, intermediate, and target reference points. Target reference points define the desirable expectations of the fishery and the stock. The level of concern for fishery sustainability is low. Intermediate reference points are established so that management actions are triggered as concern for sustainability grows. Limit reference points define a state of the resource that is to be avoided.

Calculation of the SPR indicator and reference point selection

Given that analysis and consultation is to occur in year *y*-1, where *y* is the year in which the updated management status is to be applied, data used in calculating SPR is obtained from field sampling in years *y-2, y-3, y-4.* Analysis of field sampling data suggests that 150 – 300 individual length measurements of red abalone in the exploited phase (>178 mm shell length) per site could be a reasonable rule of thumb for a minimum data collection standard (Technical Appendix 1). Within a defined fishing zone, sampling at more than 10 sites appears necessary to characterize variation in SPR at this geographic scale (Technical Appendix 1). Furthermore, this management strategy is constructed on the premise that CDFW will maintain its historical site sampling regiment. To meet site coverage expectations, this strategy will likely depend on additional sampling by RCCA or another organization. In any instance where a site is visited two or more times within the 3-year moving window, the most recent site visit is to be used in data analysis.

For each year-site combination visited within a defined fishing zone during years *y-2, y-3, y-4*, SPR is calculated according to the length-based SPR method (Hordyk et al. 2015). The maximum likelihood LB-SPR estimation routine requires input parameters of *M/K,* asymptotic length, coefficient of variation of asymptotic length, and a logistic maturity curve (Hordyk et al. 2015). Suggestions and additional details for calculating SPR from observed length-frequencies are provided in Technical Appendix 3.

Given an SPR estimate for each year-site combination, the fishing zone is characterized as red, yellow, or green according to a selected SPR reference point. A variety of issues should be addressed in selecting an SPR reference point, but perhaps the most salient is to consider the use of a limit SPR that is conservative enough to buffer abundance away from low levels, especially because red abalone are vulnerable to environmental conditions in terms of their survival, growth, and reproductive success (Tegner et al. 2001, Harley and Rogers-Bennett 2004, Rogers-Bennett et al. 2012). Analysis of red abalone and a variety of other species has shown that maintaining higher average biomass levels, in the face of environmentally-induced biomass fluctuations, carry lower probabilities of crossing thresholds representing undesirable conditions (Bellquist n.d., Punt et al. 2012, Harford et al. 2018). SPR indicator color is calculated as follows. A limit SPR reference point λ_{SPR} is compared to the empirical distribution of SPR estimates within a zone. The percentiles, T_{SPR}, determine color category as follows (Fig. 2.5):

If $> T_{SPR,red}$ of SPR estimates fall below λ_{SPR}, then RED. (e.g., If $> T_{SPR,red} = 75\%$ of SPR estimates fall below $\lambda_{SPR} = 0.75$, then RED

If $< T_{SPR,green}$ SPR estimates fall below λ_{SPR}, then GREEN. (e.g., If $< T_{SPR,green} = 25\%$ of SPR estimates fall below $\lambda_{SPR} = 0.75$, then GREEN

Otherwise, YELLOW

Calculation of density indicator

Given that analysis and consultation is to occur in year *y*-1, where *y* is the year in which the updated management status is to be applied, data used in calculating density is obtained from field sampling in years *y-2, y-3, y-4.* Since density and length frequency samples are collected during the same survey events, the same advice holds that the functioning of this indicator is constructed on the premise that CDFW will maintain its historical site sampling regiment, and that supplemental sampling by RCCA or other organizations would improve site coverage (see Technical Appendix 1). In any instance where a site is visited two or more times within the 3-year moving window, the most recent site visit is to be used in data analysis.

Project Team and modeling discussions have reflected consideration of a limit reference point in proximity to 0.2 abalone per m^2. Based on a variety of evidence, it is thought that productivity could be compromised below this density level. At Santa Rosa and Santa Cruz Islands, Kelp Forest Monitoring Program (National Parks Service) data show that red abalone populations in 1983 were below 0.2 abalone per m^2, and following these densities, populations continued to decline to <0.05 abalone per m^2 (Tegner et al. 1989a, Karpov et al. 1998). Red abalone densities before 1983 at these island sites (1978-1982) were <0.3 abalone per m^2 (Tegner et al. 1989a). In Washington State, northern abalone *H. kamtschatkana* densities have declined by 77% with all sites now <0.15 abalone per m^2 (Rothaus et al. 2008). At these low densities, populations continued to decline and there is now apparent recruitment failure (Rothaus et al. 2008, Rogers-Bennett et al. 2011). Northern abalone have also showed reduced productivity along the west coast of Vancouver Island, British Columbia, Canada following declines in density below 0.3 abalone per m^2 (Tomascik and Holmes 2003). In South Australia at West Island, given the assumption that declining parental stock contributed to poor recruitment, Shepherd and Brown (1993) measured densities between 0.25 and 0.015 abalone per m^2 prior to the period of poor recruitment. Additional reference points, termed intermediate and target densities are also required. Selection of these reference points will be guided by past CDFW densities surveys in northern California (Technical Appendix 1).

Whole-site density of emergent red abalone should be calculated according to an appropriate statistical distribution thought to give rise to the data. This consideration is explored in Technical Appendices 1 & 3, revealing a right-skewed distribution of counts and sometimes a non-negligible number of zero count transects, which is consistent with log-normal or delta log-normal sampling distributions (Pennington 1983, Lo et al. 1992, Fletcher 2008). For each year-site combination, summary statistics of density should be calculated:

1. Apply a delta-lognormal distribution to red abalone transect counts;
2. Estimate summary statistics (including confidence interval of the mean).

Once the CI of the mean of each site-year combination is calculated, the color category is calculated for each of three indicators. Thus, a CI is calculated separately for each individual site, and then the fraction (percentile) of the CIs that meet density criteria (see below) are used to evaluate traffic light status.

Density limit reference point indicator

A limit density reference point λ_{DL} (e.g., $\lambda_{DL} = 0.2$ /m^2) is defined. Percentiles, T_{DL} determine color category as follows:

If $< T_{DL}$ of density CIs are greater than λ_{DL} , then RED. (e.g., If $<$ 100% of density CIs are greater than 0.2 /m^2, then RED)

Otherwise, YELLOW

Density intermediate reference point indicator

An intermediate density reference point λ_{DI} (e.g., $\lambda_{DI} = 0.3$ /m^2) is defined. Percentiles, T_{DI} determine color category as follows:

If $< T_{DI}$ of density CIs are greater than λ_{DI} , then YELLOW. (e.g., If $<$ 100% of density CIs are greater than 0.3 /m^2, then YELLOW)

Otherwise, GREEN

Density target reference point indicator

A target density reference point λ_{DT} (e.g., $\lambda_{DT} = 0.4$ /m^2) is defined. Percentiles, T_{DT} determine color category as follows:

If $< T_{DT}$ of density CIs are greater than λ_{DT} , then YELLOW. (e.g., If $< 100\%$ of density CIs are greater than 0.4 /m^2, then YELLOW)

Otherwise, GREEN

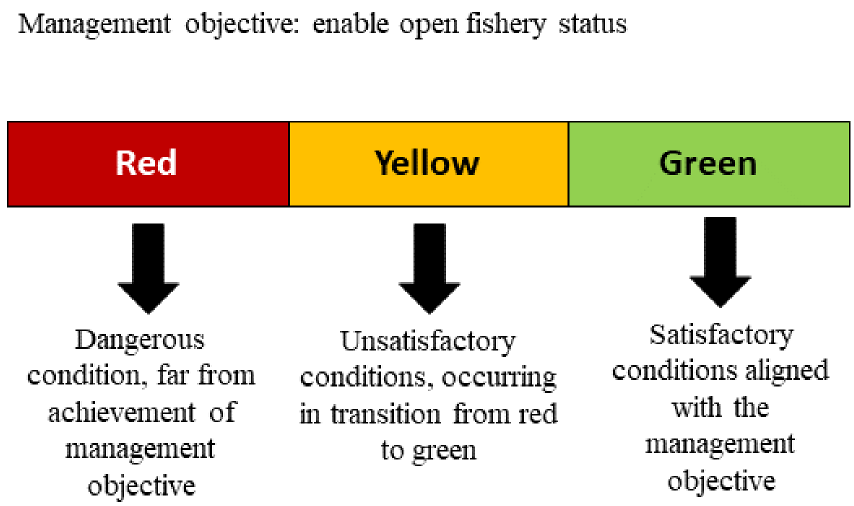


Figure 2.1. Traffic light method.

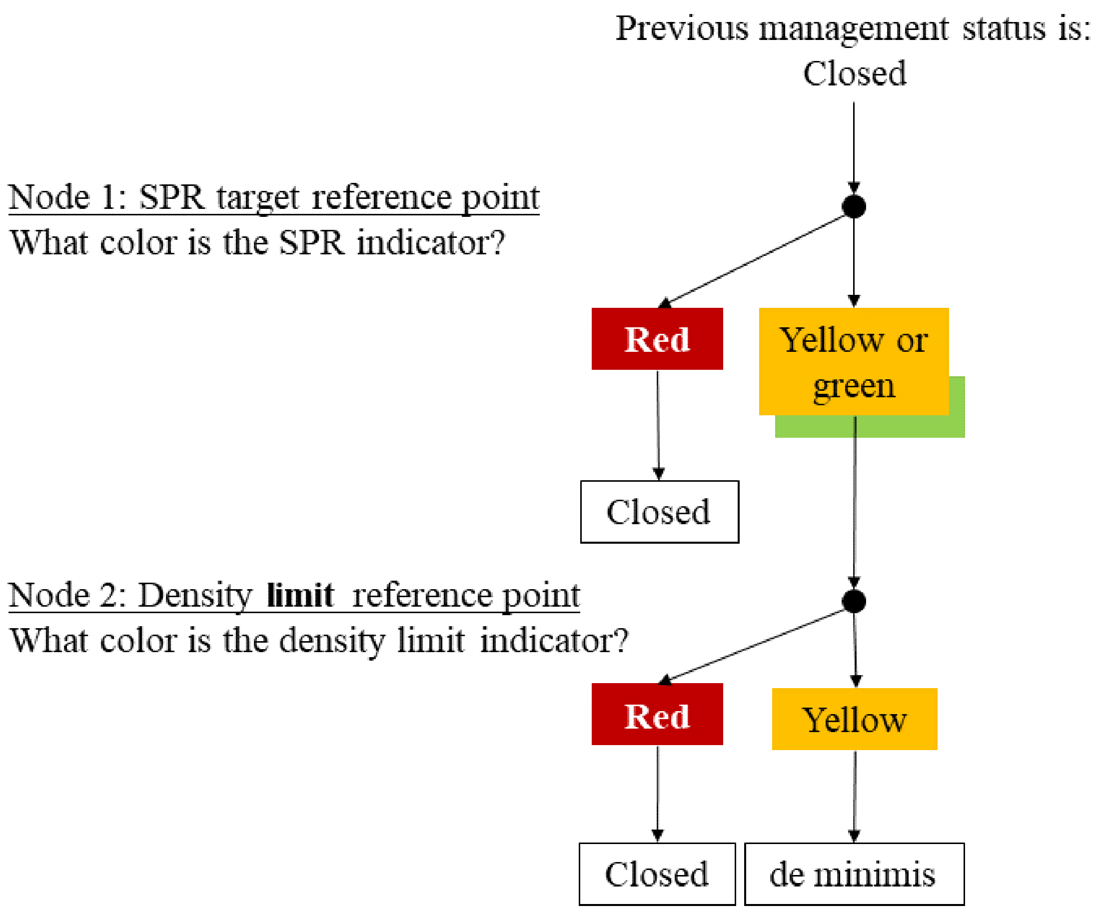


Figure 2.2. Part B of the management strategy. Decision tree #1. Applied when previous management status is closed.

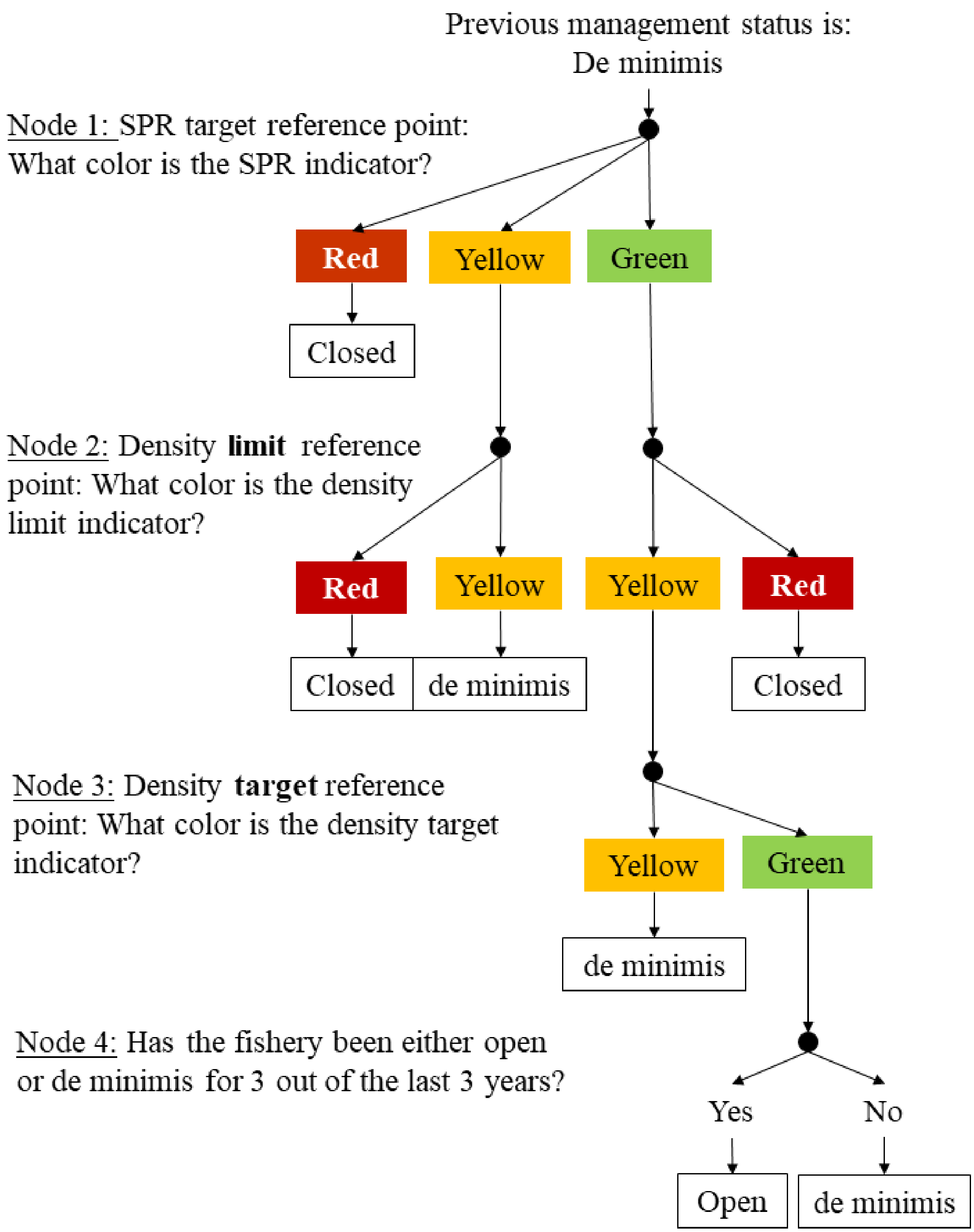


Figure 2.3. Part B of the management strategy. Decision tree #2. Applied when previous management status is de minimis.

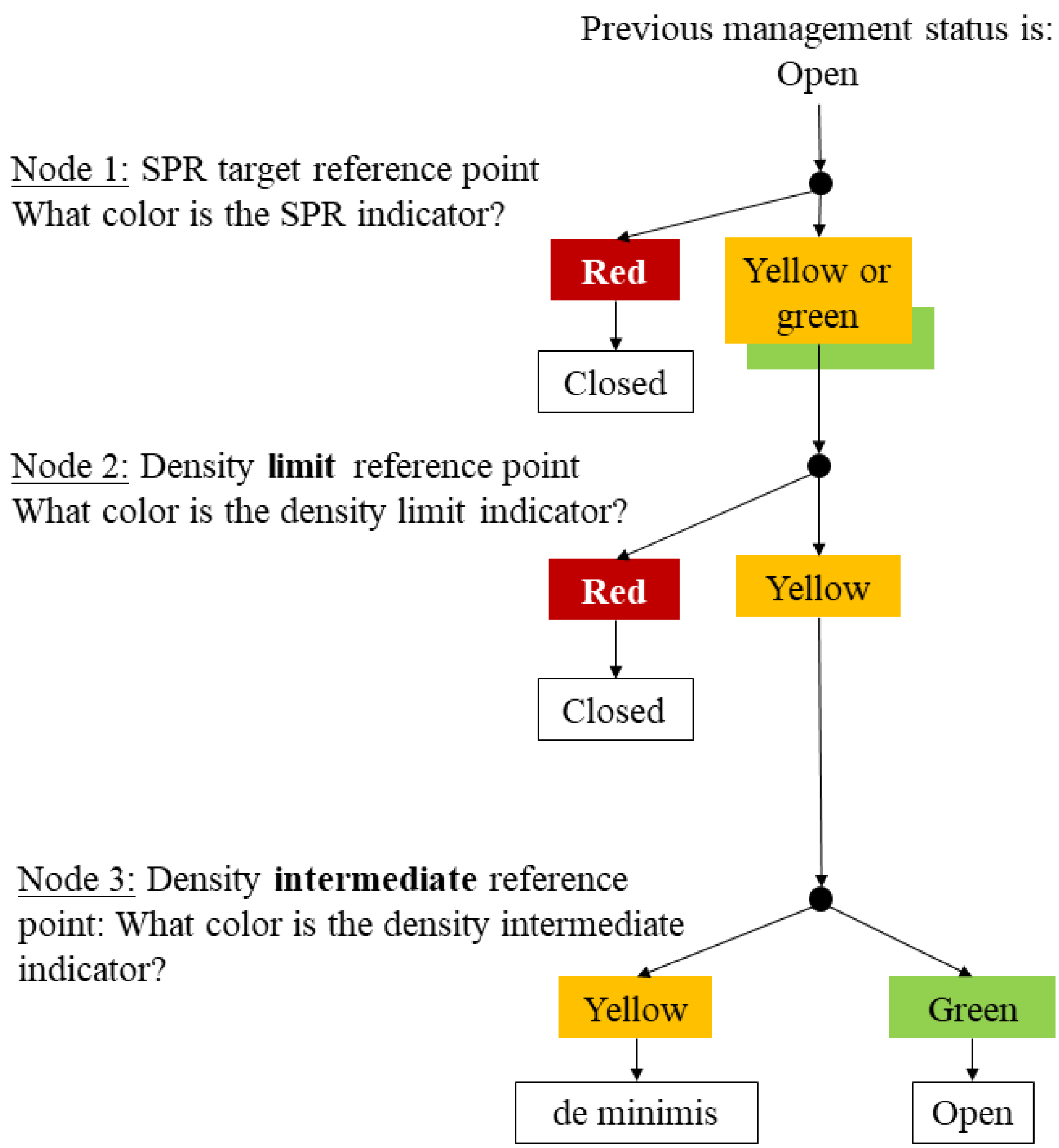


Figure 2.4. Part B of the management strategy. Decision tree #3. Applied when previous management status is open.

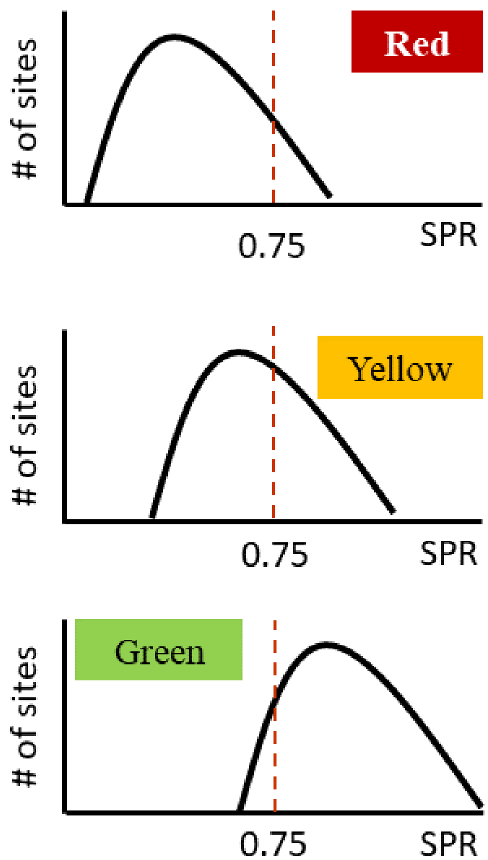


Figure 2.5. Illustration of the traffic light approach as applied to the SPR indicator.

Section 3: Two-zone management strategy evaluation

Management strategy evaluation

Base model configuration

In examining the two-zone rebuilding strategy, a key ecological uncertainty is the current state of the red abalone resource. During model tuning, an additive mortality rate, specified as 0.3 $year^{-1}$ was added to the baseline natural mortality rate (to all length classes) for the years 2015 to 2017 to reflect downward trends in RCCA and CDFW density estimates that were assumed to reflect unfavorable environmental conditions (see Technical Appendix 3). But it remains unclear how far into the future detrimental conditions will persist. Accordingly, two operating model (OM) scenarios were specified to reflect this uncertainty (Fig. 3.1). In operating model #1, termed 'short-term environmental decline', it was assumed that unfavorable conditions would continue for three years, 2018 to 2020, during which the additive natural mortality rate continued to be imposed, further depleting red abalone abundance. In operating model #2, termed 'prolonged environmental decline', unfavorable conditions were assumed to persist for five years. These two scenarios are intended to acknowledge uncertainty in the length of time that unfavorable environmental conditions may persist. The duration of unfavorable conditions could differ from these two scenarios. If unfavorable conditions persist beyond those in the scenarios, then rebuilding times could increase.

These two operating models were contrasted against a factorial design of rebuilding strategy configurations (Fig. 3.2; Table 3.1). These configurations reflected alternative options for SPR and density reference points and choices of de minimis TACs. Some preliminary MSE exploration was conducted, which highlighted focal areas of rebuilding strategy configurations. Consequently, configurations focused on choice of SPR limit reference point (levels: 0.4 and

0.5), as this quantity reflects the degree of protection in spawning abundance, and percentiles of density (levels: $T_{DL}=T_{DI}=T_{DT}$ =100% and $T_{DL}=T_{DI}=T_{DT}$ =75%), reflecting degree of among-site consistency in clearance of density thresholds. In all configurations, SPR percentiles were: $T_{SPR,red}=75\%$ and $T_{SPR,green}=25\%$. Likewise, for all configurations, density confidence intervals (CIs) were set to 50%. The density 50% CI was utilized as a way to identify a conservative threshold, as a metric aimed at ensuring sufficient red abalone abundance is present to support future catch. It does not appear advantages to utilize 95% CI, as initial MSE exploration demonstrated overly detrimental effects on fishing opportunities when the 95% CI was used because imprecision in density can produce very wide tails. Also, density reference points were set to $\lambda_{DL}=0.2$ /m^2, $\lambda_{DI}=0.3$ /m^2, and $\lambda_{DT}=0.4$ /m^2 because these quantities were consistent with historical density levels (see Technical appendix 1). De minimis TAC options were specified as 5,000, 10,000, 20,000, and 40,000 red abalone (abundance) per fishing zone. Additionally, a de minimis TAC of zero is used as a reference condition to provide a baseline time-to-open in the absence of fishing.

For a given operating model and rebuilding strategy combination, 200 simulations were implemented as follows. Historical dynamics occur from 2002 to 2017 (see Technical Appendix 3). Then, from 2018 to 2020, zone-specific TACs are each set to zero to reflect the current fishery closure. In 2021, the rebuilding strategy is implemented. Simulations are stopped when an open fishery is triggered or after 100 years if fishery opening fails to be triggered by the rebuilding strategy. It should be understood that the time required to recover to de minimis status or to open status is a function of (i) depletion levels in 2021, (ii) the chosen reference points, (iii) the productivity of the abalone stock, and (iv) the prevailing (stochastic) environmental conditions that affect growth and natural mortality. Together these factors introduce variability into recovery time. MSE is used to examine only Part B of the management strategy, as Part B is a quantitative HCR that can be specified in algorithmic form within a simulation framework. In conducting MSE, it is assumed that Part A is absent and that annual decisions are always made via Part B. This approach permits evaluations of whether Part B has satisfactory performance under a variety of conditions.

Performance metrics

Six performance metrics were calculated in summarizing rebuilding strategy performance (Fig 3.1). Performance metrics are specified to reflect milestones in fishery recovery. At the first time step where a de minimis fishery is triggered, the time duration (relative to the 2021 implementation year) is recorded along with red abalone depletion (relative spawning biomass). These metrics are summarized for (i) sampled sites where information was available in model tuning, and (ii) at all fished sites, excluding four marine reserve sites (i.e., pooling depletion estimates at sampled or all sites, respectively; Tables 3.2 & 3.3).

In calculating performance metrics related to the first time step where an open fishery is first triggered, simulations were filtered relative to whether an open fishery (i.e., a recovered red abalone population) was triggered within 100 years or not. Those simulations where recovery was not triggered were set aside and recovery performance metrics were applied only to the subset of simulations where recovery occurred. Importantly, all management strategies are subject to same sets of stochastic environmental elements. Thus, where this performance metric differs between management strategies, it is the design of the management strategy itself that lead to these performance differences. Simulations where recovery was not triggered provide important context for rebuilding strategy design, especially where reference points may appear restrictive to fishing opportunities. The percentage of simulation runs achieving rebuilt status within 100 years is reported as a separate performance metric. For the subset of simulations where recovery occurred, the following recovery performance metrics were calculated. At the first time step where an open fishery is first triggered, the time duration (relative to 2021 implementation year) is recorded along with red abalone depletion. During the time period between triggering of a de minimis fishery and triggering of an open fishery, the cumulative catch (in numbers of red abalone) is recorded. During the same time period, stability of fishery management status was calculated. This metric was calculated as the proportion of times that a switch occurred between de minimis fishery and closure over the duration of time between an initial de minimis trigger and eventual triggering of open status. Stability enables decision-makers to consider whether a more stable management status is desirable relative to alternatives that are more reactive, noting that management strategies will react both to 'true' signals and to error or noise in observed quantities of SPR and density.

Finally, during the time period between triggering of a de minimis fishery and triggering of an open fishery, the probability of depletion falling below 0.05. 0.10 or 0.20 at any point during this time period is recorded. These depletion levels were chosen to reflect low biomass states associated with uncertainty in onset of an Allee effect. This metric is calculated as:

$$S_l = \begin{cases} 1 & \text{if depletion below threshold} \\ 0 & \text{Otherwise} \end{cases},$$

where l is a report card site. Probability for a given depletion threshold is then calculated:

$$P_r = \frac{\sum_{l=1}^{X} S_l}{X},$$

where r is simulation replicate, X is the total number of sites. The range of probabilities across simulation replicates, P_r, is reported.

Sensitivity analysis

Two types of sensitivity analyses were carried out. First, sensitivity to OM configuration was evaluated by making changes to OM 1. These OM alternatives are labeled OM 1.1, OM 1.2, etc. The effects of changing the operating model were evaluated against management strategy A. Second, some sensitivity analyses were conducted to examine alterations to management strategy reference points and related regulatory criteria. These sensitivity analyses were carried out using OM 1 and by modifying management strategy A, with labels A.1, A.2, etc.

Sensitivity to red abalone productivity

Sensitivity to red abalone productivity was assessed by creating two alternative configurations of OM1. In OM 1.1, stock-recruitment steepness was changed from 0.7 to 0.6, which was a lower steepness values, but which remained consisted with values that have previously been considered in stock assessment (Gorfine et al. 2005, Fu 2014). In OM 1.2, fecundity was modified such that the exponential increase in egg production with increasing length plateaued at the length of 254 mm (baseline asymptotic length) to reflect uncertainty about patterns in egg production in the largest size classes that are not well represented in empirical data sets (Rogers-Bennett et al. 2004). As noted, the changes made to OM 1 were evaluated against management strategy A, which was implemented with a de minimis TAC of 5,000 red abalone in each fishing zone.

Sensitivity to population scaling

During model tuning, a data-limited method, known as DB-SRA, was used for estimating maximum sustainable yield (MSY) from site-specific catch histories. Site-specific MSY was used as a means to identify a site-specific population scaling parameters (see Technical Appendix 3). The absolute scaling of populations at red abalone report card sites is germane to the question of the effect of de minimis TACs on rebuilding. DB-SRA produces Monte Carlo-like outcomes, with median MSY being used to scale populations in operating models in base operating model configurations. As a precaution against overestimation of MSY, the estimated lower quantile (25^{th} percentile of Monte Carlo outcomes) was used in this sensitivity run, instead of the median. Thus, this sensitivity run examines the possibility that population sizes were smaller than originally specified in OM 1. On average, MSY at the lower quantile was only 60% of the MSY at the median. Thus, to carry out OM 1.2, the unfished recruitment parameter, R0, (this is scaling parameter in each OM; see Technical Appendix 3) was multiplied by 0.6, thus reducing site-specific population sizes to 60% of their specified values in OM 1. As noted, the changes made to OM 1 were evaluated against management strategy A. But in this scaling comparison, simulations were carried out against each of the previously considered de minimis TAC options to examine how perceptions about these options might change based on population scaling.

Alternative management strategy configurations

The following alternative configurations of management strategy A, with a de minimis TAC of 5,000 red abalone in each fishing zone, were evaluated:

- A.1: Strategy A, except changing minimum harvest size to 8 inches (203 mm)
- A.2: Strategy A, except changing minimum harvest size to 9 inches (229 mm)
- A.3: Strategy A, except changing density reference points to: limit 0.2 m^{-2}, 0.25 m^{-2}, 0.3 m^{-2}
- A.4: Strategy A, except changing percentiles of density to $T_{DL} = T_{DI} = T_{DT}$ =90%, reflecting degree of among-site consistency in clearance of density thresholds.
- A.5: Strategy A, except changing density CI to 25%
- A.6: Strategy A, except changing density CI to 10%

Results

Base model configuration

From closed to de minimis fishery status

Median rebuilding times to de minimis varied between 11 and 31 years across OMs, fishing zones, and rebuilding strategies (Table 3.4; Fig. 3.3). Prolonged environmental decline (OM 2) resulted in eight to 10 years of additional delay in recovery relative to OM 1, while the chosen reference points of each rebuilding strategy also contributed substantially to rebuilding times. Among rebuilding strategies, differences in time to de minimis were most pronounced between density percentiles, resulting in shorter times to de minimis for rebuilding strategies A & C (i.e., density percentiles $T_{DL} = T_{DI} = T_{DT}$ =75%) than for rebuilding strategies B & D (i.e., density percentiles $T_{DL} = T_{DI} = T_{DT}$ =100%). This performance difference principally reflects the degree of among-site density variation that is allowed relative to density thresholds. Accordingly, because time to de minimis is shorter for rebuilding strategies A & C, than for B & D, the state of red abalone depletion when a de minimis fishery is triggered varied considerably between these strategies (Tables 3.5 & 3.6; Figs. 3.4 & 3.5). For rebuilding strategies A & C, depletion at the first time step where a de minimis fishery is triggered tended to be approximately 0.2. Alternatively, rebuilding strategies B & D delayed triggering a de minimis fishery, enabling recovery to approximate depletion of 0.3 to 0.4. Thus, among the four rebuilding strategies a trade-off is evident. Taking the opportunity to fish sooner (options A & C) occurs during a more depleted resource state. Alternatively, delaying fishing (options B & D) occurs during a less depleted resource state.

From de minimis to open fishery status

The percentage of simulation runs that resulted in an open fishery within the 100 year durations that were simulated (i.e., a recovered red abalone population) was less than 100% for rebuilding strategies B & D (Table 3.7). Individual simulations where this occurred were set aside, with performance metrics calculated for those simulations where an open fishery was triggered within 100 years.

When a de minimis fishery is triggered, it is accompanied with the need to specify a de minimis TAC. Given the expectation that recovery will continue during a de minimis fishery (i.e., the de minimis TAC is not set too high), each of the four rebuilding strategies was also specified under the assumption of TAC = 0. Setting a TAC=0 was used as a reference, which allowed rebuilding times in the absence of fishing to be calculated. In the absence of fishing, median recovery times to open fishery status ranged between 28 and 59 years depending on rebuilding strategy reference points, operating model, and fishing zone (Table 3.8). Reference rebuilding times are compared to those for each combination of rebuilding management strategy and de minimis TAC (Tables 3.9 through 3.12). As a general pattern, a de minimis TAC of 5,000 had an unremarkable effect on Mendocino zone recovery. An effect is observed, relative to corresponding reference strategy, at levels of 20,000 to 40,000 red abalone. Whereas, for the smaller fishing zone of Sonoma, a de minimis TAC of 5,000 has a minor effect on recovery time, while de minimis TACs notably begin to affect recovery time at levels greater than 10,000 red abalone. To further highlight the extent to which rebuilding times to open status were affected by choice of de minimis TAC, a set of histograms were constructed for rebuilding strategies A & C, which allowed for more intuitive visual inspection of recovery delays (shifting of the distributions to the right) that occurs under alternative de minimis TACs (Figs. 3.6 through 3.9).

At the time of triggering an open fishery status, each of the rebuilding strategies varied in corresponding state of red abalone depletion at which an open fishery occurred (Tables 3.13 through 3.16). Rebuilding strategies A & C tended to trigger open fishery status at median depletion levels between approximately 0.4 and 0.5. Thus, the overall functioning of rebuilding strategies A & C reflects initiation of a de minimis fishery at depletion of approximately 0.2, followed by fishery opening when depletion climbs to approximately 0.4 to 0.5. More conservatively, rebuilding strategies B & D tended to trigger open fishery status at median depletion levels between approximately 0.6 and 0.8. Thus, the overall functioning of rebuilding strategies B & D reflects initiation of a de minimis fishery at depletion of approximately 0.3 to 0.4 followed by fishery opening when depletion climbs to approximately 0.6 to 0.8.

Given that each rebuilding strategy and each accompanying de minimis TAC results in different time periods of de minimis fishing prior to achieving open fishery status, it is worth also examining cumulative catches (Tables. 3.9 through 3.12). Cumulative catches tend to be higher for higher levels of de minimis TAC. This result is intuitive, suggesting that higher levels of de minimis TAC delay achievement of open fishery status, but in the interim, de minimis fishery status produce higher cumulative catches over many years. Cumulative catches also tend to be higher for rebuilding strategies B & D, compared to A & C. This result occurs because B & D have longer rebuilding times, and thus during the interim de minimis fishery status, higher cumulative catches occur. Stability of management status during rebuilding suggested that management strategies A & C was most stable, followed by B and D (Tables 3.17 & 3.18).

Taken together, recovery to open status requires consideration of three trade-offs between rebuilding strategy options: time to open fishery status, depletion at open status, and cumulative catches prior to achieving open status. To further examine the trade-offs between these three performance metrics, trade-off plots were produced (Figs. 3.10 & 3.11). These plots help to group sets of rebuilding strategy that are similar in performance. Rebuilding strategies A & C offer the shortest times to open fishery status, even under higher de minimis TAC levels. Rebuilding strategies B & D offer improved levels of depletion upon recovery (relative to A &

C), and because recovery times are longer, can offer the highest levels of cumulative catch during rebuilding.

The probabilities of depletion falling below 0.05. 0.10 or 0.20 during the period of triggering of a de minimis fishery and triggering of an open fishery were estimated to examine whether the functioning of rebuilding strategies would occasionally result in depletion levels that could be associated with the onset of an Allee effect (Table 3.19). Depletion did not fall below thresholds of 0.05 or 0.10 during any simulation runs. This result reflects delay of de minimis fishery until current depletion has had a chance to show some recovery (i.e., for rebuilding options A & C, a de minimis fishery is not typically triggered until depletion is approximately 0.2). Depletion did frequently fall below 0.20 during a de minimis fishery in rebuilding options A & C, whereas delayed triggering of a de minimis fishery in rebuilding strategies B & D resulted in a less depleted resource at the time a de minimis fishery was initiated and avoidance of depletion below 0.20.

Sensitivity analysis

Sensitivity to red abalone productivity

In evaluating how operating model assumptions may affect interpretation of management strategy performance, reducing steepness (lower productivity) delayed recovery times and slightly lowered depletion levels associated with the onset of de minimis fishery and open fishery (Table 3.20). In modifying the assumption about fecundity, performance was deemed insensitive to this change in the operating model.

Sensitivity to population scaling

This sensitivity run provides additional guidance on de minimis TAC selection and highlights how limitations in operating model specification that should be taken into consideration when selecting a de minimis TAC (Fig. 3.12). The alternative operating model reduces site-specific R0 to 60% of their values relative to the base operating model. Reduction of this scaling parameter leads to notable increases in recovery time to open, especially for de minimis TACs > 5,000. Missing data points in Figure 3.12 at de minimis fisheries of 20,000 and 40,000 reflect a lack achieving an open fishery in 100 year simulations at these TAC levels under the lower R0 operating model.

Alternative management strategy configurations

Modifying minimum harvest length (A.1 and A.2) had little effect on shorter-term metrics like time to de minimis fishery; however, time to open fishery was reduced by, on average, two to three years (Table 3.21). Similarly, changing intermediate and target density reference points to 0.25 m^{-2} and 0.3 m^{-2} (A.3) reduced time to open fishery by, on average, five years, but had no effect on time to de minimis fishery. Modifying percentiles of density to $T_{DL} = T_{DI} = T_{DT} = 90\%$ (A.4) resulted in performance of this strategy that was more similar to management strategy option B ($T_{DL} = T_{DI} = T_{DT} = 100\%$) than to management strategy option A ($T_{DL} = T_{DI} = T_{DT} = 75\%$). Strategy A.5 and A.6 modified the density confidence interval to 25% or 10%, relative to the base case of 50%. Strategy A.5 and A.6 resulted in shorter time durations to de minimis fishing, but also allowed fishing to occur at a more depleted resource state.

Discussion

How did we get here?

The objective of the MSE work presented herein was to consider options and anticipated consequences of management strategies that integrated previously proposed indicators of red abalone population status, as recommended by Peer Review and by the California Fish and Game Commission (CFGC 2018, OST 2018). The initial TNC collaborative proposal introduced a length-based approach to red abalone management, which was subjected to simulation testing under el Niño-like environmental fluctuations, but only considered population rebuilding to a minimal extent. The initial CDFW proposal took a traditional density approach, while also recognizing the potential for wider variety of ecological indicators to support decision-making (e.g., body condition, kelp cover, ocean temperature). As the peer review process proceeded in evaluating the merits of both a CDFW-submitted management strategy and a stakeholder-submitted management strategy led by TNC, the issue of focusing on both rebuilding considerations and long-term sustainability considerations came to the forefront of policy discussions (OST 2018). Finally, as the management strategy integration process proceeded during 2019 (including the MSE presented herein), the potential extent to which unfavorable environmental conditions had affected red abalone, and could continue to affect red abalone into the near future became apparent. Accordingly, the MSE focused almost solely on rebuilding because of the expected longer management timeframes required for population recovery. MSE accounted for potentially catastrophic declines in red abalone abundance, which was a novel aspect that had not been previously considered in previous red abalone management strategies. To the extent possible, the issues affecting this changing management and environmental landscape for red abalone over the last three to five years are presented in this report.

Why consider a multi-indicator approach?

Within the information-limited context of red abalone management, the presence of less-than-desirable levels of observation error remains a primary motivation for considering a multi-indicator approach. Estimation of both density and SPR are subject to non-trivial levels of observation error. Figure 3.13 provides an example of the expected degree of observation error in each indicator relative to a simulated ‘truth’ that we are attempting to observe through monitoring. MSE work presented existing sampling designs for length and density data, rather than developing new or alternative data streams; thus, integration of indicators was representative of the most routinely measured indicators. While only CDFW and Reef Check field sampling designs are represented in the MSE, the two-zone management strategy does not preclude the addition of other sampling locations from a larger network of collaborative organizations.

The inclusion of both density and SPR provides a more robust management strategy. As developed, the two-zone management strategy requires thresholds for both density and SPR to be surpassed (not one or the other). Thus, the multi-indicator approach provides for redundancy in the management system (Schnute and Richards 2001). Information contained in each indicator also offers unique merits. Density is responsive to rapid and catastrophic declines in abundance, like those seen in recent years, while SPR may be better characterized as a ‘slow reacting’ indicator. As density is utilized in the management strategy, its merits also include helping to avoid low-density situations. Although thresholds for Allee effects are not precisely known for red abalone, it is expected that the density indicator works in a precautionary way to avoid encountering Allee effects. On the other hand, SPR reflects the reproductive status of the red abalone population and, unlike density, allows for decision-making in relation to a biological reference point. Furthermore, SPR reference points can be chosen in a manner that may better optimize long-term yield (Harford et al. 2019b).

Considerations related to model parameterization

Evaluation of the two-zone management strategies was carried out using an approach known as MSE. The underlying population dynamics models are parameterized using best available scientific information. In developing the MSE, the operating models reflect current estimates of life history parameters (Rogers-Bennett et al. 2004, 2007, Leaf et al. 2007). The operating models also incorporate life history variation in space and time that is reasonably consistent with the vulnerability of red abalone to environmental perturbations, with the magnitude of such mass mortality events having been gleaned from empirical and experimental evidence (Tegner et al. 2001, Vilchis et al. 2005, Jiao et al. 2010, Rogers-Bennett et al. 2010, 2019, Cavanaugh et al. 2011). Spatial representation of population dynamics reflects considerations about abalone species larval dispersal, adult movement, and meta-population dynamics (Ault and Demartini 1987, Shepherd and Brown 1993, Temby et al. 2007, Gruenthal et al. 2007, Saunders et al. 2008, Coates et al. 2013). As a precaution against building reliance on larval exchange into management strategy performance, sites have no such exchange of red abalone represented in simulations. Finally, a model of the fishery is specified that assumes that fishing sites will continue to maintain their relative popularity with fishers into the foreseeable future, regardless of local red abalone abundance changes. It is imperative to demonstrate that a management strategy could provide satisfactory functioning if recreational fishers lack incentive to move to other sites as local abundance of red abalone declines (Post 2013).

When interpreting management strategy performance, it is important to understand that outcomes are a function of (i) the chosen reference points of a management strategy, (ii) depletion levels in 2021 specified in the operating model, (iii) the productivity of the abalone stock specified in the operating model, and (iv) the stochastic environmental conditions that affect growth and natural mortality that are specified in the operating model. The above stated conditions are explicitly described in designing these management strategies (see Section 2) and in the specification of the operating model(s) (see Technical Appendices 2 & 3). However, there are also several implicit assumptions made throughout the modeling process. Readers should be aware of the following implicit modeling assumptions. In using length-based SPR, it was assumed that life history parameters could be reliably obtained (see Prince 2016) and that field collection of length measurements would continue at previous sampling intensities that have been established by CDFW and Reef Check California (see Technical Appendix 1). Likewise, density estimates were assumed to be available for decision-making at previously established sampling intensities and it was assumed that density is not unreasonably subject to kelp cover-induced heterogeneity in abalone detection probability (i.e., time-varying detection probability; Monk 2014) nor subject to density hyper-stability owing to abalone re-distribution behavior. Hyper-stability is defined as the occurrence of stable density, while the underlying abundance declines, resulting in misleading information about population trends.

Selection of a management strategy and on-going FMP development

Turning to the question of selecting a suitable management strategy, two general suggestions are provided for interpreting MSE results. First, selection of a management strategy sometimes involves deciding whether minimum performance standards are satisfied across a sufficiently broad set of conditions, or the least across the most severe of plausible conditions. This decision-making procedure is known as satisficing (Miller and Shelton 2010). A second consideration, known as the precautionary approach, determines whether a candidate management strategy poses sufficiently low risk of damage to the resource, across as many circumstances as possible, including irreparable damage (Darcy and Matlock 1999, Restrepo and Powers 1999).

The issue of Allee effect required some careful consideration to inform management strategy performance, particularly given recent unfavorable environmental conditions and catastrophic declines in abundance (Tegner et al. 1989a, Karpov et al. 2000). The Peer Review recommended better reflecting low density dynamics in the red abalone operating model (OST 2018). However, the original operating model configuration was not changed to address Allee effects, instead maintaining site-specific recruitment failure when spawning biomass falls below 1% of its unfished level. Of course, this configuration does not acknowledge the possibility that an Allee effect could occur at a higher level of spawning biomass. This issue was instead addressed as a performance metric. The choice to examine possible Allee effects as a performance metric, and not as an operating model sub-component, reflected the difficulty in specifying a suitably realistic model representation of this complex ecological phenomenon (Kramer et al. 2009, Hutchings 2015). Thresholds for onset of Allee effect remain difficult to pinpoint, especially in terms of red abalone population depletion or site-specific abundance. Specifying such thresholds are further complicated by their interpretation either as a tipping point for reduction in per-capita population growth as abundance declines (i.e. Allee-effect threshold), or as a threshold for complete reproductive failure, resulting in local extinction (Allee threshold; Hutchings 2015). Furthermore, the possibility of re-distribution of adults and occasional larval dispersal events complicate specification of local extinction probability within the mathematical model that was used for MSE. Thus, low density dynamics, or highly depleted dynamics as they were re-cast in terms of performance metrics, were measured as the resulting probability of encountering a highly depleted site over the duration of each simulation. This metric served to address the question as to whether a given management strategy worked to keep depletion away from undesirable levels. Probability of falling to an undesirably low level was calculated relative to three depletion thresholds: 0.05 (i.e., 5% of unfished spawning biomass), 0.10, and 0.20. Thus, one's own viewpoint on risk aversion and the likely occurrence of Allee effects might result in emphasis on staying above a depletion level of 0.20, or alternatively, may result in emphasis on the probability of avoiding thresholds of 0.05 or 0.10.

As described in Section 2, the Project Team proposed a Part A exceptional circumstances clause as a precursor to applying the Part B management strategy. Only Part B was subject to MSE in this report. Part A was proposed as both an ecological safe-guard and as an opportunity to consider a wider variety of indicators (e.g., kelp abundance, sea urchin density, ocean temperature, body condition, gonad condition). The details of an exceptional circumstances clause are not explored in this report, but rather Part A is acknowledged here as a means to reflect the multi-indicator approach that has been discussed by both the Project Team and through the previous peer review process. Development of an exceptional circumstances protocol within the FMP likely requires substantially more detail than has been provided by the Project Team thus far. The previous peer review made a related statement reflecting the need for more clearly articulated procedures for the use of a variety of indicators in decision-making; especially those discussed in Part A. Thus, a more detailed description of an exceptional circumstances protocol is need if this clause is eventually included in an FMP. The identification of indicators for Part A is in itself insufficient and does not negate the need for refining the justification for the types of information and the manner in which these indicators trigger an exceptional circumstance. For some indicators identified as pertinent to Part A, additional research regarding the mechanistic linkages in system dynamics would also likely be beneficial.

Trade-offs in selecting a management strategy

Three key trade-offs are discussed that emerged in evaluating rebuilding strategies along with associated de minimis TAC options. The first trade-off is that rebuilding from a closed fishery to a de minimis fishery requires considering the level of spawning biomass (represented as depletion in the analysis) that is acceptable relative to delays in fishing opportunities. Fishing sooner and at a more depleted resource state is consistent with rebuilding strategies A & C, while delaying fishing, resulting in a less depleted resource is consistent with rebuilding strategies B & D. Likewise, the second trade-off is that the time to open fishery status must be weighed against depletion at time of fishery opening. Evidence for this trade-off can be observed by comparing time to de minimis fishing (Table 3.4; Fig. 3.3) to the corresponding level of resource depletion when de minimis fishing is triggered (Tables 3.5 & 3.6; Figs. 3.4 & 3.5). This trade-off reflects the target long-term depletion level that is desirable to maintain a sustainable open fishery. Rebuilding strategies A & C offer the shortest times to open fishery status, while rebuilding strategies B & D offer improved levels of red abalone biomass recovery, achieved over longer time horizons.

Together, these two trade-offs are shaped substantially by choice of SPR reference point and by choice of density reference points. Under options A & C, de minimis fishing is permitted when site-specific SPR and density estimates are in proximity to the corresponding reference point (some indicator variance above and below reference points is tolerated). Under these same options, A & C, an open fishery is triggered when most (> 75%) of site-specific SPR and density estimates exceed their limit reference points. Options B & D exercise some additional caution with respect to the density indicator, requiring 100% of density estimates to be above lower limit density reference point before de minimis fishery starts, and likewise, requiring 100% of density estimates to be above upper target density reference point before an open fishery is triggered.

Requiring 100% of density estimates to exceed a limit reference point introduces more management instability (i.e., fluctuations between closed and de minimis fishery status) than does allowing for some variation among indicator values (i.e., 75% density percentiles used in options A & C). While the examined density reference points were chosen relative to historical resource states, SPR reference points were chosen relative to theoretical work applied to long-lived species. Several studies have concluded that SPR targets greater than or equal to 0.4 should produce close to optimum harvest, especially for long-lived species (Mace 1994, Clark 2002, Punt and Ralston 2007, Harford et al. 2019b). And like other studies, maintaining SPR above such a target during an open fishery may be a reasonable means to buffer against environmentally-induced abundance fluctuations in the longer-term (Harford et al. 2018).

The third trade-off involves establishing a de minimis TAC. This trade-off is that delays in attaining open fishery status can be mediated to some extent through higher de minimis TACs. That is, some gains in cumulative catches can be obtained during the de minimis fishery at the cost of delaying the timeline to reaching open fishery status. As a caveat to this trade-off, consideration must be given to how a de minimis fishery is defined. If a de minimis fishery is defined to have little to no effect on the continued rebuilding of the resource, then delaying recovery through a higher de minimis TAC, would be inconsistent with this definition. In conducting sensitivity analysis, an additional caution became evident in selecting a de minimis TAC. While there is little consensus on the precise approach to doing so, data-limited fishery management tends to reduce catch limits in acknowledgement of scientific uncertainty (Newman et al. 2015). Given the sensitivity of de minimis TAC performance to uncertainty in population scaling parameters, some additional caution should be considered in establishing the level of de minimis TAC. Population scaling (in technical terms this refers site-specific unfished recruitment parameters) is a necessary component of building a population dynamics model, but for red abalone this aspect of model building is uncertain. Sensitivity analysis revealed that alternative assumptions about population scaling can have remarkable effects on rebuilding timeframes depending on how high a de minimis TAC is set. In general, data-limited management strategies tend to require catch limits that are more precautionary than those that could be implemented under equivalent data-rich fishery circumstances (Ralston et al. 2011, Dichmont et al. 2017).

Table 3.1. Reference points and other criteria used in two-zone management strategies

Criteria	Description	Alternative values examined via MSE?	Value(s)
λ_{SPR}	SPR limit reference point	Yes	0.4, 0.5
$T_{SPR,red}$	If $>T_{SPR,red}$ of SPR estimates fall below λ_{SPR} , then RED	No	75%
$T_{SPR,green}$	If $<T_{SPR,green}$ SPR estimates fall below λ_{SPR} , then GREEN	No	25%
λ_{DL}	Density limit reference point	In sensitivity analysis	0.2 m^{-2}
λ_{DI}	Density intermediate reference point	In sensitivity analysis	0.3 m^{-2}
λ_{DT}	Density target reference point	In sensitivity analysis	0.4 m^{-2}
CI	Lower bound of site-specific density confidence interval used as site-specific density estimate	No	50%
$T_{DL}=T_{DI}=T_{DT}$	Percentile of site-specific density estimates that must cross corresponding threshold. Subscripts refer to limit, intermediate, and target density reference points.	Yes	75%, 100%

Table 3.2. Summary of sites in Del Norte, Humboldt, and Mendocino counties.

Site	No-take Zone	Reef Check Sampling	CDFW Sampling
Crescent City			
Other Del Norte			
Patrick's Point			
Trinidad			
Punta Gorda			
Shelter Cove			
Other Humboldt			
Bear Harbor			
Usal			
Hardy Creek			
Abalone Point			
Westport			
Bruhel Point			
Kibesillah	✓		
MacKerricher			
Glass Beach		✓	
Georgia Pacific			
Todds Point			✓
Hare Creek			
Mitchell Creek			
Jughandle			
Caspar Cove		✓	✓
Russian Gulch		✓	✓
Jack Peters Gulch		✓	
Mendocino Hdlnds		✓	
Gordon Lane			
Van Damme		✓	✓
Dark Gulch			
Albion Cove			
Salmon Creek			
Navarro River			
Elk			
Point Arena Lighthouse		✓	
Arena Cove		✓	✓
Moat Creek			
Schooner Gulch			
Saunders Landing	✓		
Anchor Bay			
Robinson Point			

Table 3.3. Summary of sites in Sonoma and Marin counties.

Site	No-take Zone	Reef Check Sampling	CDFW Sampling
Gualala Point			
Sea Ranch		✓	✓
Black Point			
Stewarts Point			
Rocky Point			
Horseshoe Cove	✓		
Fisk_Mill Cove			
Salt_Point State Park		✓	✓
Ocean Cove		✓	✓
Stillwater Cove		✓	
Timber Cove			✓
Fort Ross		✓	✓
Jenner			
Bodega Head		✓	
Tomales Point			
Point Reyes			
Other Marin			

Table 3.4. Time in years to reach de minimis fishery status for four rebuilding strategies. OM is operating model; 25th and 75th are percentiles.

Rebuilding strategy	Average	SD	25th	Median	75th
OM 1					
Mendocino zone					
A	11.64	2.48	10.00	11.0	13.00
B	24.12	5.93	20.00	23.0	27.00
C	11.36	2.28	10.00	11.0	13.00
D	23.33	5.73	20.00	23.0	26.00
Sonoma zone					
A	16.32	2.70	15.00	16.0	18.00
B	20.33	3.50	18.00	20.0	23.00
C	15.51	2.58	14.00	16.0	17.25
D	20.02	3.30	18.00	20.0	22.00
OM 2					
Mendocino zone					
A	21.41	2.73	20.00	21.0	23.00
B	31.49	5.01	28.00	31.0	35.00
C	20.11	2.39	18.00	20.0	22.00
D	31.64	4.67	28.00	31.0	34.00
Sonoma zone					
A	25.00	2.40	24.00	25.0	26.00
B	29.68	3.75	27.00	29.5	32.00
C	24.61	2.34	23.00	25.0	26.00
D	29.09	3.39	26.75	29.0	31.00

Table 3.5. Depletion at sampled sites at the first time step where a de minimis fishery is triggered. OM is operating model; 25th and 75th are percentiles.

Rebuilding strategy	Average	SD	25th	Median	75th
OM 1					
Mendocino zone					
A	0.22	0.05	0.19	0.22	0.25
B	0.40	0.10	0.33	0.40	0.47
C	0.22	0.05	0.18	0.22	0.25
D	0.39	0.10	0.32	0.39	0.45
Sonoma zone					
A	0.24	0.05	0.20	0.23	0.27
B	0.29	0.07	0.24	0.29	0.34
C	0.23	0.05	0.19	0.22	0.26
D	0.29	0.07	0.24	0.28	0.33
OM 2					
Mendocino zone					
A	0.20	0.06	0.16	0.20	0.24
B	0.34	0.10	0.28	0.33	0.40
C	0.19	0.05	0.15	0.18	0.22
D	0.34	0.09	0.28	0.33	0.40
Sonoma zone					
A	0.22	0.06	0.18	0.22	0.26
B	0.29	0.08	0.23	0.28	0.34
C	0.22	0.05	0.18	0.21	0.25
D	0.28	0.07	0.23	0.28	0.32

Table 3.6. Depletion at all sites at the first time step where a de minimis fishery is triggered. OM is operating model; 25th and 75th are percentiles.

Rebuilding strategy	Average	SD	25th	Median	75th
OM 1					
Mendocino zone					
A	0.24	0.05	0.20	0.23	0.27
B	0.42	0.10	0.35	0.41	0.48
C	0.23	0.05	0.20	0.23	0.27
D	0.41	0.10	0.34	0.40	0.47
Sonoma zone					
A	0.25	0.06	0.21	0.25	0.29
B	0.31	0.07	0.26	0.31	0.36
C	0.24	0.06	0.20	0.24	0.28
D	0.31	0.07	0.26	0.30	0.35
OM 2					
Mendocino zone					
A	0.20	0.06	0.16	0.20	0.24
B	0.36	0.10	0.29	0.35	0.42
C	0.20	0.05	0.16	0.20	0.23
D	0.36	0.09	0.30	0.35	0.42
Sonoma zone					
A	0.22	0.06	0.18	0.22	0.26
B	0.30	0.08	0.25	0.30	0.35
C	0.23	0.05	0.19	0.23	0.27
D	0.30	0.07	0.24	0.29	0.34

Table 3.7. Percent of simulations where open fishery status (i.e., a recovered red abalone population) occurred within 100 years. Ranges presented as minimum to maximum reflect outcomes across factorial combinations of fishing zone and operating model configuration. Strategies are defined as combinations of rebuilding strategy A through D, with accompanying de minimis TAC (numbers of red abalone 5,000 to 40,000).

Rebuilding strategy	Minimum		Maximum
A 5,000	100	-	100
A 10,000	100	-	100
A 20,000	100	-	100
A 40,000	98	-	100
B 5,000	82	-	100
B 10,000	80	-	100
B 20,000	79	-	100
B 40,000	75	-	92
C 5,000	100	-	100
C 10,000	100	-	100
C 20,000	100	-	100
C 40,000	100	-	100
D 5,000	82	-	100
D 10,000	82	-	100
D 20,000	80	-	100
D 40,000	72	-	95

Table 3.8. Reference rebuilding strategy. Rebuilding time to open fishery status in the absence of fishing. OM is operating model; 25th and 75th are percentiles.

Rebuilding strategy	Average	SD	25th	Median	75th
OM 1					
Mendocino zone					
A	30.29	4.00	27.75	30	33.00
B	59.38	16.51	45.00	58	70.00
C	27.82	4.54	25.00	28	31.00
D	62.14	15.44	51.00	59	75.00
Sonoma zone					
A	35.90	4.97	33.00	36	39.00
B	49.02	10.86	42.00	48	54.25
C	33.68	5.05	31.00	33	37.00
D	47.16	9.72	39.00	46	53.25
OM 2					
Mendocino zone					
A	38.88	4.27	36.00	39	42.00
B	61.43	12.74	52.00	59	70.50
C	35.53	3.70	33.00	35	38.00
D	61.31	13.09	52.00	59	70.00
Sonoma zone					
A	43.65	4.21	40.75	44	46.00
B	57.95	10.67	50.00	57	65.00
C	41.47	4.42	38.75	41	45.00
D	56.20	10.14	49.00	55	62.00

Table 3.9. Rebuilding time to open fishery status for Mendocino zone, operating model 1. Strategies are labeled according to combinations of rebuilding strategy A through D, with accompanying de minimis TAC (numbers of red abalone 0 to 40,000). 25th and 75th are percentiles.

	Time to open					Cumulative catch x 1 million				
Rebuilding strategy	**Average**	**SD**	**25th**	**Median**	**75th**	**Average**	**SD**	**25th**	**Median**	**75th**
A 5000	30.45	4.43	27.0	30.0	33.25	0.08	0.02	0.06	0.08	0.10
A 10000	31.11	4.83	28.0	30.5	34.00	0.17	0.05	0.13	0.17	0.20
A 20000	32.26	4.64	29.0	32.0	35.00	0.36	0.10	0.28	0.36	0.40
A 40000	35.08	6.14	31.0	35.0	39.00	0.81	0.26	0.63	0.80	0.96
B 5000	62.74	16.00	50.0	62.0	75.00	0.13	0.06	0.08	0.13	0.18
B 10000	62.14	16.84	49.0	63.0	74.00	0.26	0.12	0.17	0.25	0.34
B 20000	64.71	15.41	51.0	62.0	76.00	0.56	0.23	0.38	0.52	0.74
B 40000	63.00	14.52	50.0	64.0	74.75	1.09	0.48	0.73	1.00	1.40
C 5000	28.00	5.03	24.0	28.0	32.00	0.07	0.02	0.06	0.07	0.09
C 10000	28.07	5.06	24.0	28.0	31.00	0.15	0.05	0.11	0.14	0.18
C 20000	28.80	5.06	25.0	28.5	31.00	0.31	0.10	0.24	0.30	0.38
C 40000	30.07	5.38	26.0	30.0	33.25	0.65	0.23	0.48	0.64	0.84
D 5000	62.05	16.36	48.5	60.0	74.50	0.13	0.06	0.08	0.12	0.18
D 10000	61.26	16.17	50.0	60.0	73.50	0.26	0.12	0.16	0.24	0.35
D 20000	63.16	16.48	51.0	62.0	75.00	0.53	0.24	0.34	0.52	0.68
D 40000	61.73	15.66	49.0	61.0	74.00	1.02	0.46	0.68	0.96	1.29

Table 3.10. Rebuilding time to open fishery status for Mendocino zone, operating model 2. Strategies are labeled according to combinations of rebuilding strategy A through D, with accompanying de minimis TAC (numbers of red abalone 0 to 40,000). 25th and 75th are percentiles.

	Time to open					Cumulative catch x 1 million				
Rebuilding strategy	**Average**	**SD**	**25th**	**Median**	**75th**	**Average**	**SD**	**25th**	**Median**	**75th**
A 5000	39.59	4.38	36.00	39	43	0.08	0.02	0.06	0.08	0.10
A 10000	40.38	4.84	37.00	40	43	0.17	0.05	0.14	0.16	0.21
A 20000	41.92	4.31	39.00	41	44	0.37	0.08	0.32	0.37	0.42
A 40000	46.07	5.15	43.00	46	50	0.88	0.22	0.75	0.88	1.01
B 5000	62.03	12.71	53.00	61	70	0.12	0.05	0.08	0.12	0.15
B 10000	62.79	11.94	54.00	62	71	0.25	0.10	0.17	0.23	0.32
B 20000	63.26	11.59	54.00	61	72	0.50	0.20	0.34	0.46	0.64
B 40000	65.78	12.12	56.00	65	74	1.10	0.41	0.80	1.04	1.32
C 5000	35.67	3.92	33.00	36	38	0.07	0.02	0.06	0.07	0.08
C 10000	35.84	4.01	33.00	35	39	0.14	0.04	0.11	0.13	0.16
C 20000	36.82	4.15	34.00	37	39	0.29	0.09	0.22	0.30	0.34
C 40000	39.12	5.33	35.75	39	43	0.68	0.22	0.52	0.68	0.80
D 5000	60.58	11.95	52.00	60	68	0.11	0.05	0.08	0.11	0.14
D 10000	62.16	12.72	53.00	60	69	0.25	0.11	0.17	0.23	0.31
D 20000	64.71	13.97	53.00	63	75	0.53	0.24	0.36	0.52	0.70
D 40000	64.64	13.24	54.25	64	75	1.04	0.43	0.72	0.98	1.32

Table 3.11. Rebuilding time to open fishery status for Sonoma zone, operating model 1. Strategies are labeled according to combinations of rebuilding strategy A through D, with accompanying de minimis TAC (numbers of red abalone 0 to 40,000). 25th and 75th are percentiles.

	Time to open					Cumulative catch x 1 million				
Rebuilding strategy	**Average**	**SD**	**25th**	**Median**	**75th**	**Average**	**SD**	**25th**	**Median**	**75th**
A 5000	36.13	4.95	32.75	36.0	39.00	0.09	0.02	0.08	0.09	0.10
A 10000	38.41	5.40	35.00	38.0	42.00	0.21	0.05	0.17	0.20	0.24
A 20000	41.94	6.83	38.00	41.0	46.00	0.47	0.14	0.38	0.46	0.54
A 40000	55.98	12.17	47.75	54.0	62.25	1.42	0.48	1.08	1.32	1.68
B 5000	49.34	10.35	42.00	48.0	56.00	0.12	0.04	0.09	0.11	0.14
B 10000	51.16	10.14	44.00	51.0	57.00	0.25	0.09	0.19	0.25	0.30
B 20000	54.72	11.80	46.75	54.0	61.00	0.56	0.21	0.42	0.54	0.68
B 40000	64.82	14.15	55.00	62.0	74.00	1.45	0.54	1.04	1.36	1.88
C 5000	34.87	5.85	31.00	35.0	38.00	0.09	0.03	0.07	0.09	0.11
C 10000	35.65	5.04	32.00	36.0	40.00	0.19	0.05	0.15	0.19	0.22
C 20000	37.01	5.84	33.00	37.0	41.00	0.39	0.12	0.32	0.40	0.46
C 40000	46.59	9.69	40.00	45.5	52.00	1.13	0.39	0.88	1.08	1.36
D 5000	46.45	9.41	40.00	45.0	52.00	0.10	0.04	0.08	0.10	0.13
D 10000	48.15	10.51	41.00	47.0	56.00	0.22	0.09	0.16	0.21	0.28
D 20000	52.11	11.69	44.00	51.0	59.00	0.51	0.20	0.38	0.50	0.60
D 40000	58.94	13.53	50.00	57.0	67.50	1.24	0.49	0.84	1.20	1.52

Table 3.12. Rebuilding time to open fishery status for Sonoma zone, operating model 2. Strategies are labeled according to combinations of rebuilding strategy A through D, with accompanying de minimis TAC (numbers of red abalone 0 to 40,000). 25th and 75th are percentiles.

	Time to open					Cumulative catch x 1 million				
Rebuilding strategy	**Average**	**SD**	**25th**	**Median**	**75th**	**Average**	**SD**	**25th**	**Median**	**75th**
A 5000	44.83	4.82	42.00	45.0	48.00	0.09	0.02	0.08	0.09	0.11
A 10000	46.68	4.60	44.00	46.5	50.00	0.20	0.05	0.17	0.20	0.24
A 20000	50.65	6.36	46.75	51.0	55.00	0.47	0.13	0.38	0.48	0.56
A 40000	60.28	8.72	54.00	60.0	65.75	1.26	0.34	1.04	1.24	1.44
B 5000	60.09	10.88	52.00	58.0	67.00	0.13	0.05	0.10	0.12	0.16
B 10000	59.42	9.50	52.25	59.0	65.00	0.25	0.09	0.19	0.24	0.29
B 20000	64.43	10.18	57.00	63.0	71.00	0.59	0.20	0.44	0.56	0.72
B 40000	70.90	12.05	61.00	71.0	80.00	1.41	0.48	1.01	1.40	1.72
C 5000	41.98	4.71	39.00	41.0	45.00	0.08	0.02	0.06	0.08	0.10
C 10000	43.56	4.41	40.75	43.0	46.00	0.18	0.05	0.15	0.18	0.21
C 20000	45.77	5.18	42.00	45.0	50.00	0.40	0.11	0.32	0.38	0.48
C 40000	54.45	8.91	49.00	53.5	60.00	1.12	0.36	0.87	1.12	1.32
D 5000	57.20	10.45	50.00	56.0	63.00	0.12	0.05	0.08	0.11	0.14
D 10000	57.26	10.19	50.00	56.0	63.00	0.23	0.10	0.17	0.21	0.29
D 20000	59.90	11.25	52.00	57.0	66.00	0.50	0.21	0.34	0.46	0.61
D 40000	63.91	11.80	53.50	64.0	71.00	1.16	0.48	0.80	1.12	1.48

Table 3.13. Depletion at open fishery status for Mendocino zone, operating model 1. Strategies are labeled according to combinations of rebuilding strategy A through D, with accompanying de minimis TAC (numbers of red abalone 5,000 to 40,000). 25th and 75th are percentiles.

	Depletion at sampled sites					**Depletion at all sites**				
Rebuilding strategy	**Average**	**SD**	**25th**	**Median**	**75th**	**Average**	**SD**	**25th**	**Median**	**75th**
A 5000	0.49	0.09	0.42	0.48	0.54	0.50	0.09	0.44	0.50	0.57
A 10000	0.48	0.09	0.42	0.48	0.54	0.51	0.10	0.44	0.50	0.57
A 20000	0.48	0.09	0.42	0.48	0.54	0.51	0.09	0.44	0.51	0.57
A 40000	0.48	0.10	0.41	0.48	0.55	0.51	0.10	0.44	0.51	0.58
B 5000	0.74	0.12	0.66	0.74	0.83	0.74	0.12	0.66	0.75	0.83
B 10000	0.72	0.13	0.63	0.73	0.81	0.73	0.12	0.65	0.74	0.82
B 20000	0.72	0.12	0.64	0.73	0.80	0.74	0.12	0.66	0.74	0.82
B 40000	0.68	0.13	0.60	0.68	0.77	0.70	0.12	0.62	0.71	0.79
C 5000	0.45	0.10	0.38	0.44	0.51	0.47	0.10	0.40	0.46	0.53
C 10000	0.45	0.09	0.38	0.44	0.50	0.47	0.10	0.40	0.46	0.53
C 20000	0.44	0.09	0.37	0.44	0.50	0.47	0.10	0.40	0.46	0.53
C 40000	0.43	0.10	0.36	0.42	0.49	0.46	0.10	0.39	0.46	0.53
D 5000	0.74	0.12	0.66	0.75	0.83	0.75	0.12	0.66	0.75	0.83
D 10000	0.73	0.12	0.64	0.73	0.81	0.74	0.12	0.65	0.74	0.82
D 20000	0.71	0.13	0.62	0.72	0.81	0.73	0.12	0.65	0.73	0.81
D 40000	0.67	0.13	0.59	0.68	0.77	0.70	0.12	0.62	0.70	0.78

Table 3.14. Depletion at open fishery status for Mendocino zone, operating model 2. Strategies are labeled according to combinations of rebuilding strategy A through D, with accompanying de minimis TAC (numbers of red abalone 5,000 to 40,000). 25th and 75th are percentiles.

	Depletion at sampled sites					**Depletion at all sites**				
Rebuilding strategy	**Average**	**SD**	**25th**	**Median**	**75th**	**Average**	**SD**	**25th**	**Median**	**75th**
A 5000	0.45	0.10	0.38	0.44	0.52	0.47	0.10	0.40	0.47	0.53
A 10000	0.45	0.10	0.38	0.45	0.52	0.47	0.10	0.40	0.47	0.54
A 20000	0.45	0.10	0.38	0.45	0.51	0.48	0.10	0.41	0.47	0.54
A 40000	0.45	0.12	0.38	0.45	0.53	0.49	0.11	0.41	0.49	0.57
B 5000	0.67	0.13	0.59	0.67	0.76	0.68	0.13	0.60	0.69	0.77
B 10000	0.67	0.12	0.59	0.67	0.76	0.68	0.12	0.60	0.69	0.77
B 20000	0.65	0.12	0.57	0.65	0.73	0.67	0.12	0.59	0.67	0.75
B 40000	0.61	0.13	0.52	0.62	0.71	0.65	0.13	0.56	0.65	0.73
C 5000	0.39	0.09	0.33	0.40	0.46	0.41	0.09	0.35	0.41	0.47
C 10000	0.39	0.09	0.33	0.38	0.45	0.41	0.09	0.35	0.41	0.47
C 20000	0.39	0.10	0.32	0.38	0.45	0.41	0.09	0.35	0.41	0.47
C 40000	0.38	0.11	0.31	0.38	0.45	0.41	0.11	0.34	0.41	0.49
D 5000	0.66	0.13	0.58	0.66	0.75	0.68	0.12	0.59	0.68	0.76
D 10000	0.66	0.13	0.57	0.66	0.75	0.68	0.12	0.59	0.68	0.76
D 20000	0.65	0.13	0.56	0.65	0.74	0.67	0.12	0.58	0.67	0.76
D 40000	0.60	0.14	0.52	0.61	0.70	0.64	0.13	0.55	0.64	0.73

Table 3.15. Depletion at open fishery status for Sonoma zone, operating model 1. Strategies are labeled according to combinations of rebuilding strategy A through D, with accompanying de minimis TAC (numbers of red abalone 5,000 to 40,000). 25th and 75th are percentiles.

	Depletion at sampled sites					Depletion at all sites				
Management strategy	**Average**	**SD**	**25th**	**Median**	**75th**	**Average**	**SD**	**25th**	**Median**	**75th**
A 5000	0.50	0.10	0.43	0.49	0.56	0.52	0.10	0.45	0.52	0.58
A 10000	0.50	0.10	0.43	0.50	0.57	0.53	0.10	0.46	0.53	0.60
A 20000	0.49	0.11	0.42	0.49	0.57	0.54	0.12	0.46	0.53	0.61
A 40000	0.49	0.14	0.39	0.49	0.59	0.56	0.14	0.47	0.57	0.65
B 5000	0.62	0.12	0.54	0.63	0.71	0.64	0.12	0.56	0.64	0.73
B 10000	0.62	0.12	0.53	0.62	0.70	0.64	0.12	0.56	0.65	0.72
B 20000	0.59	0.13	0.50	0.59	0.67	0.63	0.12	0.55	0.63	0.71
B 40000	0.55	0.15	0.45	0.55	0.66	0.62	0.14	0.52	0.63	0.72
C 5000	0.48	0.10	0.41	0.48	0.54	0.50	0.11	0.43	0.50	0.57
C 10000	0.47	0.10	0.40	0.46	0.53	0.50	0.10	0.43	0.50	0.57
C 20000	0.44	0.11	0.37	0.44	0.51	0.49	0.11	0.41	0.49	0.56
C 40000	0.44	0.13	0.35	0.43	0.52	0.50	0.13	0.41	0.50	0.60
D 5000	0.60	0.12	0.52	0.60	0.68	0.62	0.12	0.54	0.62	0.70
D 10000	0.59	0.12	0.50	0.58	0.68	0.62	0.12	0.53	0.62	0.70
D 20000	0.58	0.13	0.48	0.58	0.67	0.62	0.13	0.53	0.62	0.70
D 40000	0.53	0.15	0.43	0.54	0.63	0.59	0.14	0.50	0.60	0.69

Table 3.16. Depletion at open fishery status for Sonoma zone, operating model 2. Strategies are labeled according to combinations of rebuilding strategy A through D, with accompanying de minimis TAC (numbers of red abalone 5,000 to 40,000). 25th and 75th are percentiles.

	Depletion at sampled sites					Depletion at all sites				
Management strategy	**Average**	**SD**	**25th**	**Median**	**75th**	**Average**	**SD**	**25th**	**Median**	**75th**
A 5000	0.48	0.10	0.41	0.48	0.55	0.51	0.10	0.44	0.50	0.57
A 10000	0.49	0.10	0.42	0.49	0.56	0.52	0.10	0.45	0.52	0.59
A 20000	0.49	0.12	0.42	0.50	0.56	0.53	0.12	0.46	0.53	0.61
A 40000	0.49	0.15	0.41	0.50	0.58	0.56	0.15	0.46	0.56	0.66
B 5000	0.64	0.12	0.56	0.63	0.72	0.66	0.12	0.57	0.65	0.74
B 10000	0.61	0.12	0.53	0.62	0.69	0.64	0.12	0.56	0.64	0.72
B 20000	0.60	0.13	0.53	0.61	0.69	0.64	0.13	0.56	0.65	0.73
B 40000	0.55	0.15	0.47	0.56	0.65	0.62	0.15	0.52	0.62	0.72
C 5000	0.45	0.10	0.38	0.44	0.51	0.47	0.10	0.40	0.46	0.53
C 10000	0.45	0.10	0.38	0.45	0.52	0.48	0.10	0.41	0.48	0.54
C 20000	0.44	0.11	0.36	0.45	0.52	0.48	0.11	0.41	0.48	0.56
C 40000	0.44	0.14	0.36	0.45	0.54	0.51	0.15	0.42	0.51	0.61
D 5000	0.61	0.12	0.53	0.61	0.69	0.63	0.12	0.55	0.63	0.71
D 10000	0.59	0.12	0.50	0.59	0.68	0.62	0.12	0.53	0.62	0.70
D 20000	0.57	0.13	0.48	0.57	0.66	0.61	0.13	0.53	0.61	0.70
D 40000	0.52	0.15	0.45	0.53	0.62	0.59	0.15	0.50	0.59	0.69

Table 3.17. Stability metric, operating model 1. Strategies are labeled according to combinations of rebuilding strategy A through D, with accompanying de minimis TAC (numbers of red abalone 5,000 to 40,000). 25th and 75th are percentiles.

	Mendocino zone					Sonoma zone				
Management strategy	**Average**	**SD**	**25th**	**Median**	**75th**	**Average**	**SD**	**25th**	**Median**	**75th**
A 5000	0.22	0.12	0.13	0.20	0.30	0.18	0.11	0.11	0.18	0.24
A 10000	0.21	0.11	0.14	0.21	0.27	0.16	0.10	0.09	0.15	0.21
A 20000	0.21	0.11	0.12	0.20	0.29	0.16	0.10	0.09	0.15	0.22
A 40000	0.21	0.11	0.14	0.20	0.28	0.17	0.08	0.12	0.16	0.22
B 5000	0.26	0.09	0.21	0.26	0.31	0.22	0.10	0.16	0.21	0.29
B 10000	0.26	0.09	0.20	0.27	0.32	0.21	0.09	0.15	0.21	0.27
B 20000	0.27	0.09	0.20	0.27	0.33	0.22	0.10	0.15	0.21	0.28
B 40000	0.26	0.09	0.20	0.26	0.32	0.20	0.09	0.15	0.19	0.26
C 5000	0.22	0.13	0.13	0.21	0.31	0.15	0.11	0.08	0.14	0.22
C 10000	0.20	0.13	0.11	0.20	0.29	0.16	0.09	0.10	0.15	0.22
C 20000	0.20	0.12	0.12	0.20	0.26	0.16	0.10	0.10	0.14	0.22
C 40000	0.21	0.12	0.12	0.20	0.29	0.13	0.08	0.08	0.12	0.18
D 5000	0.27	0.10	0.20	0.26	0.32	0.23	0.11	0.15	0.22	0.30
D 10000	0.28	0.09	0.22	0.29	0.33	0.22	0.11	0.15	0.23	0.29
D 20000	0.28	0.09	0.24	0.29	0.33	0.22	0.10	0.15	0.22	0.29
D 40000	0.27	0.09	0.21	0.27	0.33	0.23	0.08	0.18	0.23	0.27

Table 3.18. Stability metric, operating model 2. Strategies are labeled according to combinations of rebuilding strategy A through D, with accompanying de minimis TAC (numbers of red abalone 5,000 to 40,000). 25th and 75th are percentiles.

	Mendocino zone					**Sonoma zone**				
Management strategy	**Average**	**SD**	**25th**	**Median**	**75th**	**Average**	**SD**	**25th**	**Median**	**75th**
A 5000	0.19	0.11	0.12	0.17	0.26	0.15	0.10	0.09	0.14	0.21
A 10000	0.19	0.13	0.11	0.17	0.27	0.14	0.10	0.08	0.13	0.19
A 20000	0.19	0.11	0.11	0.18	0.26	0.14	0.09	0.08	0.12	0.20
A 40000	0.19	0.10	0.12	0.17	0.25	0.16	0.08	0.10	0.15	0.21
B 5000	0.21	0.10	0.15	0.20	0.27	0.18	0.10	0.11	0.17	0.24
B 10000	0.21	0.10	0.14	0.20	0.28	0.18	0.09	0.11	0.17	0.23
B 20000	0.22	0.09	0.16	0.22	0.27	0.17	0.09	0.11	0.16	0.22
B 40000	0.19	0.09	0.14	0.19	0.25	0.17	0.09	0.11	0.16	0.21
C 5000	0.20	0.13	0.12	0.20	0.30	0.11	0.11	0.00	0.11	0.18
C 10000	0.19	0.14	0.10	0.17	0.27	0.13	0.10	0.08	0.12	0.20
C 20000	0.18	0.13	0.11	0.18	0.25	0.12	0.09	0.07	0.11	0.18
C 40000	0.18	0.13	0.10	0.17	0.27	0.12	0.09	0.06	0.11	0.17
D 5000	0.23	0.10	0.16	0.22	0.30	0.19	0.10	0.11	0.18	0.26
D 10000	0.21	0.10	0.12	0.21	0.29	0.19	0.11	0.11	0.18	0.25
D 20000	0.19	0.10	0.12	0.18	0.24	0.19	0.10	0.12	0.19	0.26
D 40000	0.21	0.11	0.15	0.21	0.26	0.18	0.09	0.11	0.18	0.24

Table 3.19. Probabilities of falling below depletion thresholds of 0.05, 0.10, and 0.20. Results are summarized at across combinations of operating model and fishing zone, with range of outcomes shown according to Min (minimum) and Max (maximum) values.

	Low threshold at sampled sites						**Low threshold at all sites**					
	Prob < 0.05		**Prob < 0.10**		**Prob < 0.20**		**Prob < 0.05**		**Prob < 0.10**		**Prob < 0.20**	
Management strategy	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
A 5,000	0	0	0	0	0.29	0.56	0	0	0	0	0.16	0.43
A 10,000	0	0	0	0	0.29	0.44	0	0	0	0	0.19	0.35
A 20,000	0	0	0	0	0.29	0.56	0	0	0	0	0.12	0.39
A 40,000	0	0	0	0	0.29	0.56	0	0	0	0	0.19	0.41
B 5,000	0	0	0	0	0.00	0.00	0	0	0	0	0.00	0.00
B 10,000	0	0	0	0	0.00	0.00	0	0	0	0	0.00	0.06
B 20,000	0	0	0	0	0.00	0.14	0	0	0	0	0.00	0.06
B 40,000	0	0	0	0	0.00	0.14	0	0	0	0	0.00	0.06
C 5,000	0	0	0	0	0.29	0.67	0	0	0	0	0.19	0.51
C 10,000	0	0	0	0	0.29	0.56	0	0	0	0	0.19	0.49
C 20,000	0	0	0	0	0.29	0.56	0	0	0	0	0.19	0.49
C 40,000	0	0	0	0	0.29	0.67	0	0	0	0	0.19	0.49
D 5,000	0	0	0	0	0.00	0.14	0	0	0	0	0.00	0.06
D 10,000	0	0	0	0	0.00	0.14	0	0	0	0	0.00	0.06
D 20,000	0	0	0	0	0.00	0.14	0	0	0	0	0.00	0.06
D 40,000	0	0	0	0	0.00	0.14	0	0	0	0	0.00	0.06

Table 3.20. Sensitivity to productivity. Alternate operating models (OMs) are labeled 1.1 and 1.2. For comparison, the base OM 1 is shown. The effect of changes in OM configuration are examined against management strategy performance of management strategy A, using de minimis TAC of 5,000.

	Time to de minimis			Depletion at de minimis			Time to open			Depletion at open			Catch x 1 million			Stability		
Management strategy	**25th**	**Median**	**75th**	**25th**	**Median**	**75th**	**25th**	**Median**	**75th**	**25th**	**Median**	**75th**	**25th**	**Median**	**75th**	**25th**	**Median**	**75th**
Mendocino zone																		
OM1 A 5,000	10	11	13.00	0.19	0.22	0.25	27.00	30	33.25	0.42	0.48	0.54	0.06	0.08	0.10	0.13	0.20	0.30
OM1.1 A 5,000	11	13	15.00	0.16	0.20	0.24	32.00	35	38.00	0.38	0.44	0.50	0.08	0.09	0.10	0.16	0.21	0.28
OM1.2 A 5,000	9	11	12.25	0.20	0.23	0.27	27.00	30	32.00	0.46	0.52	0.59	0.06	0.08	0.10	0.14	0.22	0.29
Sonoma zone																		
OM1 A 5,000	15	16	18.00	0.20	0.23	0.27	32.75	36	39.00	0.43	0.49	0.56	0.08	0.09	0.10	0.11	0.18	0.24
OM1.1 A 5,000	18	20	22.00	0.18	0.22	0.26	40.00	44	48.00	0.40	0.46	0.53	0.08	0.11	0.12	0.10	0.15	0.22
OM1.2 A 5,000	13	15	17.00	0.21	0.25	0.29	31.00	35	38.00	0.46	0.53	0.60	0.08	0.09	0.10	0.10	0.17	0.23

Table 3.21. Sensitivity to alternate management strategies. Alternate management strategies are labelled A.1, A.2, etc. Labels are described in the main text. The effect of management strategy changes is examined relative to the performance of management strategy A, using de minimis TAC of 5,000.

	Time to de minimis			**Depletion at de minimis**			**Time to open**			**Depletion at open**			**Catch x 1 million**			**Stability**		
Management strategy	**25th**	**Median**	**75th**	**25th**	**Median**	**75th**	**25th**	**Median**	**75th**	**25th**	**Median**	**75th**	**25th**	**Median**	**75th**	**25th**	**Median**	**75th**
Mendocino zone																		
A 5,000	10	11.0	13	0.19	0.22	0.25	27.00	30	33.25	0.42	0.48	0.54	0.06	0.08	0.10	0.13	0.20	0.30
A.1 5,000	10	11.0	13	0.18	0.22	0.25	24.00	27	30.00	0.38	0.44	0.50	0.06	0.06	0.08	0.14	0.22	0.32
A.2 5,000	10	11.0	13	0.18	0.21	0.25	25.00	28	31.00	0.39	0.44	0.51	0.06	0.07	0.09	0.12	0.20	0.29
A.3 5,000	10	12.0	13	0.19	0.22	0.26	24.00	26	29.00	0.37	0.43	0.49	0.05	0.06	0.08	0.17	0.27	0.36
A.4 5,000	20	23.5	27	0.33	0.39	0.46	48.00	59	71.00	0.64	0.73	0.81	0.08	0.12	0.16	0.21	0.26	0.32
A.5 5,000	8	10.0	11	0.17	0.19	0.22	25.00	27	30.00	0.38	0.44	0.50	0.06	0.08	0.10	0.12	0.21	0.30
A.6 5,000	7	9.0	10	0.15	0.18	0.21	25.00	27	29.00	0.39	0.44	0.49	0.07	0.08	0.10	0.12	0.20	0.28

	Time to de minimis			Depletion at de minimis			Time to open			Depletion at open			Catch x 1 million			Stability		
Management strategy	**25th**	**Median**	**75th**	**25th**	**Median**	**75th**	**25th**	**Median**	**75th**	**25th**	**Median**	**75th**	**25th**	**Median**	**75th**	**25th**	**Median**	**75th**
Sonoma zone																		
A 5,000	15	16.0	18	0.20	0.23	0.27	32.75	36	39.00	0.43	0.49	0.56	0.08	0.09	0.10	0.11	0.18	0.24
A.1 5,000	14	16.0	17	0.19	0.22	0.26	31.00	34	37.25	0.41	0.47	0.53	0.07	0.08	0.10	0.09	0.13	0.22
A.2 20000	14	15.0	17	0.19	0.22	0.26	31.00	33	38.00	0.40	0.47	0.53	0.06	0.08	0.10	0.08	0.15	0.24
A.3 5,000	14	16.0	18	0.20	0.23	0.27	28.00	31	34.00	0.36	0.42	0.49	0.05	0.06	0.08	0.12	0.20	0.29
A.4 5,000	18	20.0	22	0.24	0.29	0.34	44.00	48	55.00	0.55	0.63	0.71	0.09	0.12	0.14	0.14	0.21	0.27
A.5 5,000	12	14.0	15	0.17	0.20	0.23	30.00	33	36.00	0.39	0.46	0.52	0.08	0.09	0.10	0.10	0.17	0.24
A.6 5,000	11	13.0	15	0.16	0.19	0.22	29.00	31	34.00	0.37	0.43	0.49	0.07	0.08	0.10	0.11	0.17	0.25

Table 3.22. Sensitivity to alternate management strategies. Alternate management strategies are labelled A.1, A.2, etc. Probabilities of falling below depletion thresholds of 0.05, 0.10, and 0.20. Results for A 5,000 are slightly different than those presented in 3.19 because only OM 1 is included in the table below.

	Low threshold at sampled sites						Low threshold at all sites					
	Prob < 0.05		Prob < 0.10		Prob < 0.20		Prob < 0.05		Prob < 0.10		Prob < 0.20	
Management strategy	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
A 5,000	0	0	0	0	0.29	0.33	0	0	0	0	0.16	0.19
A.1 5,000	0	0	0	0	0.29	0.33	0	0	0	0	0.19	0.22
A.2 5,000	0	0	0	0	0.29	0.39	0	0	0	0	0.19	0.22
A.3 5,000	0	0	0	0	0.14	0.33	0	0	0	0	0.12	0.19
A.4 5,000	0	0	0	0	0.00	0.00	0	0	0	0	0.00	0.00
A.5 5,000	0	0	0	0	0.43	0.56	0	0	0	0	0.38	0.41
A.6 5,000	0	0	0	0	0.67	0.71	0	0	0	0	0.50	0.51

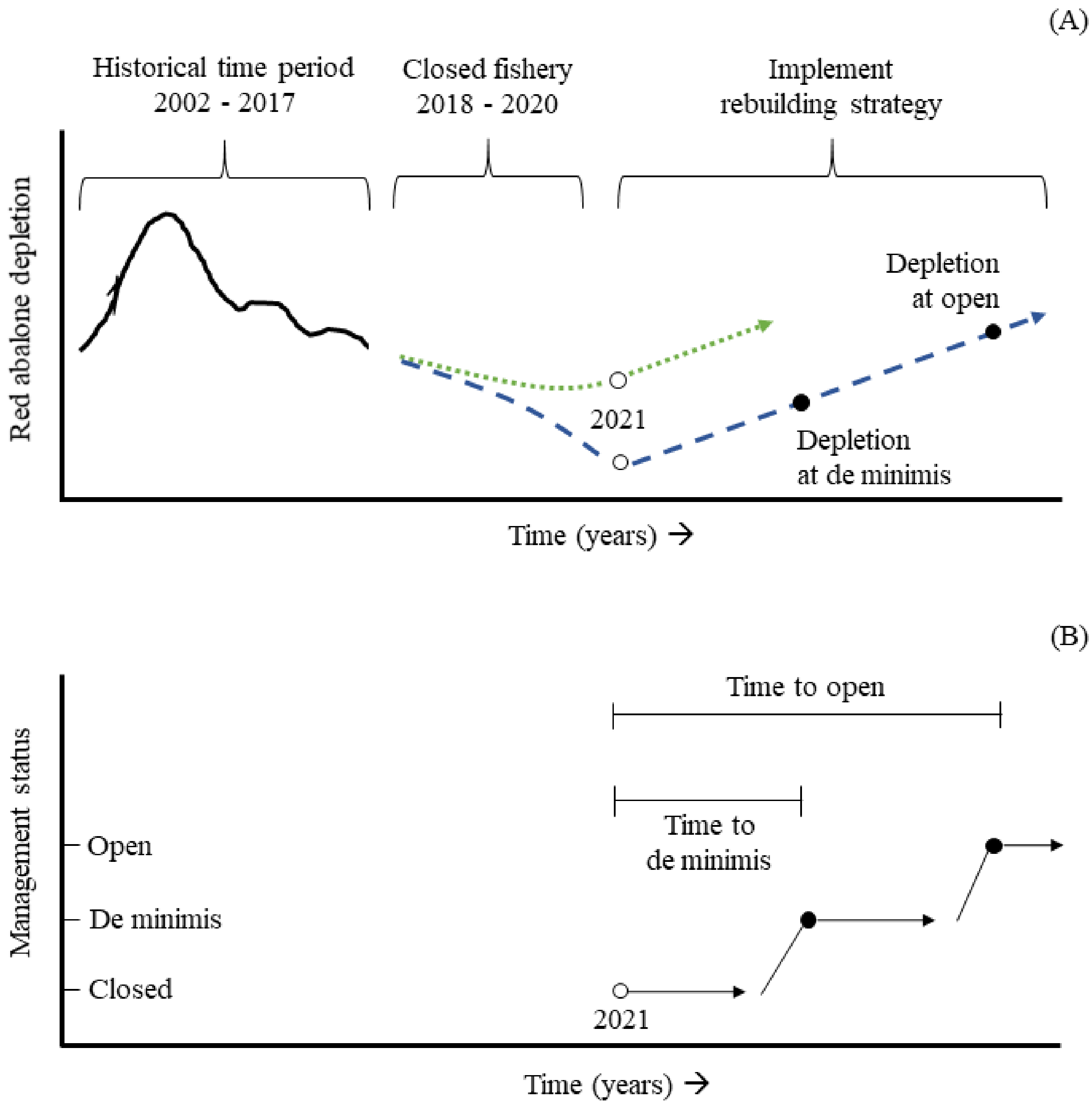


Figure 3.1. Rebuilding strategy description and summary of performance metric. (A) highlights two operating model configurations that differ in the duration of poor environmental conditions, along with the measurement of depletion at different fishery statuses. (B) Demonstrates the transition from closed, to de minimis, to open fishery status and the measurement of rebuilding time performance metrics.

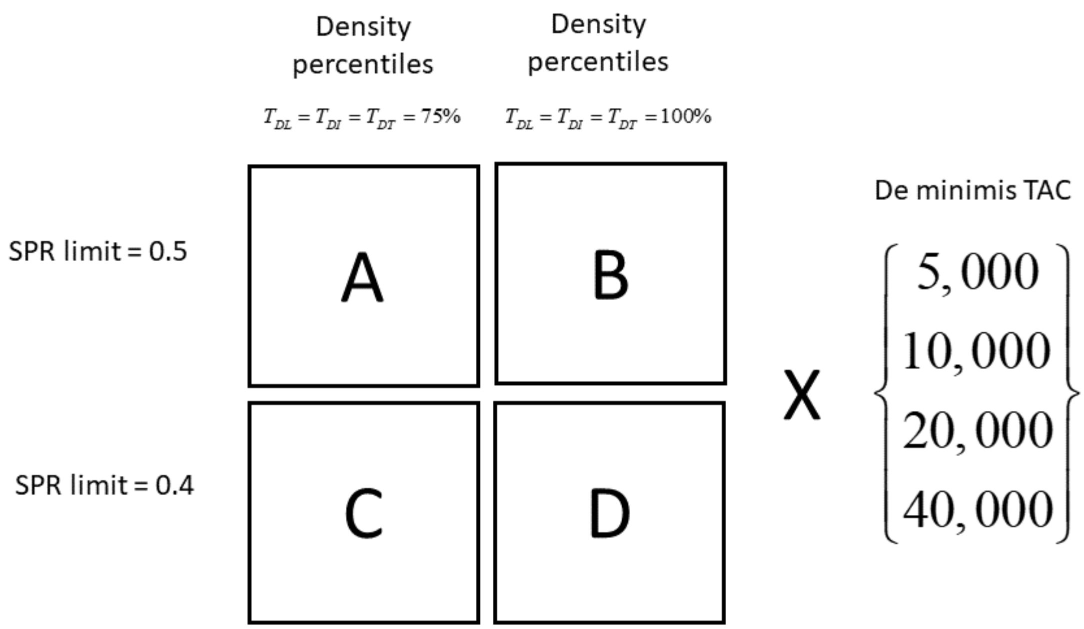


Figure 3.2. Factorial design of rebuilding strategies.

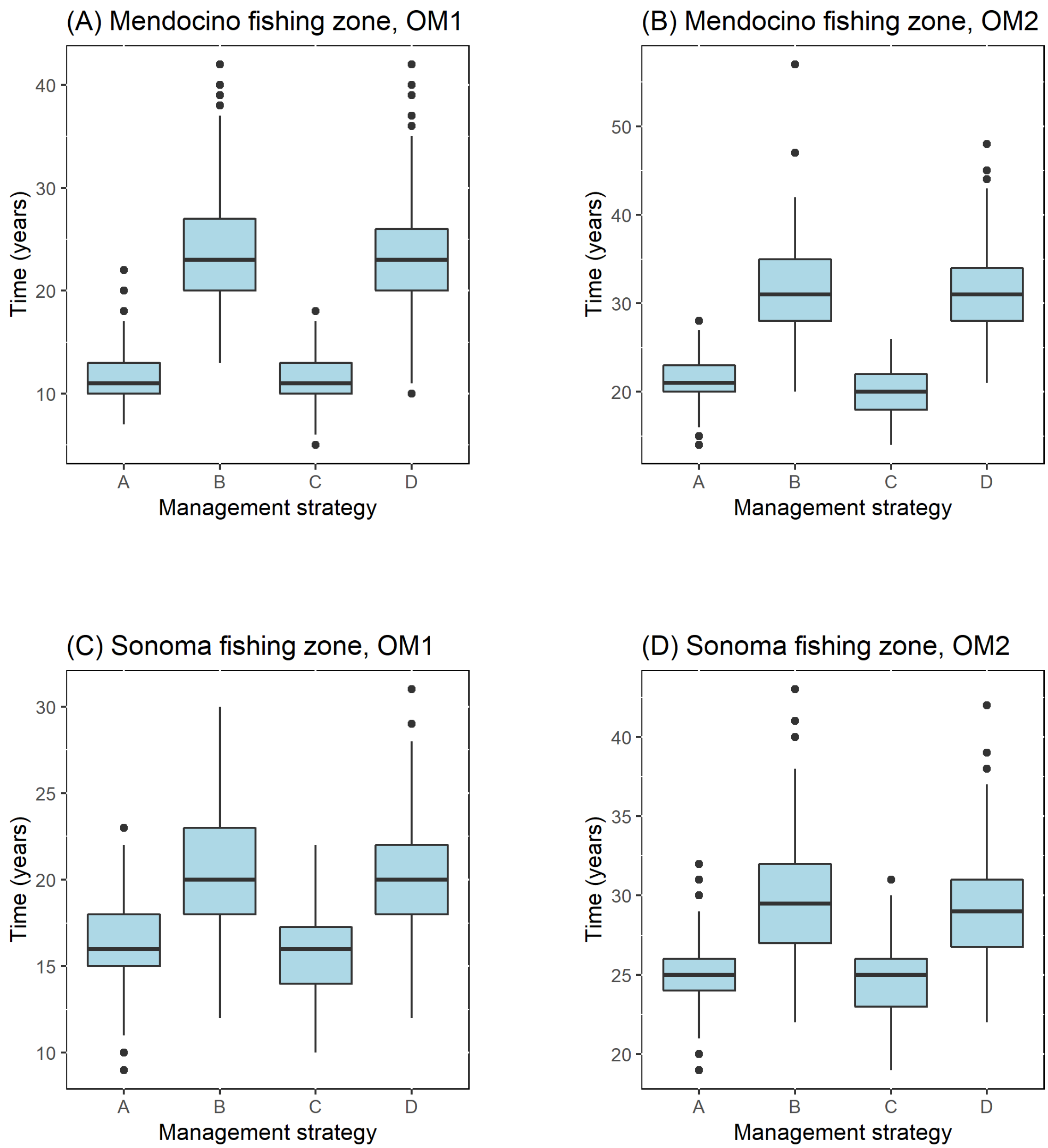


Figure 3.3. Box plots of time in years to reach de minimis fishery status for four rebuilding strategies. (A) through (D) indicate fishing zone and operating model (OM) configurations. Boxes are inter-quartile range, whiskers extend 1.5 times the inter-quartile range, and points are outliers.

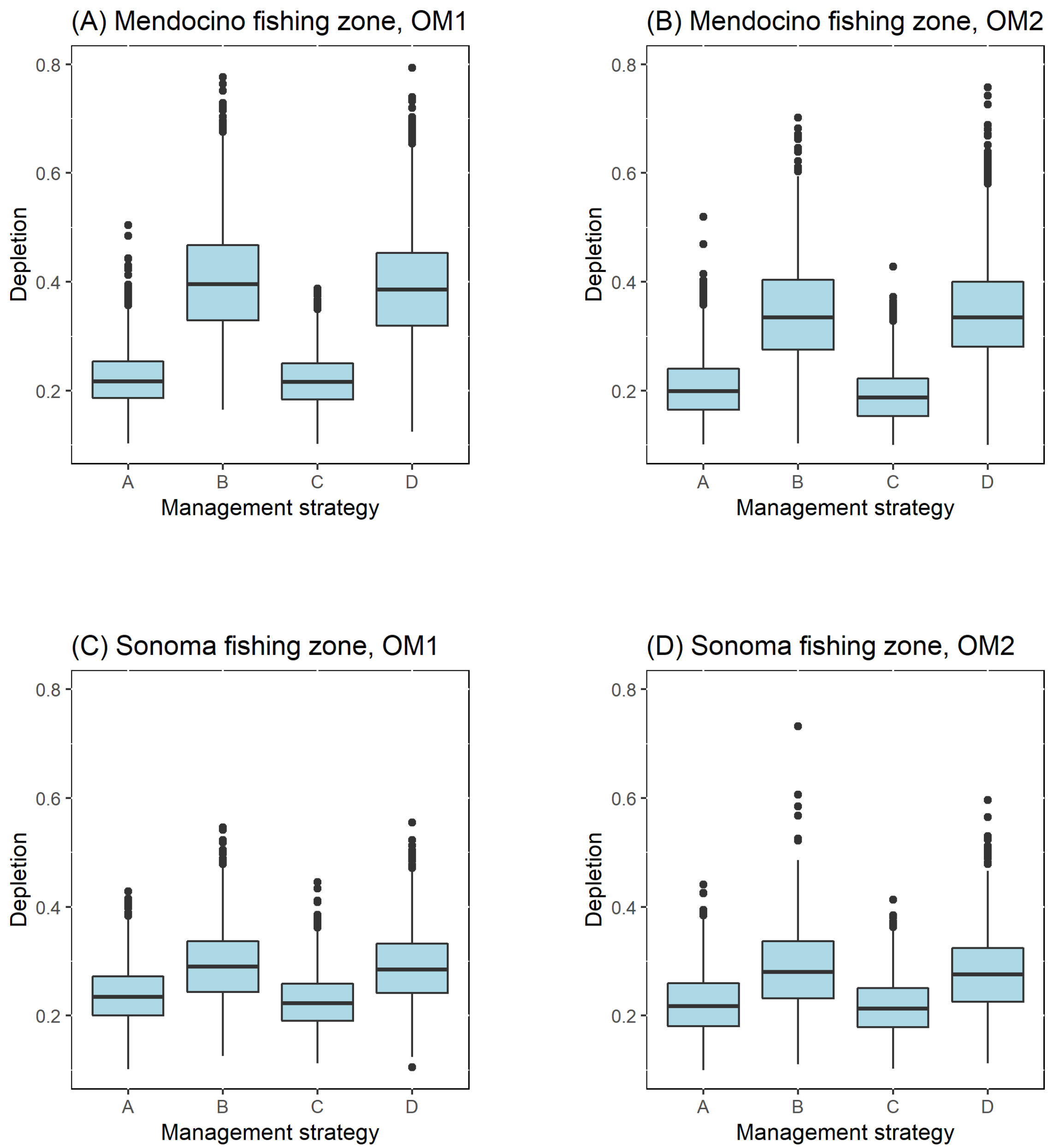


Figure 3.4. Box plots of depletion at sampled sites at the first time step where a de minimis fishery is triggered. (A) through (D) indicate fishing zone and operating model (OM) configurations. Boxes are inter-quartile range, whiskers extend 1.5 times the inter-quartile range, and points are outliers.

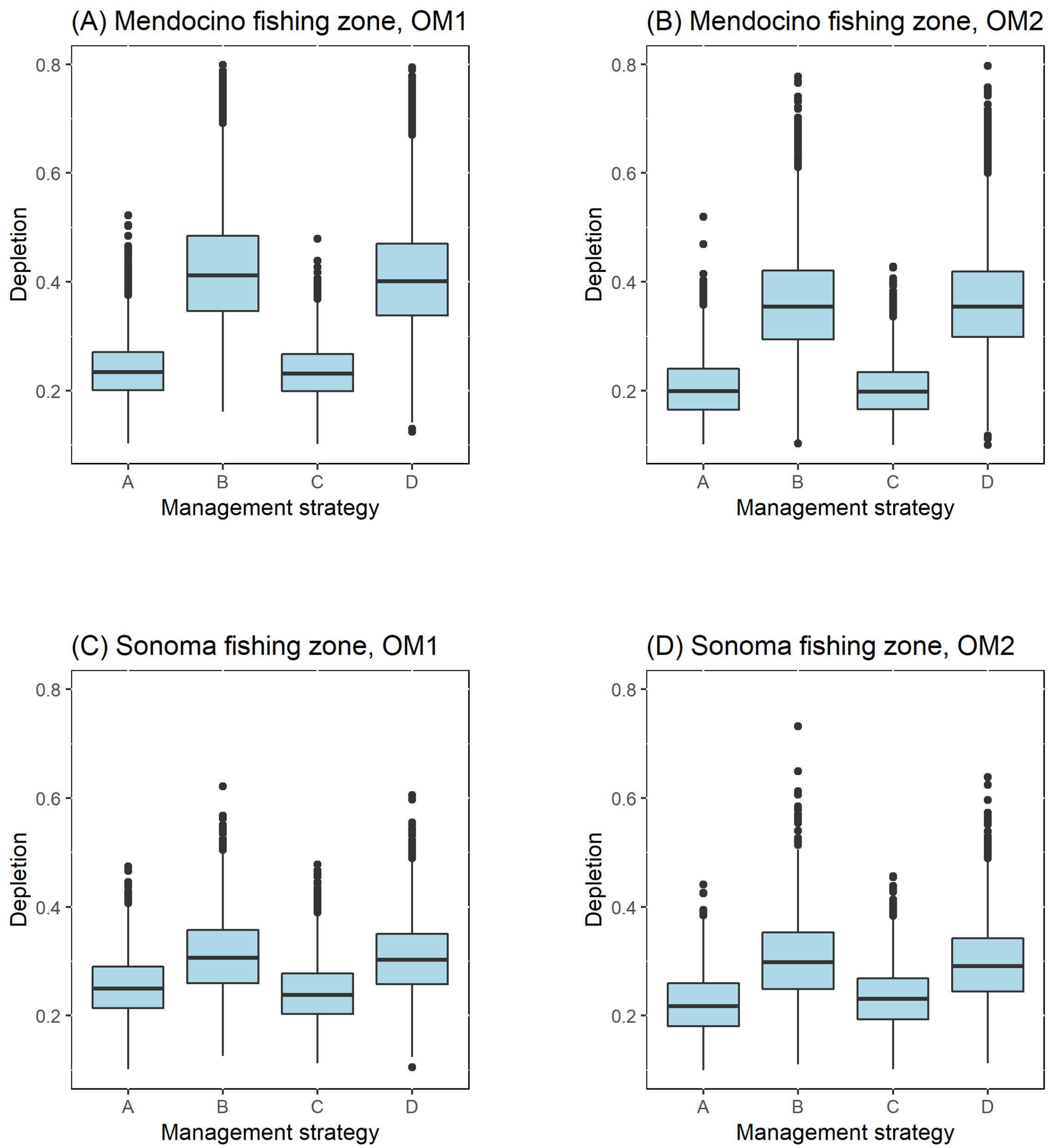


Figure 3.5. Box plots of depletion at all sites at the first time step where a de minimis fishery is triggered. (A) through (D) indicate fishing zone and operating model (OM) configurations. Boxes are inter-quartile range, whiskers extend 1.5 times the inter-quartile range, and points are outliers.

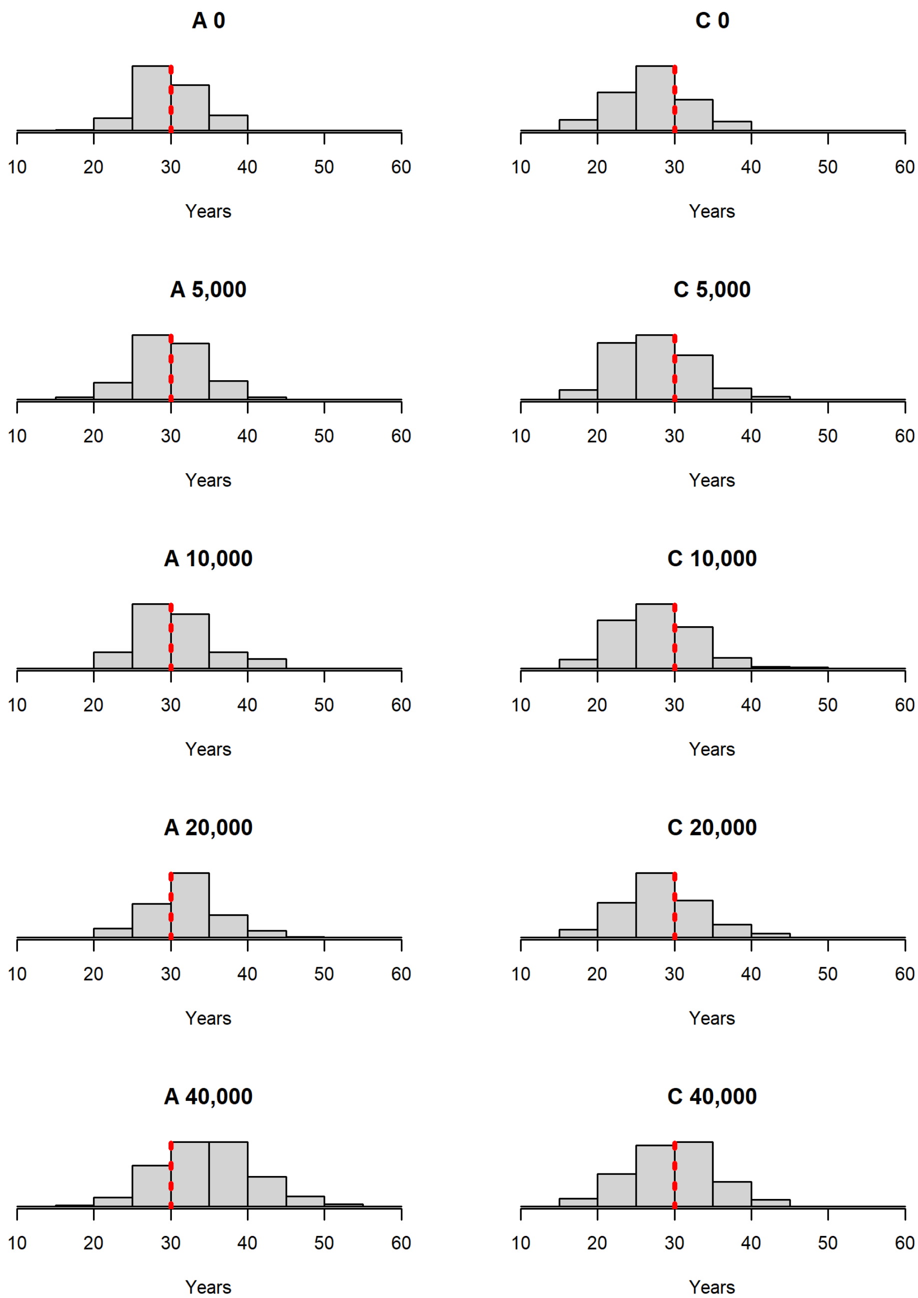


Figure 3.6. Rebuilding time to open fishery status for Mendocino zone, operating model 1. Red dashed line provides frame of reference to visualize shifting of distributions to the right as TACs increase. Inspect each column separately. Strategies are labeled according to combinations of rebuilding strategy A and C, with accompanying de minimis TAC (numbers of red abalone 0 to 40,000).

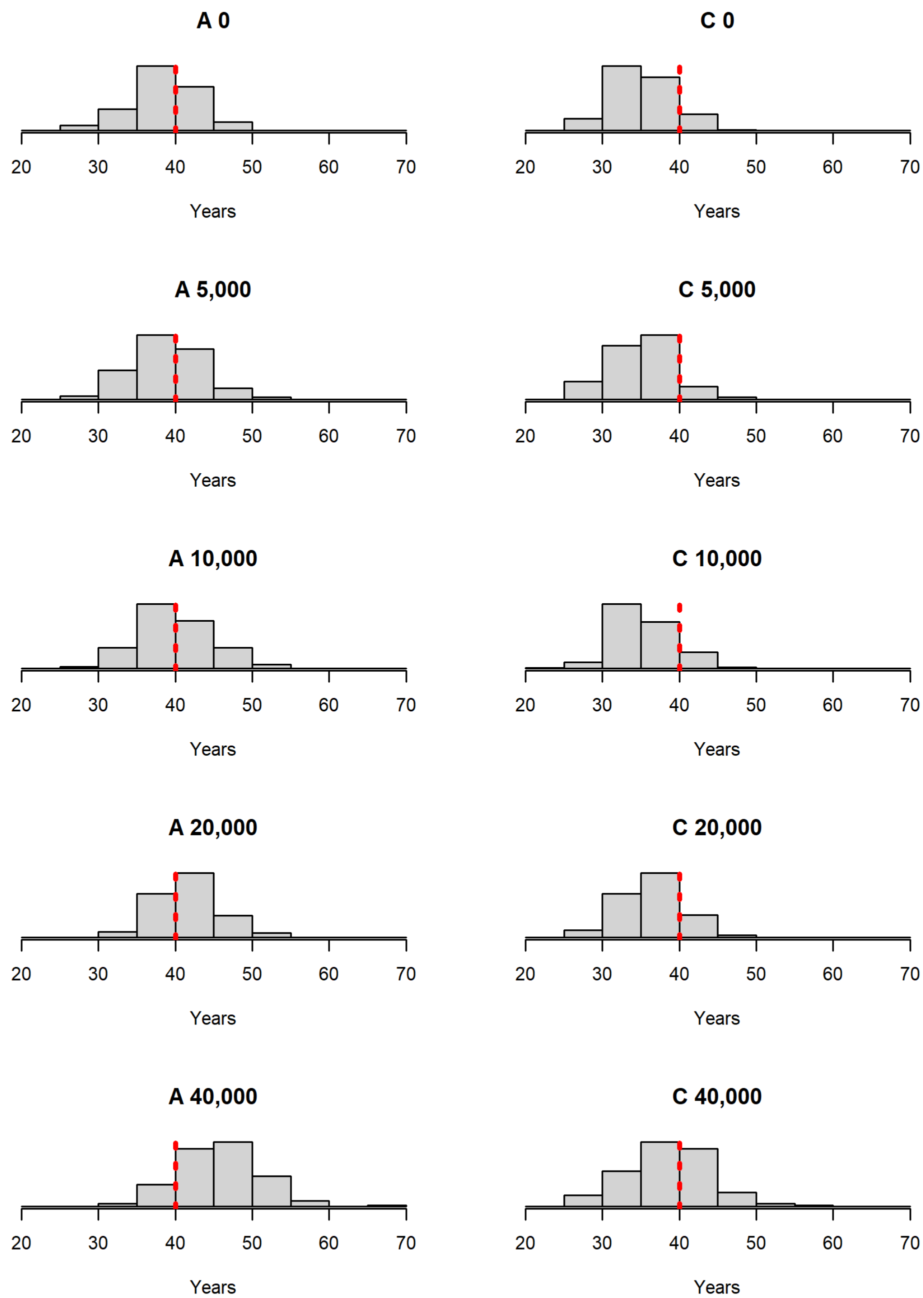


Figure 3.7. Rebuilding time to open fishery status for Mendocino zone, operating model 2. Red dashed line provides frame of reference to visualize shifting of distributions to the right as TACs increase. Inspect each column separately. Strategies are labeled according to combinations of rebuilding strategy A and C, with accompanying de minimis TAC (numbers of red abalone 0 to 40,000).

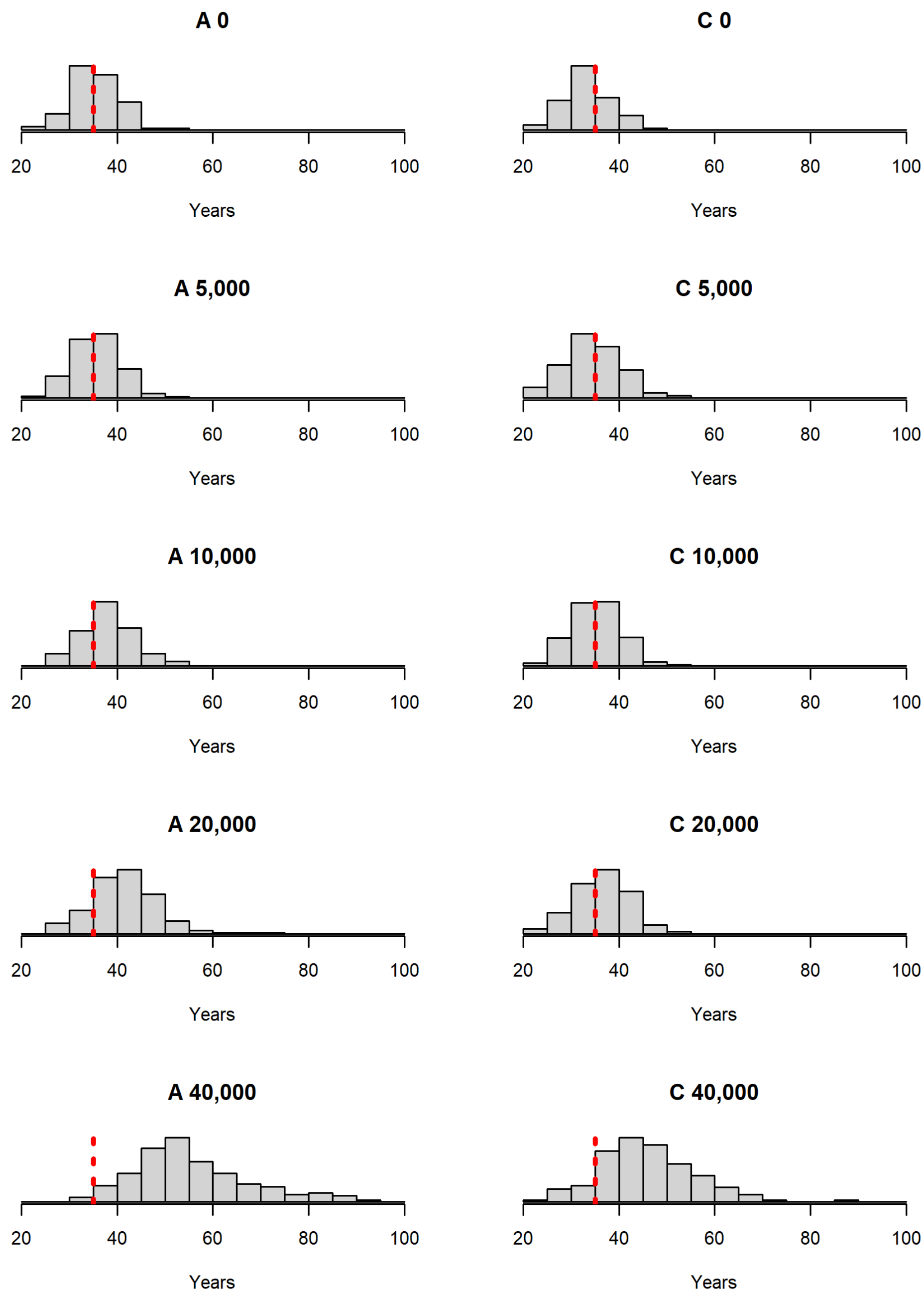


Figure 3.8. Rebuilding time to open fishery status for Sonoma zone, operating model 1. Red dashed line provides frame of reference to visualize shifting of distributions to the right as TACs increase. Inspect each column separately. Strategies are labeled according to combinations of rebuilding strategy A and C, with accompanying de minimis TAC (numbers of red abalone 0 to 40,000).

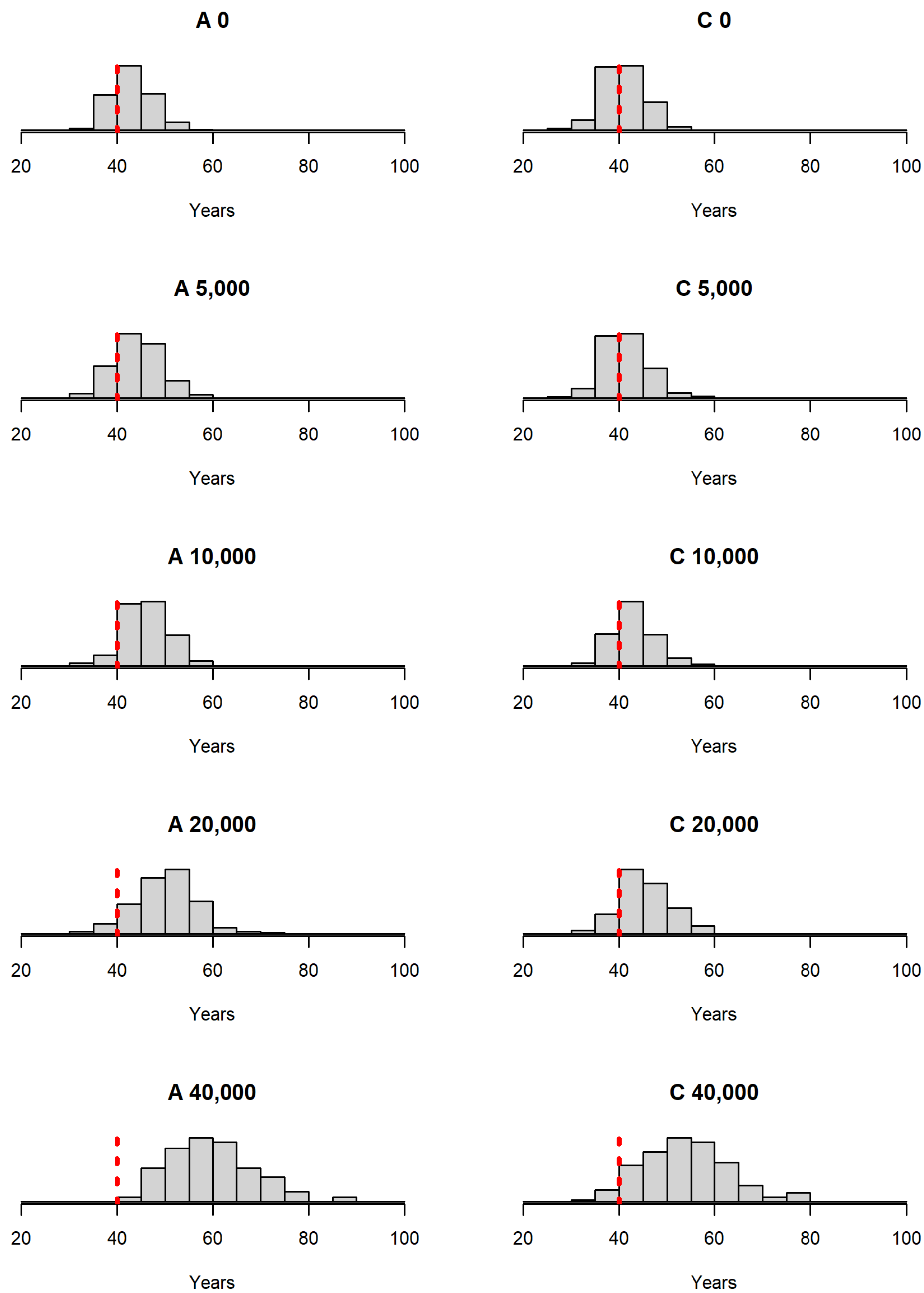


Figure 3.9. Rebuilding time to open fishery status for Sonoma zone, operating model 2. Red dashed line provides frame of reference to visualize shifting of distributions to the right as TACs increase. Inspect each column separately. Strategies are labeled according to combinations of rebuilding strategy A and C, with accompanying de minimis TAC (numbers of red abalone 0 to 40,000).

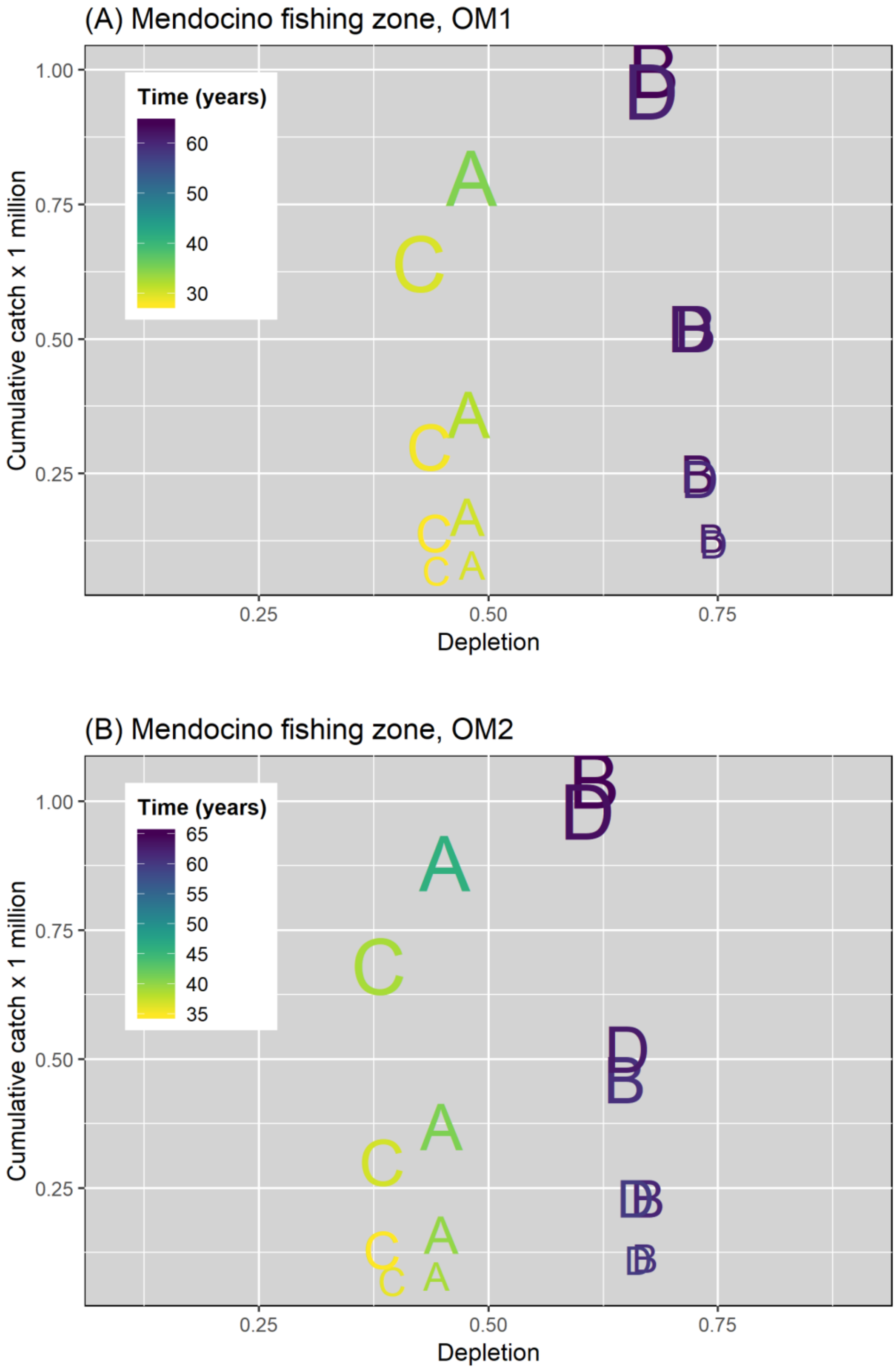
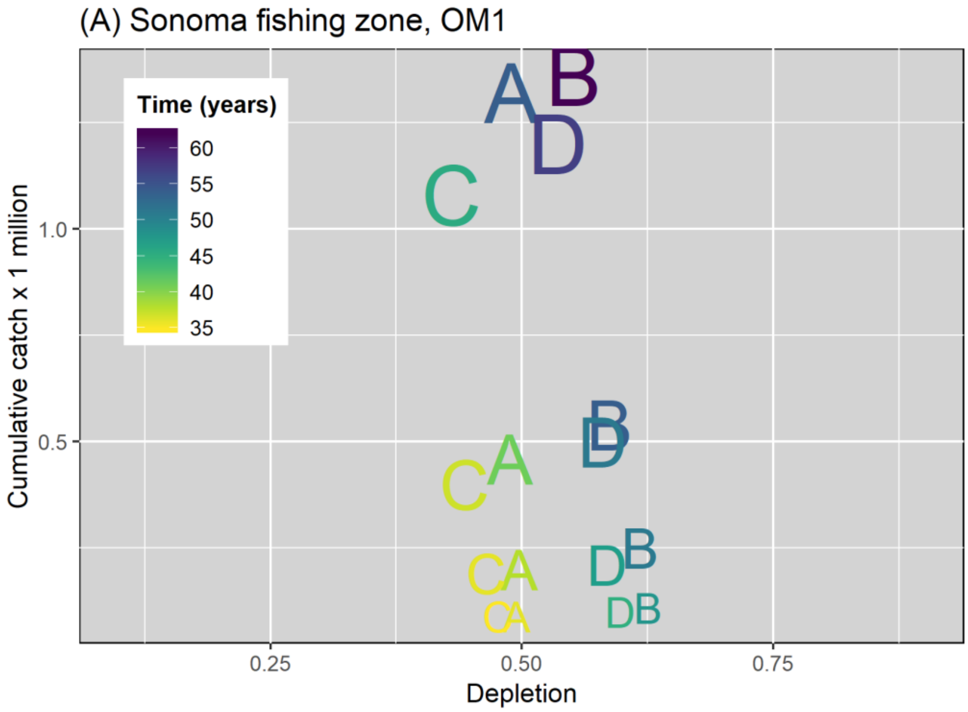


Figure 3.10. Trade-off plot of recovery to open fishery status for Mendocino zone. Placement of letters on plot reflects median values for rebuilding strategies A through D. Color reflects median rebuilding time to open fishery status (see legend) and size of letters reflects the de minimis TAC options of 5,000, 10,000, 20,000, and 40,000 red abalone.



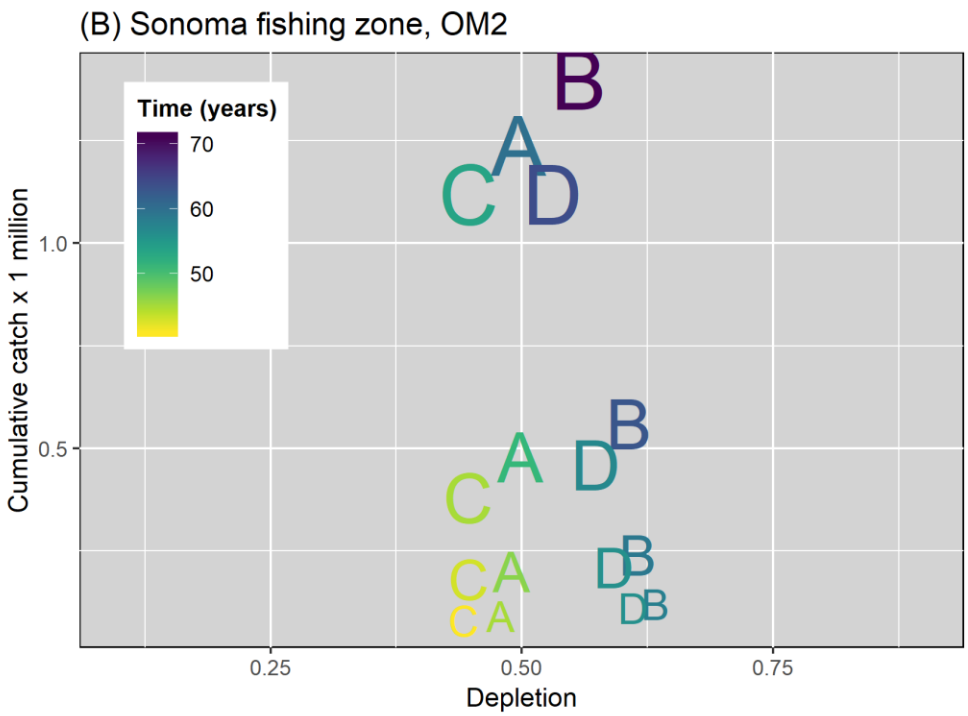
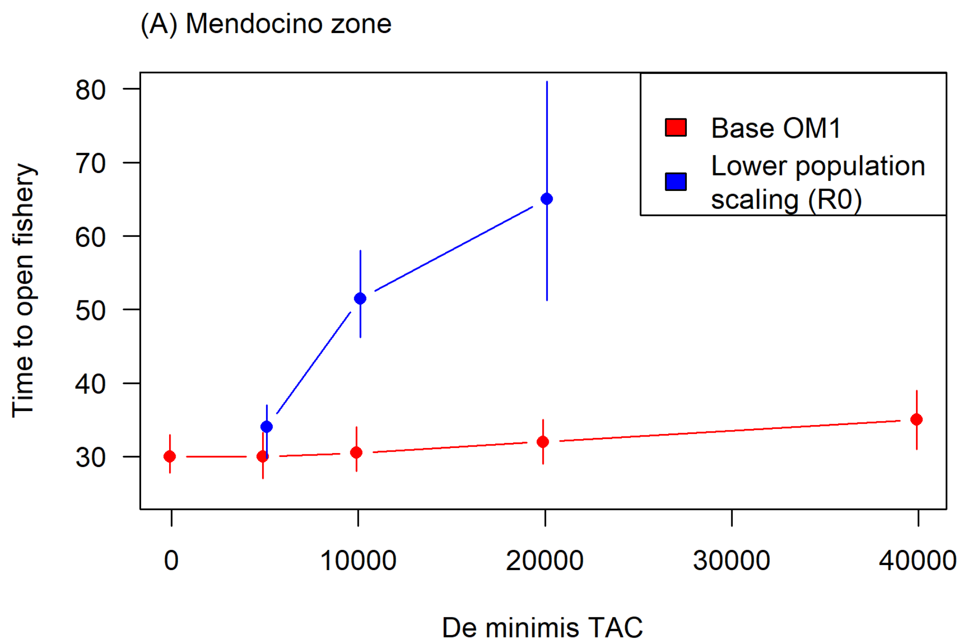


Figure 3.11. Trade-off plot of recovery to open fishery status for Sonoma zone. Placement of letters on plot reflects median values for rebuilding strategies A through D. Color reflects median rebuilding time to open fishery status (see legend) and size of letters reflects the de minimis TAC options of 5,000, 10,000, 20,000, and 40,000 red abalone.



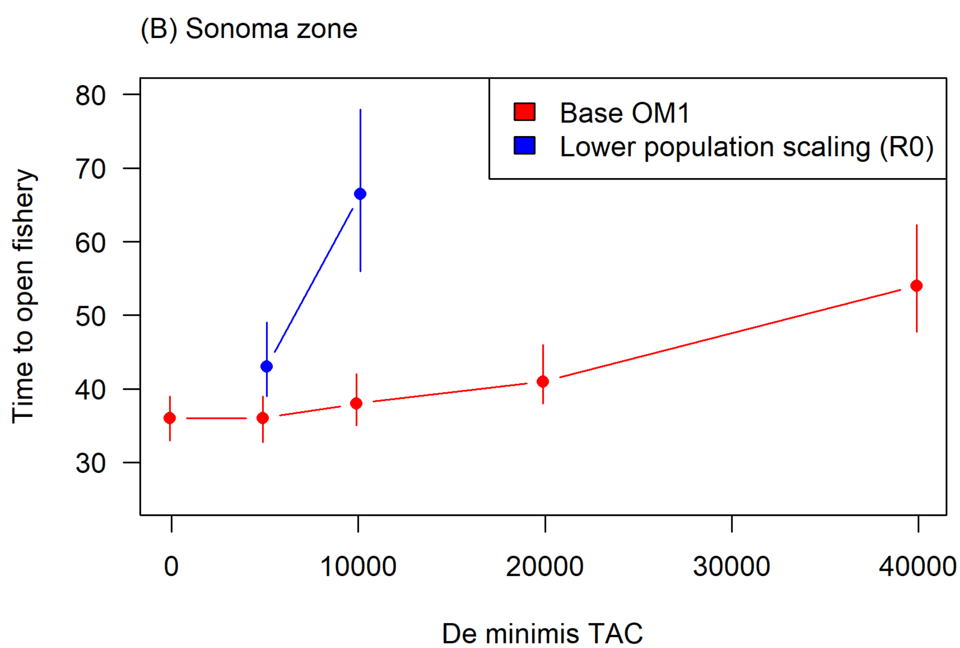


Figure 3.12. Sensitivity to population scaling of unfished recruitment (R0). The alternative operating model (OM; blue lines) reduce site-specific R0 to 60% of their values relative to the base OM 1 (red lines). Reduction of the scaling parameter leads to increases in recovery time to open, especially for de minimis TACs > 5,000. Missing data points at de minimis fisheries of 20,000 and 40,000 reflect a lack achieving an open fishery in 100 years under the lower R0 operating model.

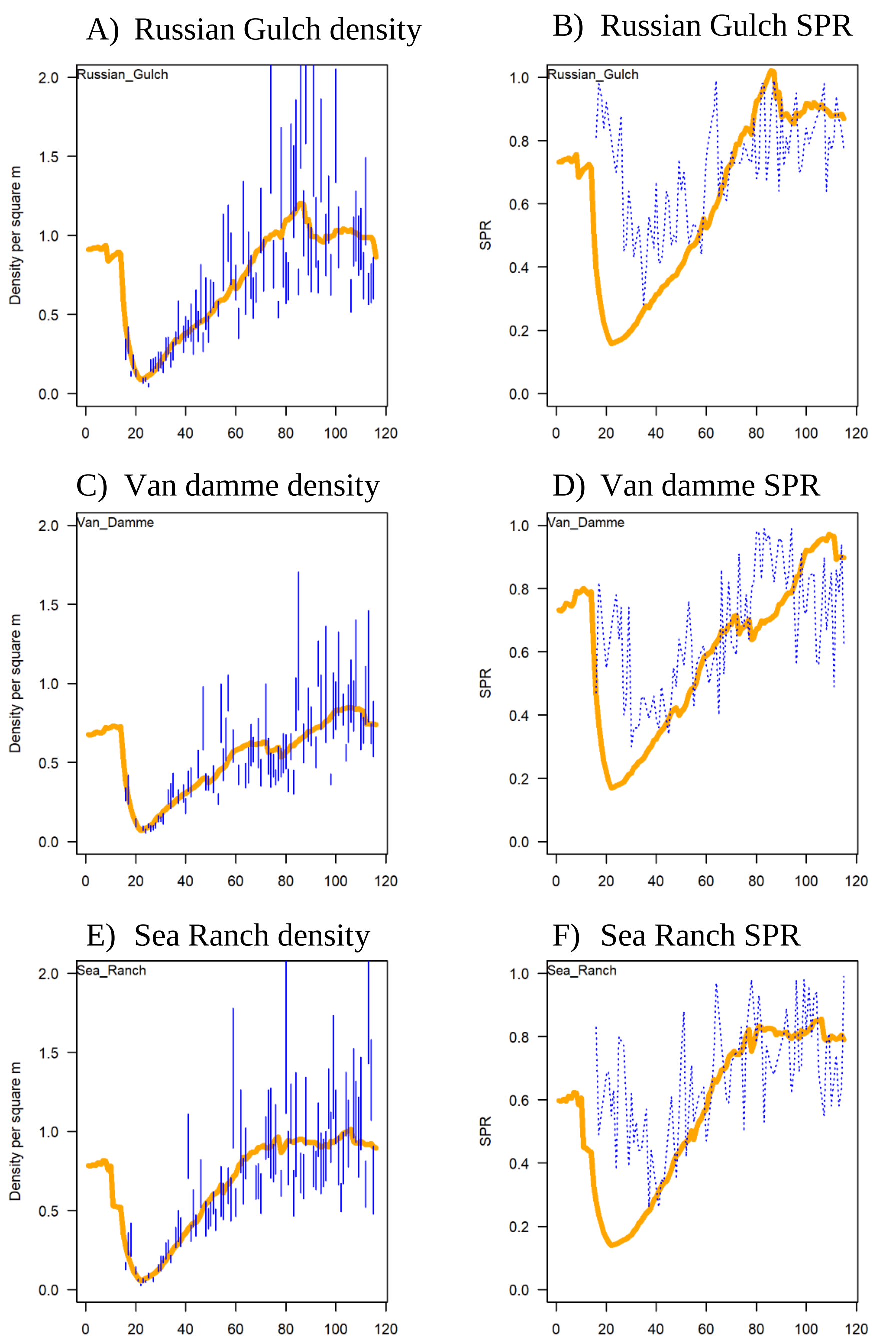


Figure 3.13. Illustration of propensity for observation error (blue lines) relative to true-simulated resource state (orange lines). Shown in the left column is a typical example from one simulation of observed densities, showing 50% confidence intervals (vertical lines) of those observed densities relative to corresponding true density trends. Shown in the right column are simulation of observed SPR point estimates plotted against corresponding true SPR. Examples are shown for three sampling sites (rows) using OM 2 (prolonged environmental decline).

Section 4: Three-zone sampling considerations

Simulation testing

Through discussions with the Project Team, there was interest in considering whether a three-zone management strategy could be developed. As proposed by the Project Team, three zones are defined as:

- **Humboldt and del Norte counties.**
- **Mendocino county**
- **Marin and Sonoma counties**

In thinking about the development of a three-zone management strategy it became evident that a paucity of information from Humboldt and del Norte counties (hereafter referred to collectively as HDN) presented a challenge to developing suitable indicators on which to base decision-making. As a preliminary step in considering design options for an HDN management strategy, an analysis is conducted here to examine whether rather limited collection of length frequency data could theoretically support a SPR-based harvest control rule (HCR). The analysis is carried out using operating model 1 (OM 1), which is described in Section 3 and in Technical Appendix 2.

This analysis is intended to support design considerations for a management strategy for HDN, noting that the severity of data limitations in this region of the northern coastline still likely requires considerable thinking and research regarding how to conduct field sampling and also about the form of management strategy that could be implemented.

Through discussions with the Project Team, it became apparent that large quantities of length observations that are obtained at some red abalone report card site in Mendocino or Sonoma counties would be rather difficult to obtain in HDN. Thus, the concept of sampling according to index sites in HDN could be difficult to implement. Instead, a sampling design is simulated that treats HDN as one geographic area, with respect to field sampling and compares relatively small samples sizes to those that would likely be regarded as sufficiently large.

Test 1: Equilibrium SPR estimation

The operating model was used to generate equilibrium conditions, with each HDN site depleted to an SPR of 0.5. Length-frequency sampling was then simulated according to a multinomial distribution using effective sample sizes of 30, 60, and 300. Then, these samples are used to estimate SPR using the LB-SPR method (Hordyk et al. 2015). Life history parameters required for SPR estimation are obtained from the operating model. These life history parameters reflect average growth patterns specified in the operating model, which can be thought of as the average growth characteristics of HDN, ignoring between-site growth variation. To examine the effect of inter-site variability in growth on ‘average’ SPR estimation across HDN, testing was repeated for a scenario where among-site variation occurred in the observation of length samples (see Technical Appendix 2 for methods) and a scenario where each site had the same average growth characteristics. Two-hundred simulations were carried out for each combination of sample size and growth variation scenario, and estimated SPR was compared with the ‘true’ simulated value of 0.5.

Test 2: Performance within a management strategy

To carry-out a preliminary examination of length sampling intensity, a length-based management strategy was constructed by the lead analyst. However, this management strategy only serves to demonstrate how sampling intensity could affect decision-making and does not explore issues of risk in applying such a strategy (e.g., alternative reference points are not explored). The examination of sampling intensity is intended to support related discussions about the feasibility of field data collection.

The management strategy is implemented by first recognizing that samples of 60 to 300 individuals is unlikely to be collected each year. Thus, the collection of 20 length samples is simulated each year for three year intervals. These 60 length samples (an effective sample size of 60; see Technical Appendix 1), collected every three years via a uniform sampling effort applied to each report card site in HDN, are pooled together. These 60 samples are used to estimate SPR according to the LB-SPR method (Hordyk et al. 2015). Accordingly, each 3-year SPR estimate ignores any spatial variation in growth that may occur in HDN, providing a sort of 'average' SPR across this geographic area. Life history parameters required for SPR estimation are obtained from the operating model. These life history parameters reflect average growth patterns specified in the operating model, which can be thought of as the average growth characteristics of HDN, ignoring between-site growth variation. For comparison, a second sampling design reflective of sampling intensities in Mendocino and Sonoma counties was implemented, with 100 length measurement per year (an effective sample size of 300). Although this level of sampling intensity may be infeasible for HDN, this sampling regime was included as an approximate comparison with sampling implemented elsewhere.

Having calculated an estimate of SPR every third year, a TAC is calculated and applied in the subsequent three years, according to the following harvest control rule (HCR):

1. If the median SPR ≤ 0.5, proceed to Step 4. Otherwise, proceed to step 2.
2. If the region was under rebuilding status last year, proceed to Step 3; otherwise proceed to Step 5.

3. If the median SPR > 0.6, then rebuilding has been completed. Set the TAC in this first post-rebuilding year to a pre-determined (moderate) TAC. Otherwise proceed to step 4.
4. The region is under rebuilding status. Rebuilding is implemented or is continued from last year. Set the TAC to a pre-determined rebuilding (low) TAC that will enable rebuilding.
5. The region is not in rebuilding phase, adjust the previous year's TAC according to the following adjustment process:
    a. If median SPR > 0.75, then multiply last year's TAC by 1.03
    b. If 0.6 < median SPR ≤ 0.75, then retain last year's TAC (no change)
    c. If 0.5 < median SPR ≤ 0.6, then multiply last year's TAC by 0.95

Thus, this HCR implements rebuilding of a region when SPR ≤ 0.5, requires SPR > 0.6 before rebuilding is considered complete, and attempts to maintain a target SPR range of 0.6 to 0.75 through annual TAC adjustments.

Given that the objective of the example management strategy is to maintain long-term population status in proximity to the SPR range of 0.6 to 0.75, the SPR status of the HND region is summarized after 100-year simulation runs. This summary examines how sampling intensity may affect the expected achievement of the target SPR range. For comparison, sampling of 20 length measurement per year is compared to sampling of 100 length measurement per year.

Results

As sample size is reduced, the reliability of SPR estimates likewise erodes (Fig. 4.1). While a reasonably large sample size (i.e., 300) provides accurate SPR estimates, there is cause for concern at the smallest sample size of 30, which may be too small to reliably support decision-making. Simulation of among-site growth variation did not dramatically bias SPR estimates (Fig. 4.2; Table 4.1).

In conducting MSE, sampling of 20 length measurements per year (60 observations each time the HCR rule is applied) leads to reasonably similar recovery trajectories relative to sampling 100 length measures per year (300 observations each decision interval) (Fig. 4.3). Accordingly, the long-term performance of the lower intensity sampling regime is similar to that of the higher intensity sampling regime (Fig. 4.2).

Discussion

The degree of dispersion in equilibrium outcomes as well as outcomes from MSE using low sampling intensity, relative to the higher sampling intensity, provides cautious optimism about the potential for a length-based indicator. This result is supported by Bellquist et al. (n.d.). It should be noted however, that the general trend in recovery shown through MSE is mediated by the low rebuilding TAC, which by itself promotes recovery. Coupling this data-limited strategy with a suitably cautions TAC speaks to the complex interactions between sampling design, data analysis, and HCR that together comprise a management strategy.

This preliminary analysis is perhaps best viewed as a means to identify research priorities for exploring the feasibility of HDN fishing zone. Research could address the following concerns:

- It remains unclear whether 60 length observations collected over 3 year intervals is feasible for HDN. This may require some pilot field studies. It may also require more than 60 length observations to achieve an effective sample size of 60, but that remains unclear as the relationship between total sample size and effective sample size has not been explored for HDN (see Technical Appendix 1 for examples from Sonoma and Mendocino);
- To conduct this analysis, life history parameters (including growth parameters) were borrowed from the operating model. Prince (2016) proposed a method to obtain these

parameters from observation of the left-hand side of the length frequency distribution. It remains unclear whether sufficient sample sizes in HDN could be obtained to estimate these parameters.

- Alternatively, growth studies could be conducted in HDN to understand growth in this region, both the average growth across this region as well as the magnitude of inter-site growth variation, if any. However, it is questionable whether suitable sampling sizes (e.g., in mark-recapture study) could be obtained to support such a study and creative alternative approaches may be required.
- The simple demonstration of a length-based management strategy speaks to a broader need to for a more thorough investigation of viable management strategy options. As wide as possible a net should be cast in creatively developing such options, and options may not be restricted to length-based approaches alone. A length-based option was considered here because density has not been supported by the Project Team for this geographic area, which left demonstration of a length-based indicator as a convenient alternative starting point for approaching management strategy design for HDN. Of course, a much wider variety of options should be considered, including multi-indicator approaches and experimental approaches aimed at learning about the HDN region.

Table 4.1. Summary statistics for SPR estimation reliability under equilibrium conditions. Shown is variation in estimated SPR under different scenarios and sampling intensity.

	25th percentile	**Median**	**75^{th} percentile**
No growth variation			
30 samples	0.43	0.50	0.61
60 samples	0.44	0.51	0.59
300 samples	0.50	0.53	0.56
With growth variation			
30 samples	0.43	0.50	0.60
60 samples	0.46	0.52	0.58
300 samples	0.50	0.53	0.57

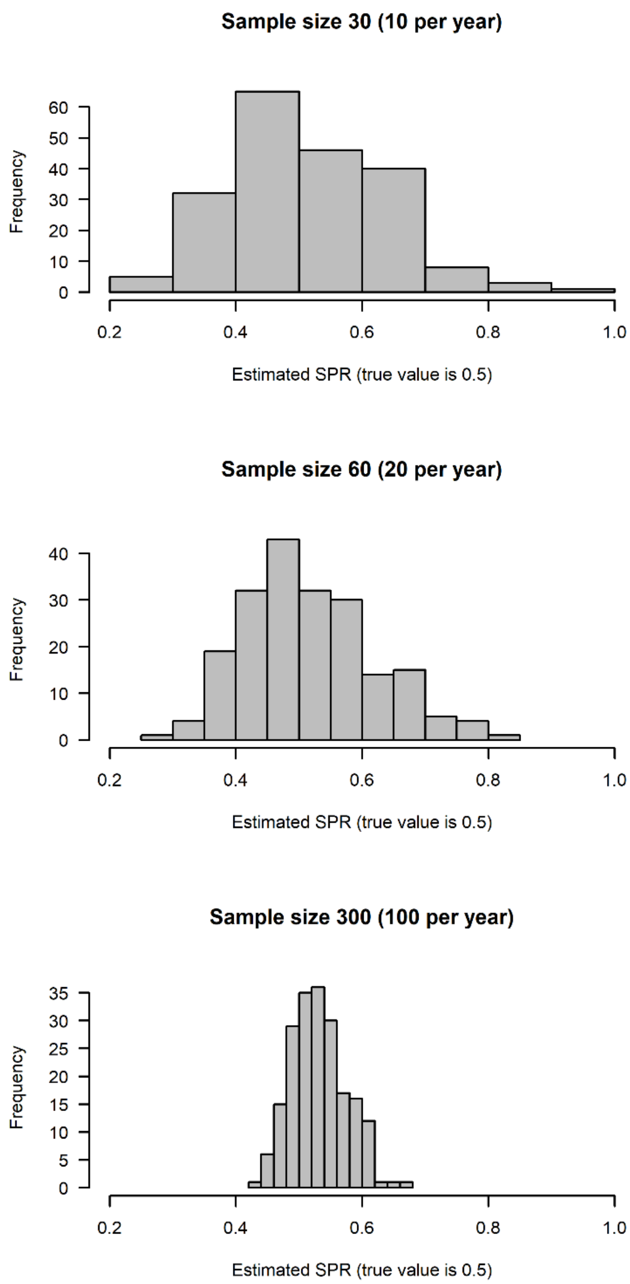


Figure 4.1. Simulation testing of the SPR estimation reliability under equilibrium conditions, when each HDN site had the same average growth characteristics. True SPR value is 0.5.

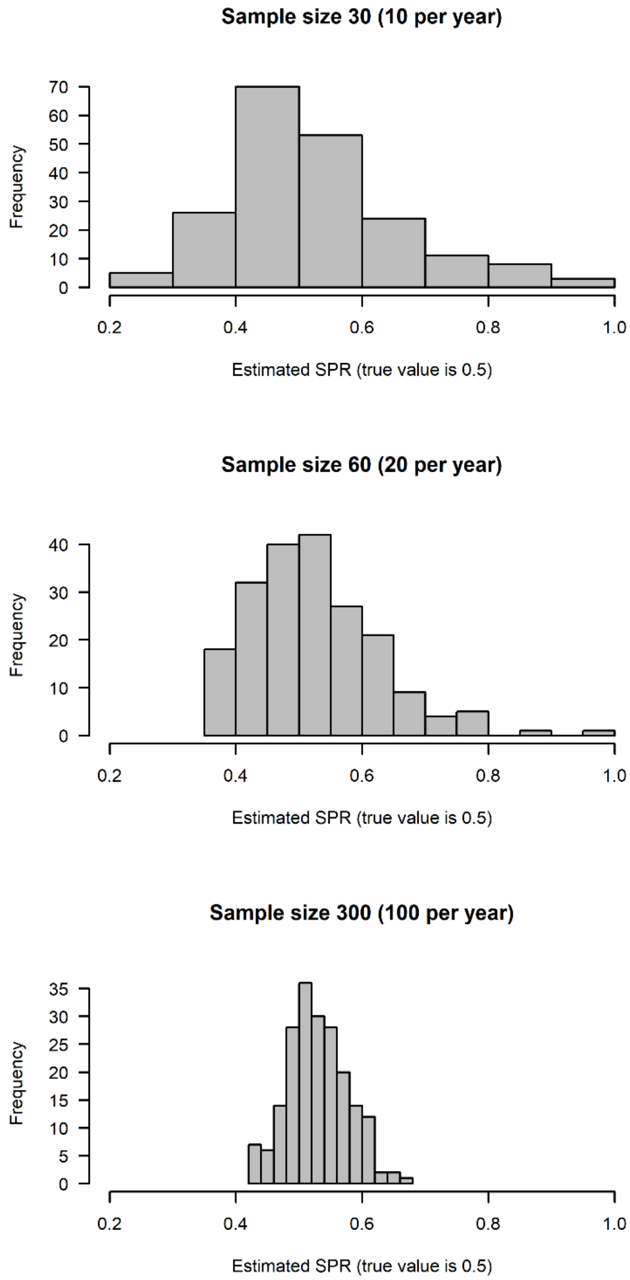


Figure 4.2. Simulation testing of the SPR estimation reliability under equilibrium conditions, when among-site growth variation occurred. True SPR value is 0.5.

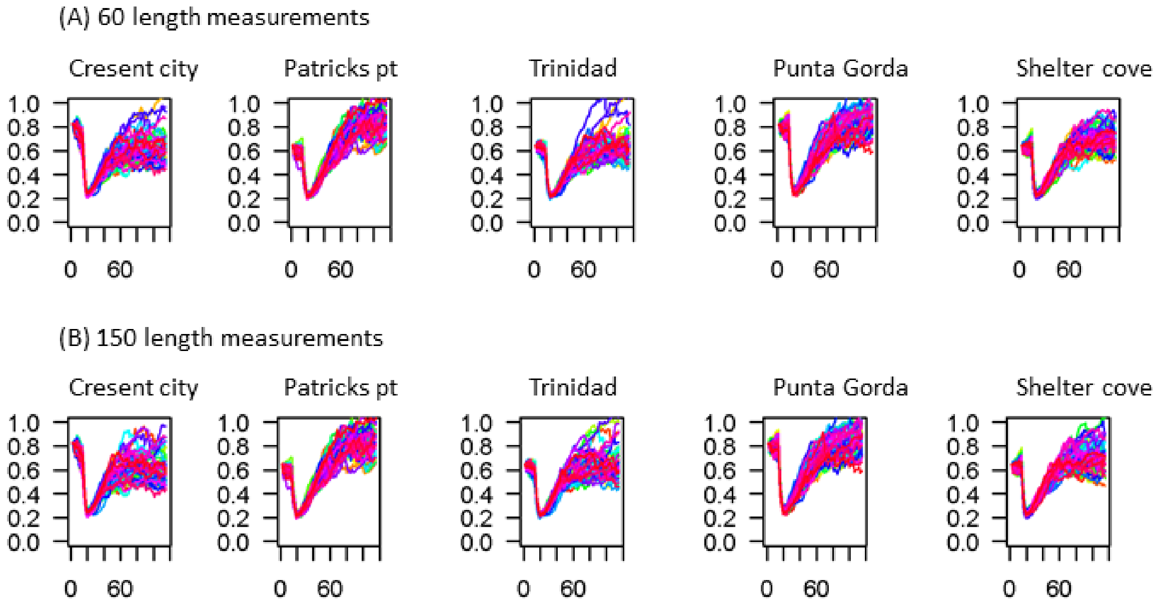


Figure 4.3. Example of rebuilding trends from 50 simulation runs (colored lines).

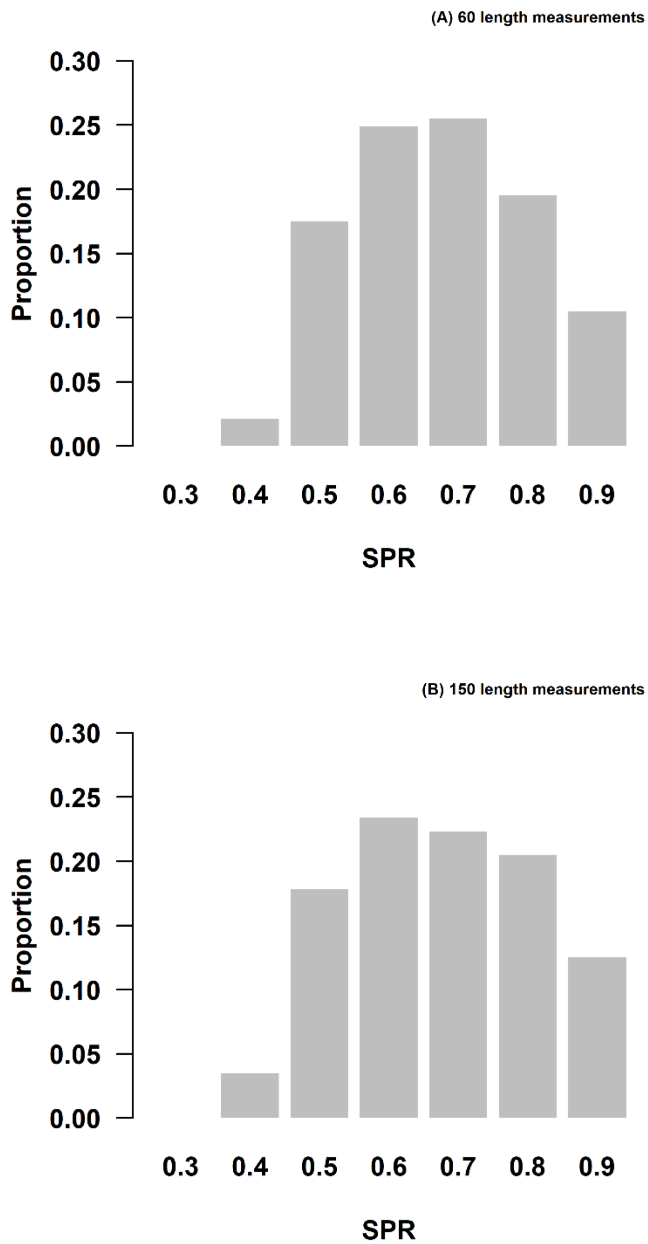


Figure 4.4. Long-term outcomes of a management strategy

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Technical appendix 1. Statistical properties of length frequency and density data.

Reef check length-frequency and density sampling

A technical description of Reef Check California (RCCA) monitoring protocol can be found on Reef Check California's website: *https://reefcheck.org/california/ca-overview*

CDFW length-frequency and density sampling

A technical description of California Department of Fish and Wildlife (CDFW) sampling protocols can be found in the follow source:

CDFW. 2013. Estimating red abalone density for managing California's recreational red abalone fishery. Prepared by: California Department of Fish and Wildlife. For: Ocean Science Trust, Technical Review of Red Abalone Density Methods and Results. Oct, 6, 2013.

Brief introduction

The data and analyses contained in this appendix are not an exhaustive examination of data available, nor do these data necessarily represent complete inventories of available data. The datasets were those available at the time document preparation and serve the purpose of addressing the measurable precision of two data streams for red abalone: length frequency compositions and density surveys. Quantifying sampling precision is a necessary step in re-recreating this level of sampling precision in the MSE operating model. Sampling precision is examined from the perspective of the variance of samples obtained from individual site visits. Doing so enables, to the extent possible, the precision of field sampling to be reflected in the simulated performance of management strategies. Further, where sampling precision is also used in defining management strategy reference points or triggers for management responses, quantifying sampling precision here is a relevant primer in support of specifying details of management strategies.

Statistical properties of length frequency distributions

Precision of length frequency sampling

The precision of length frequency sampling is quantified by examining the observed sample sizes at each site. Specifically, this requires quantifying effective sample size (ESS). Observation of abalone lengths are assumed to arise from a multinomial distribution; however, the observed sample size may overestimate the precision with which the multinomial distribution of length frequencies is characterized. Instead, when it comes to field data collection of length frequencies, ESS may be less than the actual sample sizes. The ESS reflects the idea that, given complications of field sampling, length samples collected from *n* sampling events (i.e., transects) may not represent a completely random sample, but instead may be subject to errors attributable to data collection methods, especially measurement of clusters of individuals with similar lengths (Hulson et al. 2012). This circumstance can lead to less information about the population being contained in the *m* total individual length observations than would have been obtained from sampling animals at random from the population (Pennington et al. 2002). ESS reveals the extent to which the observed sample size is consistent with a random sample of the statistical population. Thus, ESS is a measure of the information content of length observations as ESS is less than or equal to *m*. ESS was calculated for RCCA data collected between 2007 and 2017. Steps necessary to estimate ESS are found in Pennington et al. (2002). The two types of length sampling events, transect and roving diver, were separately analyzed.

Estimates of ESS varied annually, among roving diver and transect sampling approaches, and according to sampling of emergent abalone (i.e., approximately 100 mm to 178 mm shell length) or exploited phase abalone (i.e., >178 mm shell length). In the emergent phase, roving diver surveys for the period of 2015 to 2017 had a mean ESS of 195 (median: 118; range: 31 – 963), while transect surveys for the period of 2007 to 2017 had a mean ESS of 74 (median: 36; range: 2 – 928). In the exploited phase, roving diver surveys had a mean ESS of 197 (median: 118; range: 12 – 653), while transect surveys had a mean ESS of 62 (median: 34; range: 6 – 788). Observed sample sizes and ESSs in the exploited phase were directly compared, as data collection in this phase is essential for SPR calculation, highlighting the observed sample sizes that are likely necessary to achieve a desired level of sampling precision (Fig. A1.1). To put the needed ESSs in context, simulation modeling of length-based management strategies for red abalone has suggested the ESS of 50 to 100 can lead to reasonable decision-making and management outcomes (Bellquist n.d., Harford et al. 2019a). Thus, corresponding observed samples sizes between 150 – 300 individual red abalone per site could be a reasonable rule of thumb for a minimum data collection standard (Fig. A1.1)

Site coverage in length frequency sampling

For each site-year combination of available length-frequency data, spawning potential ratio (SPR) was calculated using both CDFW and RCCA datasets (Tables A1.1 and A1.2). In instances where CDFW and RCCA both sampled the same site in a given year, data were pooled in making SPR calculations. RCCA transect and roving diver data were also pooled for each given year-site combination. SPR was estimated using the LB-SPR approach, consistent with the approaches Hordyk et al. (2015) and Prince (2016). Parameters were: M/K=0.9, coefficient of variation of asymptotic length of 0.1 and fecundity exponent of 4.7. Site-specific $L50$ and corresponding *L95* and $L\infty$ were obtained by examining the left-hand side of the length frequency distribution, consistent with the approach outlined by Prince (2016). As a baseline, length frequency distribution for Van Damme (pooling all years of data collected by both organizations) was examined, noting that size-at-maturity has been reported at 130 mm for this site (Rogers-Bennett et al. 2004). The reported size-at-maturity occurs approximately between 15% and 25% of cumulative size-frequency distribution of emergent abalone (i.e., emergence from smallest size to the main mode of distribution, which approximates the left-hand side of the distribution). Thus, the interval of 15%, 20%, and 25% cumulative size frequency was used to identify three *L50* options at each site. As a check, obtained *L50* parameters less than 110 mm or greater than 170 mm were replaced, by default, with 130 mm, since Prince (2016) did not identify any values outside of this range. Given *L50* estimates, corresponding $L\infty = L50/0.6$ and $L95=1.15L50$, were calculated as in Prince (2016). An additional check was made that $L\infty$ was not underestimated, noting that length frequencies were collected only at fished sites, thus if $L\infty$ was less than 95% of the maximum observed length (*Lmax*), it was likely to be low and was replaced with the value 0.95*Lmax*. Three additional notes are needed. First, once life history parameters were obtained for a site, separate estimates of SPR were made for each annual subset of length-frequency observation ≥ 178 mm (7 inches). Second, SPR estimates were made only where annual subsets of length-frequency observations had a sufficient sample size of at least 150 length measurements (see Section: *Precision of length frequency sampling*). And third, given three estimates of life history parameters, three SPR estimates were made for each site-year visit. The median value of each set of estimates was retained for use in model tuning.

Given the calculated SPR estimates, a bootstrap analysis was conducted to provide some guidance on the minimum number of sites that should be visited to sufficiently characterize the among-site variation in SPR. This analysis was conducted by sampling with replacement from site-specific SPR estimates. The question of how many sites to visit is confronted by (i) first specifying a set number of sites to sample (e.g., 3 sites) from the pool of available SPR estimates, (ii) calculating the variance of each of 1,000 bootstrap samples, and (iii) calculating the relative variance among 1,000 bootstrap variance estimates. This process can be thought of as calculating the variance of the variance among bootstrap samples. By repeating this process with sequentially increasing numbers of sites (i.e., 2 – 14 sites, as our observed sample sizes would allow), it can be shown how the variance of the variance declines towards an asymptote as sample size increases (Fig A1.2). Also, given the likely scenario of SPR estimates changing through time, and not only varying spatially among sites, these calculations were made by parsing available SPR estimates according to county or for the entire north coast and by time block, using prior to 2011 and 2011 and thereafter as a break point, noting environmental changes that were occurring during these time blocks (Rogers-Bennett 2011, Rogers-Bennett et al. 2019). Across all temporal and spatial parsing of data, sampling more than 10 sites appears necessary to characterize variation in SPR at the geographic scales considered in the analysis. Further, this analysis may underestimate the number of sites needed to sufficiently characterize regional SPR variation because most SPR estimates made to date are obtained from the most heavily fished sites, rather than some randomized and/or stratified-random design with respect to fishing intensity.

Statistical properties of density surveys

The precision of CDFW and RCCA density surveys were explored as follows. Given the right-skewed and zero-inflated nature of these data, a model selection exercise was conducted to determine the best approximating sampling distribution(s). Statistical distributions of the forms normal, log-normal, Poisson, zero-inflated Poisson, and zero-inflated log-normal were fit to count data for each survey (for each site and year combination) and Akaike Information Criteria was used to identify the ‘best approximating model’. Data available for this analysis were CDFW transects sampled between 1999 and 2018, and RCC transects sampled between 2007 and 2017. The analysis is used to consider the appropriate statistical model to characterize abundance distributions of red abalone (Lo et al. 1992, Hall 2000, Warton 2005).

For CDFW surveys, the ‘best approximating model’ was either log-normal or zero-inflated log-normal with the key difference between selection of these models being the frequency of zero-count transects (Tables A1.3). For RCCA, the best approximating model’ was more varied among sites and years (Tables A1.4). To highlight the level of sampling precision in density estimates, density means and confidence intervals (50%, 75% and 95%) were calculated for each survey using the normal distribution by default, and using the delta-lognormal distribution (Tables A1.5 through A1.8).

Table A1.1 Length frequency distributions used in SPR calculations from RCCA. Entries are observed sample sizes of the exploited phase (i.e., >178 mm shell length). Where applicable, transect and roving diver samples are pooled.

	2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Glass_Beach									157		
Caspar_Cove		29		85				170	229	432	327
Russian_Gulch								86	107	172	119
Mendocino_Hdlnds	267	180	151	128	171	255		129	138	70	136
Van_Damme	222	72	180	85	147	103	78	70	58	266	55
Point_Arena_Lighthouse	114			61	3	41	37				
Arena_Cove					11	120	16				
Sea_Ranch										375	183
Salt_Point_State_Park	168	85	64	105	104	123	28	82	82	217	64
Ocean_Cove	45	81	89		75	98	144	104	59	191	
Stillwater_Cove	62	122	91	178	66	130	58	102	56	211	5
Fort_Ross	77	64	90	78	99	73	101	115	97	316	233
Bodega_Head	39	37	261	85	72	126		36			97
Jack Peters											53

Table A1.2. Length frequency distributions used in SPR calculations from CDFW. Entries are observed sample sizes of the exploited phase (i.e., >178 mm shell length).

	1999	**2000**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**
Todds_Point						436		
Caspar_Cove					427			633
Russian_Gulch								
Van_Damme	505		544				448	
Arena_Cove			652				595	
Sea_Ranch								
Salt_Point		460			525			366
Ocean_Cove							591	
Timber_Cove						877		
Fort_Ross	294	101		371		493		

	2009	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Todds_Point	521				475		
Caspar_Cove			547		318		
Russian_Gulch						387	
Van_Damme		475			392		
Arena_Cove		766				443	
Sea_Ranch				440			
Salt_Point				328			
Ocean_Cove		453		300			
Timber_Cove	586			302			226
Fort_Ross	463			319			323

Table A1.3. Selection of sampling distribution of red abalone counts based on the CDFW dataset. Quantities of are delta-AIC values, which are calculated as the difference between the AIC score of the best model (i.e., the model with the lowest AIC value) and the AIC score of each other model. The best approximating model has a delta AIC score of 0.0. delta-AIC scores should be interpreted separately for each site-year, that is only compare delta-AIC within rows.

	Normal	Log normal	Poisson	ZIP	ZIL	n	nZero	Depth type
Caspar Cove2005	73.2	0	1863	1252.9	0.6	34	8	All
Caspar Cove2008	112.6	16.3	1806	782.2	0	49	17	All
Caspar Cove2011	107.7	24.9	1579	623	0	55	18	All
Caspar Cove2013	92.8	9.4	1449.6	728.5	0	45	14	All
Caspar Cove2017	72.5	0	178.2	78	0	43	18	All
Fort Ross1999	43.2	4.6	894	576.7	0	31	6	All
Fort Ross2006	20.6	0	991.1	867.5	2.8	37	2	All
Fort Ross2009	24	7.9	582.7	384.3	0	40	5	All
Fort Ross2012	45.6	9.6	527.5	226.1	0	37	10	All
Fort Ross2015	26.6	0	783.5	689	4.7	35	2	All
Fort Ross2017	43.3	0	548.8	404.3	2.8	30	5	All
Fort Ross2018	34.1	0	118.6	79.2	2.1	30	6	All
Ocean Cove2007	8.2	2.1	1297.4	995.6	0	36	3	All
Ocean Cove2010	40.6	19.3	1110.4	566.6	0	36	7	All
Ocean Cove2012	32.2	12.1	528.2	190.7	0	31	8	All
Ocean Cove2016	71.1	0	1291.5	1206.7	2.9	36	2	All
Ocean Cove2017	115.6	0	989.2	742.2	3.9	33	10	All
Ocean Cove2018	75.7	0	367.6	245.6	3.6	30	10	All
Point Arena2003	20	11.2	906.1	494.1	0	38	6	All
Point Arena2007	23.3	0	1189.4	971	0.8	36	3	All
Point Arena2010	27.1	21.6	1193.7	811	0	40	4	All
Point Arena2014-15	0.8	0	709.3	456.5	0.8	26	3	All
Point Arena2017	48.9	10.5	645.2	265	0	41	11	All
Russian Gulch2014	10	0	849.9	709.6	1.2	32	2	All
Russian Gulch2017	51.7	0	179.6	118.3	3.5	37	9	All
Russian Gulch2018	67.6	2.4	138.4	64.5	0	32	14	All
Salt Point State Park2016	60.3	0	989.3	839.8	4.2	36	4	All
Salt Point2000	22	0	1275.8	1178.2	4.8	24	1	All
Salt Point2005	37.6	0	2120.1	1685.5	4.3	36	4	All
Salt Point2008	44.7	0.5	964.4	710.8	0	43	6	All
Salt Point2012	64.4	8.7	879.6	395.8	0	41	12	All
Salt Point2017	23.9	0	59.8	33.8	3.4	32	7	All

Sea Ranch2012	32.4	0	745.6	476.5	0.2	34	6	All
Sea Ranch2017	76.3	0	1187.6	859.4	4.4	37	8	All
Timber Cove2006	0	14.8	550.1	465.3	9.9	36	1	All
Timber Cove2009	16	0	628.8	489.2	1.5	35	3	All
Timber Cove2012	55.4	0.6	985.1	570.1	0	36	9	All
Timber Cove2015	58.2	0	1083.5	866.6	4	36	5	All
Timber Cove2017	119.1	0	854	577.9	0.5	40	13	All
Timber Cove2018	92.2	0	754.9	610.5	4.8	29	7	All
Todds Point2006	52.9	0.3	1098	668.7	0	34	8	All
Todds Point2009-10	36.2	0	1042	663.2	0.3	31	6	All
Todds Point2013	34.3	17.7	782.5	379.6	0	37	7	All
Todds Point2017	51.4	9.6	424.9	162.8	0	36	11	All
Todds Point2018	90.8	0	675.5	568.7	4.2	24	6	All
Van Damme1999	32	0.3	1495.4	1228	0	34	3	All
Van Damme2003	6.1	7	1443.2	921.6	0	34	4	All
Van Damme2007	59.7	4.5	1709.3	1257.1	0	38	6	All
Van Damme2010	50	0	2115	1631.1	4	36	5	All
Van Damme2013	44.7	0	1131.4	809.8	0.7	38	6	All
Van Damme2016	62.5	0	888.8	824.5	2.6	33	2	All
Van Damme2017	85.2	0	544.9	508	2.1	40	3	All
Van Damme2018	82.1	1	636.1	384.7	0	34	11	All

Table A1.4. Selection of sampling distribution of red abalone counts based on the RCCA dataset. Quantities of are delta-AIC values, which are calculated as the difference between the AIC score of the best model (i.e., the model with the lowest AIC value) and the AIC score of each other model. The best approximating model has a delta AIC score of 0.0. delta-AIC scores should be interpreted separately for each site-year, that is only compare delta-AIC within rows. The zero-inflated lognormal model is not shown as no sampling events contained zero counts.

Site	Normal	Log normal	Poisson	ZIP	ZIL	n	nZero	Depth type
Arena Cove2007	0	3.6	13.9	NA	NA	6	0	All
Arena Cove2010	0.5	0	8	NA	NA	6	0	All
Arena Cove2013	4.6	0	39	6.5	0.3	6	2	All
Bodega Head2007	4.7	0	36.8	NA	NA	6	0	All
Bodega Head2008	7.8	5.7	35.1	0.1	0	6	2	All
Bodega Head2009	0.7	0	101.6	NA	NA	6	0	All
Bodega Head2010	10.9	6.4	89.7	14.2	0	6	2	All
Bodega Head2011	4.6	0	60.4	NA	NA	6	0	All
Bodega Head2012	3.1	0	80.8	NA	NA	6	0	All
Bodega Head2014	7.5	0.8	71.9	49.1	0	6	1	All
Bodega Head2017	4.2	0	223.9	NA	NA	6	0	All
Caspar2008	3.9	0	7.5	NA	NA	6	0	All
Caspar2010	2.5	1.5	0	NA	NA	6	0	All
Caspar2014	8.2	0	184.7	NA	NA	18	0	All
Caspar2015	0.2	0	117.9	NA	NA	18	0	All
Caspar2016	31.3	0	76.4	NA	NA	16	0	All
Caspar2017	4.1	0	20.3	NA	NA	6	0	All
Fort Ross2007	0	0.1	13.4	NA	NA	6	0	All
Fort Ross2008	0	1.2	28.1	NA	NA	6	0	All
Fort Ross2009	0	0.4	8.6	NA	NA	6	0	All
Fort Ross2010	0	1.6	3.2	NA	NA	6	0	All
Fort Ross2011	1.5	2.7	0	NA	NA	6	0	All
Fort Ross2012	0	1.1	0.7	NA	NA	6	0	All
Fort Ross2013	1.1	0	3.5	NA	NA	6	0	All
Fort Ross2014	1.9	0	84.1	NA	NA	6	0	All
Fort Ross2015	0	5	24.8	NA	NA	6	0	All
Fort Ross2016	0.3	0.9	0	NA	NA	6	0	All
Fort Ross2017	1.4	0	4	NA	NA	6	0	All
Glass Beach2015	3.5	0	44.2	NA	NA	6	0	All
Jack Peters Creek2017	NA	NA	NA	NA	NA	6	6	All
Mendocino Headlands2007	0	2.8	26.9	NA	NA	6	0	All

Mendocino Headlands2008	0	2.8	25.6	NA	NA	6	0	All
Mendocino Headlands2009	0.8	1	0	NA	NA	6	0	All
Mendocino Headlands2010	0.8	1.7	0	NA	NA	6	0	All
Mendocino Headlands2011	9.4	16.8	116.2	0	0.5	6	1	All
Mendocino Headlands2012	0	0.9	6.2	NA	NA	6	0	All
Mendocino Headlands2014	0.9	2.5	0	NA	NA	6	0	All
Mendocino Headlands2015	0	1.4	6.6	NA	NA	6	0	All
Mendocino Headlands2016	3.7	0	68	NA	NA	7	0	All
Mendocino Headlands2017	13.2	0	148.6	NA	NA	6	0	All
Ocean Cove2007	6.4	0	67.3	NA	NA	6	0	All
Ocean Cove2008	5.3	3.7	50.2	22.6	0	6	1	All
Ocean Cove2009	0.7	0	18.6	NA	NA	6	0	All
Ocean Cove2011	0	2	16.6	NA	NA	6	0	All
Ocean Cove2012	0	3.1	8.6	NA	NA	6	0	All
Ocean Cove2013	0	3.7	16.7	NA	NA	6	0	All
Ocean Cove2014	8.9	15.6	69.5	0	0.5	6	1	All
Ocean Cove2015	0	0.4	28.6	NA	NA	6	0	All
Ocean Cove2016	3.5	6.6	11.9	0	1.9	6	1	All
Point Arena Lighthouse2011	1.8	1.8	0	0.8	3.3	6	1	All
Point Arena Lighthouse2012	0	0.8	40.7	NA	NA	6	0	All
Point Arena Lighthouse2013	10.4	5.7	14.7	0	1.6	6	3	All
Russian Gulch2014	0.6	0	77.3	NA	NA	6	0	All
Russian Gulch2015	0	2.9	19.9	NA	NA	6	0	All
Russian Gulch2016	0	1.6	38.6	NA	NA	6	0	All
Russian Gulch2017	0	1.4	93.2	NA	NA	6	0	All
Salt Point2007	0	0.1	27.7	NA	NA	6	0	All
Salt Point2008	1	1.4	0	NA	NA	6	0	All
Salt Point2009	1.1	0	12.6	NA	NA	6	0	All
Salt Point2010	2.5	0	33.8	NA	NA	6	0	All
Salt Point2011	0	2.2	10.5	NA	NA	6	0	All
Salt Point2012	0	2.9	4.5	NA	NA	6	0	All
Salt Point2013	2.5	1	0	NA	NA	6	0	All
Salt Point2014	0.4	0	1	NA	NA	6	0	All
Salt Point2015	0.2	1.4	0	NA	NA	6	0	All
Salt Point2016	0.7	0	0.5	NA	NA	6	0	All
Salt Point2017	1.5	1.8	0	NA	NA	6	0	All
Sea Ranch2015	0	0.4	4.6	NA	NA	6	0	All
Sea Ranch2016	8.8	0	100.5	NA	NA	6	0	All
Sea Ranch2017	NA	NA	NA	NA	NA	6	5	All
Stillwater Cove2007	0.9	2.9	0	NA	NA	6	0	All
Stillwater Cove2008	0	4.6	33.1	NA	NA	6	0	All

Stillwater Cove2009	0	2.8	3.2	NA	NA	6	0	All
Stillwater Cove2010	0.5	0	0.5	NA	NA	6	0	All
Stillwater Cove2011	1.3	0	11.5	NA	NA	6	0	All
Stillwater Cove2012	0	2.1	1.3	NA	NA	6	0	All
Stillwater Cove2013	2	1.8	0	NA	NA	6	0	All
Stillwater Cove2014	1.5	1.9	0	NA	NA	6	0	All
Stillwater Cove2015	1.6	0	3.6	NA	NA	6	0	All
Stillwater Cove2016	4.8	0	47.7	NA	NA	6	0	All
Stillwater Cove2017	6.3	0	6.3	4.3	2.1	6	2	All
Van Damme2007	0	1.9	5.2	NA	NA	6	0	All
Van Damme2008	2.6	0	6.6	NA	NA	6	0	All
Van Damme2009	0	1.1	15.9	NA	NA	6	0	All
Van Damme2010	0.2	0	28.7	NA	NA	6	0	All
Van Damme2011	0	1.5	41.4	NA	NA	6	0	All
Van Damme2012	0	1	38.7	NA	NA	6	0	All
Van Damme2013	0	1.1	12.7	NA	NA	6	0	All
Van Damme2014	0	1.2	39.2	NA	NA	6	0	All
Van Damme2015	2.2	0	16.1	NA	NA	6	0	All
Van Damme2016	7.2	0	12	NA	NA	6	0	All

Table A1.5. Normal distribution confidence intervals of density estimates for CDFW site visits. SEM is standard error of the mean, CV is coefficient of variation of the mean, CI is confidence interval of the mean (L is lower value and U is upper value), n is number of transects, n zero is transects with zero counts.

				50% CI of mean		75% CI of mean		95% CI of man				
Site	Mean	SEM	CV	L	U	L	U	L	U	n	n zero	Depth type
Caspar Cove2005	0.59	0.15	0.26	0.49	0.70	0.42	0.77	0.29	0.89	34	8	All
Caspar Cove2008	0.43	0.08	0.19	0.38	0.49	0.34	0.53	0.27	0.60	49	17	All
Caspar Cove2011	0.39	0.06	0.16	0.35	0.44	0.32	0.47	0.27	0.52	55	18	All
Caspar Cove2013	0.39	0.08	0.20	0.33	0.44	0.30	0.48	0.24	0.54	45	14	All
Caspar Cove2017	0.06	0.01	0.25	0.05	0.07	0.04	0.07	0.03	0.08	43	18	All
Fort Ross1999	0.44	0.09	0.22	0.37	0.50	0.33	0.55	0.25	0.62	31	6	All
Fort Ross2006	0.57	0.09	0.16	0.51	0.63	0.47	0.68	0.39	0.75	37	2	All
Fort Ross2009	0.36	0.05	0.14	0.32	0.39	0.30	0.42	0.26	0.46	40	5	All
Fort Ross2012	0.25	0.04	0.18	0.22	0.28	0.20	0.30	0.16	0.33	37	10	All
Fort Ross2015	0.45	0.08	0.18	0.40	0.51	0.36	0.55	0.29	0.61	35	2	All
Fort Ross2017	0.26	0.06	0.24	0.22	0.31	0.19	0.34	0.14	0.39	30	5	All
Fort Ross2018	0.09	0.02	0.23	0.07	0.10	0.06	0.11	0.05	0.13	30	6	All
Ocean Cove2007	0.86	0.12	0.14	0.78	0.94	0.72	1.00	0.63	1.10	36	3	All
Ocean Cove2010	0.62	0.10	0.16	0.55	0.69	0.51	0.74	0.42	0.82	36	7	All
Ocean Cove2012	0.34	0.06	0.17	0.30	0.38	0.27	0.40	0.22	0.45	31	8	All
Ocean Cove2016	0.41	0.11	0.27	0.34	0.49	0.29	0.54	0.20	0.63	36	2	All
Ocean Cove2017	0.20	0.09	0.43	0.14	0.26	0.10	0.30	0.03	0.37	33	10	All
Ocean Cove2018	0.11	0.04	0.35	0.08	0.14	0.07	0.16	0.03	0.19	30	10	All
Point Arena2003	0.57	0.08	0.14	0.52	0.62	0.48	0.66	0.41	0.73	38	6	All
Point Arena2007	0.64	0.11	0.17	0.57	0.71	0.52	0.76	0.43	0.85	36	3	All
Point Arena2010	0.81	0.11	0.14	0.74	0.89	0.68	0.94	0.60	1.03	40	4	All
Point Arena2014-15	0.71	0.11	0.16	0.64	0.79	0.58	0.84	0.49	0.94	26	3	All
Point Arena2017	0.28	0.05	0.17	0.25	0.31	0.23	0.33	0.19	0.37	41	11	All

Russian Gulch2014	0.63	0.10	0.16	0.57	0.70	0.52	0.75	0.44	0.83	32	2	All
Russian Gulch2017	0.08	0.02	0.23	0.07	0.10	0.06	0.11	0.05	0.12	37	9	All
Russian Gulch2018	0.05	0.02	0.34	0.04	0.07	0.03	0.08	0.02	0.09	32	14	All
Salt Point State Park2016	0.35	0.08	0.24	0.29	0.40	0.25	0.44	0.19	0.51	36	4	All
Salt Point2000	0.88	0.20	0.23	0.75	1.01	0.65	1.11	0.49	1.27	24	1	All
Salt Point2005	0.91	0.16	0.18	0.80	1.02	0.72	1.10	0.58	1.23	36	4	All
Salt Point2008	0.37	0.06	0.17	0.33	0.42	0.30	0.45	0.25	0.50	43	6	All
Salt Point2012	0.31	0.06	0.19	0.27	0.35	0.25	0.38	0.20	0.43	41	12	All
Salt Point2017	0.06	0.01	0.20	0.06	0.07	0.05	0.08	0.04	0.09	32	7	All
Sea Ranch2012	0.38	0.07	0.19	0.33	0.43	0.30	0.47	0.24	0.52	34	6	All
Sea Ranch2017	0.34	0.08	0.24	0.29	0.40	0.25	0.43	0.18	0.50	37	8	All
Timber Cove2006	0.79	0.08	0.10	0.73	0.84	0.70	0.88	0.63	0.95	36	1	All
Timber Cove2009	0.43	0.07	0.16	0.38	0.48	0.35	0.51	0.30	0.57	35	3	All
Timber Cove2012	0.37	0.08	0.21	0.32	0.42	0.28	0.46	0.22	0.52	36	9	All
Timber Cove2015	0.38	0.09	0.23	0.32	0.44	0.28	0.48	0.21	0.56	36	5	All
Timber Cove2017	0.17	0.06	0.35	0.13	0.22	0.10	0.24	0.05	0.29	40	13	All
Timber Cove2018	0.19	0.08	0.41	0.13	0.24	0.10	0.27	0.04	0.33	29	7	All
Todds Point2006	0.43	0.09	0.22	0.37	0.49	0.32	0.53	0.25	0.61	34	8	All
Todds Point2009-10	0.51	0.10	0.20	0.44	0.58	0.39	0.63	0.31	0.72	31	6	All
Todds Point2013	0.47	0.07	0.16	0.42	0.52	0.39	0.56	0.33	0.62	37	7	All
Todds Point2017	0.20	0.04	0.20	0.17	0.22	0.15	0.24	0.12	0.27	36	11	All
Todds Point2018	0.16	0.09	0.54	0.10	0.22	0.06	0.27	-0.01	0.34	24	6	All
Van Damme1999	0.77	0.15	0.20	0.67	0.87	0.59	0.94	0.47	1.07	34	3	All
Van Damme2003	1.07	0.14	0.13	0.98	1.17	0.91	1.24	0.79	1.36	34	4	All
Van Damme2007	0.62	0.14	0.22	0.53	0.71	0.47	0.78	0.36	0.89	38	6	All
Van Damme2010	0.80	0.16	0.20	0.69	0.90	0.62	0.98	0.49	1.11	36	5	All
Van Damme2013	0.46	0.09	0.19	0.40	0.51	0.36	0.55	0.29	0.62	38	6	All
Van Damme2016	0.33	0.09	0.27	0.27	0.39	0.23	0.43	0.15	0.50	33	2	All
Van Damme2017	0.16	0.04	0.28	0.13	0.19	0.11	0.21	0.07	0.25	40	3	All

Van Damme2018	0.19	0.06	0.30	0.15	0.22	0.12	0.25	0.08	0.30	34	11	All

Table A1.6. delta-lognormal confidence intervals of density estimates for CDFW site visits. p is probability of zero count transect (i.e., Binomial component of delta-lognormal model), n is number of transects, n zero is zero count transects, CV is coefficient of variation, CI is confidence interval of the mean (L is lower value and U is upper value).

Site	Mean of lognormal part	CV of lognormal part	p	Overall Mean	50% CI of mean L	50% CI of mean U	75% CI of mean L	75% CI of mean U	95% CI of man L	95% CI of man U	n	n zero	Depth type
Caspar Cove2005	1.08	2.46	0.24	0.83	0.52	1.13	0.31	1.35	0.00	1.73	34	8	All
Caspar Cove2008	0.84	1.73	0.35	0.55	0.42	0.67	0.33	0.76	0.18	0.92	49	17	All
Caspar Cove2011	0.68	1.39	0.33	0.46	0.38	0.54	0.32	0.59	0.23	0.69	55	18	All
Caspar Cove2013	0.70	1.80	0.31	0.48	0.36	0.59	0.28	0.68	0.14	0.82	45	14	All
Caspar Cove2017	0.10	1.25	0.42	0.06	0.05	0.07	0.04	0.08	0.02	0.09	43	18	All
Fort Ross1999	0.61	1.52	0.19	0.49	0.38	0.60	0.29	0.69	0.15	0.83	31	6	All
Fort Ross2006	0.77	1.89	0.05	0.73	0.56	0.89	0.45	1.00	0.24	1.21	37	2	All
Fort Ross2009	0.45	1.21	0.13	0.39	0.33	0.45	0.29	0.49	0.22	0.57	40	5	All
Fort Ross2012	0.38	1.27	0.27	0.28	0.22	0.33	0.19	0.37	0.12	0.43	37	10	All
Fort Ross2015	0.65	2.13	0.06	0.61	0.45	0.77	0.34	0.89	0.14	1.09	35	2	All
Fort Ross2017	0.36	1.79	0.17	0.30	0.22	0.38	0.16	0.44	0.06	0.55	30	5	All
Fort Ross2018	0.11	1.15	0.20	0.09	0.07	0.10	0.06	0.12	0.04	0.14	30	6	All
Ocean Cove2007	1.24	1.79	0.08	1.14	0.88	1.39	0.70	1.57	0.39	1.89	36	3	All
Ocean Cove2010	0.86	1.15	0.19	0.69	0.58	0.81	0.50	0.89	0.36	1.03	36	7	All
Ocean Cove2012	0.52	1.19	0.26	0.39	0.31	0.46	0.26	0.52	0.16	0.61	31	8	All
Ocean Cove2016	0.44	1.89	0.06	0.41	0.32	0.51	0.25	0.58	0.13	0.70	36	2	All
Ocean Cove2017	0.25	2.00	0.30	0.18	0.12	0.23	0.08	0.28	0.00	0.35	33	10	All
Ocean Cove2018	0.16	1.69	0.33	0.10	0.07	0.14	0.05	0.16	0.01	0.20	30	10	All
Point Arena2003	0.82	1.38	0.16	0.69	0.57	0.81	0.48	0.90	0.32	1.06	38	6	All
Point Arena2007	0.89	1.90	0.08	0.81	0.62	1.00	0.49	1.14	0.24	1.38	36	3	All
Point Arena2010	0.96	1.00	0.10	0.86	0.76	0.97	0.68	1.04	0.55	1.17	40	4	All
Point Arena2014-15	1.24	2.00	0.12	1.10	0.74	1.46	0.49	1.71	0.03	2.17	26	3	All
Point Arena2017	0.45	1.37	0.27	0.33	0.27	0.39	0.22	0.44	0.14	0.52	41	11	All

Russian Gulch2014	0.86	1.76	0.06	0.80	0.62	0.99	0.48	1.13	0.25	1.36	32	2	All
Russian Gulch2017	0.11	1.31	0.24	0.08	0.07	0.10	0.06	0.11	0.04	0.13	37	9	All
Russian Gulch2018	0.09	1.01	0.44	0.05	0.04	0.06	0.03	0.07	0.02	0.08	32	14	All
Salt Point State Park2016	0.45	2.14	0.11	0.40	0.29	0.50	0.21	0.58	0.08	0.72	36	4	All
Salt Point2000	1.39	2.56	0.04	1.34	0.77	1.90	0.37	2.30	0.00	3.03	24	1	All
Salt Point2005	1.74	3.03	0.11	1.55	0.97	2.13	0.56	2.54	0.00	3.27	36	4	All
Salt Point2008	0.50	1.74	0.14	0.43	0.35	0.52	0.28	0.58	0.17	0.69	43	6	All
Salt Point2012	0.55	1.59	0.29	0.39	0.30	0.47	0.24	0.54	0.13	0.65	41	12	All
Salt Point2017	0.09	1.10	0.22	0.07	0.06	0.08	0.05	0.09	0.03	0.10	32	7	All
Sea Ranch2012	0.60	1.86	0.18	0.50	0.37	0.63	0.27	0.72	0.11	0.89	34	6	All
Sea Ranch2017	0.53	2.47	0.22	0.42	0.28	0.56	0.18	0.66	0.00	0.83	37	8	All
Timber Cove2006	0.90	1.01	0.03	0.88	0.77	0.98	0.70	1.06	0.56	1.19	36	1	All
Timber Cove2009	0.59	1.69	0.09	0.54	0.42	0.66	0.34	0.74	0.20	0.88	35	3	All
Timber Cove2012	0.65	2.06	0.25	0.49	0.34	0.64	0.24	0.74	0.05	0.93	36	9	All
Timber Cove2015	0.54	2.19	0.14	0.47	0.33	0.60	0.24	0.69	0.07	0.86	36	5	All
Timber Cove2017	0.24	1.69	0.33	0.16	0.12	0.21	0.09	0.23	0.04	0.29	40	13	All
Timber Cove2018	0.20	2.01	0.24	0.15	0.10	0.20	0.06	0.24	0.00	0.31	29	7	All
Todds Point2006	0.75	2.10	0.24	0.57	0.39	0.75	0.26	0.88	0.04	1.11	34	8	All
Todds Point2009-10	0.88	2.11	0.19	0.71	0.48	0.94	0.32	1.10	0.02	1.40	31	6	All
Todds Point2013	0.65	1.11	0.19	0.53	0.45	0.61	0.39	0.67	0.29	0.77	37	7	All
Todds Point2017	0.31	1.20	0.31	0.22	0.18	0.26	0.15	0.29	0.09	0.34	36	11	All
Todds Point2018	0.14	1.80	0.25	0.11	0.07	0.14	0.04	0.17	0.00	0.22	24	6	All
Van Damme1999	1.06	1.83	0.09	0.97	0.74	1.20	0.57	1.36	0.28	1.65	34	3	All
Van Damme2003	1.67	1.71	0.12	1.47	1.14	1.81	0.90	2.05	0.47	2.47	34	4	All
Van Damme2007	0.87	1.74	0.16	0.73	0.57	0.89	0.45	1.01	0.25	1.22	38	6	All
Van Damme2010	1.49	2.97	0.14	1.28	0.80	1.77	0.46	2.11	0.00	2.72	36	5	All
Van Damme2013	0.68	2.01	0.16	0.58	0.43	0.72	0.32	0.83	0.14	1.01	38	6	All
Van Damme2016	0.34	1.70	0.06	0.32	0.25	0.39	0.20	0.44	0.11	0.53	33	2	All
Van Damme2017	0.16	1.55	0.08	0.14	0.12	0.17	0.10	0.19	0.07	0.22	40	3	All

Van Damme2018	0.28	1.60	0.32	0.19	0.14	0.24	0.10	0.28	0.04	0.34	34	11	All

Table A1.7. Normal distribution confidence intervals for RCCA site visits, based on. SEM is standard error of the men, CV is coefficient of variation of the mean, CI is confidence interval of the mean (L is lower value and U is upper value).

				50% CI of mean		75% CI of mean		95% CI of mean				
Site	Mean	SEM	CV	L	U	L	U	L	U	n	n zero	Depth type
Arena Cove2007	0.4806	0.08124	0.1691	0.42576	0.5354	0.3871	0.57401	0.32132	0.6398	6	0	All
Arena Cove2010	0.2861	0.06227	0.2177	0.24411	0.3281	0.21447	0.35775	0.16406	0.4082	6	0	All
Arena Cove2013	0.1444	0.06378	0.4416	0.10143	0.1875	0.07108	0.21781	0.01944	0.2695	6	2	All
Bodega Head2007	0.2194	0.09062	0.4129	0.15832	0.2806	0.1152	0.32369	0.04184	0.397	6	0	All
Bodega Head2008	0.1528	0.05938	0.3887	0.11273	0.1928	0.08447	0.22109	0.03639	0.2692	6	2	All
Bodega Head2009	0.8806	0.24508	0.2783	0.71525	1.0459	0.59863	1.16248	0.40021	1.3609	6	0	All
Bodega Head2010	0.2917	0.12559	0.4306	0.20696	0.3764	0.14719	0.43614	0.04551	0.5378	6	2	All
Bodega Head2011	0.2278	0.10289	0.4517	0.15838	0.2972	0.10942	0.34614	0.02612	0.4294	6	0	All
Bodega Head2012	0.4389	0.16174	0.3685	0.3298	0.548	0.25283	0.62495	0.12188	0.7559	6	0	All
Bodega Head2014	0.2306	0.12303	0.5336	0.14757	0.3135	0.08902	0.37209	-0.0106	0.4717	6	1	All
Bodega Head2017	0.7111	0.29993	0.4218	0.50881	0.9134	0.36609	1.05613	0.12326	1.299	6	0	All
Caspar2008	0.1139	0.04	0.3513	0.08691	0.1409	0.06787	0.15991	0.03548	0.1923	6	0	All
Caspar2010	0.2722	0.03033	0.1114	0.25177	0.2927	0.23734	0.30711	0.21278	0.3317	6	0	All
Caspar2014	0.3315	0.06966	0.2102	0.2845	0.3785	0.25135	0.41162	0.19495	0.468	18	0	All
Caspar2015	0.4407	0.0643	0.1459	0.39737	0.4841	0.36677	0.51471	0.31472	0.5668	18	0	All
Caspar2016	0.0833	0.03463	0.4155	0.05998	0.1067	0.0435	0.12317	0.01546	0.1512	16	0	All
Caspar2017	0.1417	0.0564	0.3981	0.10363	0.1797	0.07679	0.20654	0.03113	0.2522	6	0	All
Fort Ross2007	0.2306	0.06374	0.2765	0.18756	0.2736	0.15723	0.30388	0.10562	0.3555	6	0	All
Fort Ross2008	0.2333	0.07084	0.3036	0.18555	0.2811	0.15184	0.31483	0.09449	0.3722	6	0	All
Fort Ross2009	0.2917	0.06321	0.2167	0.24903	0.3343	0.21895	0.36438	0.16778	0.4156	6	0	All
Fort Ross2010	0.2583	0.04709	0.1823	0.22657	0.2901	0.20416	0.3125	0.16604	0.3506	6	0	All
Fort Ross2011	0.3611	0.02876	0.0796	0.34171	0.3805	0.32803	0.3942	0.30474	0.4175	6	0	All
Fort Ross2012	0.2583	0.04255	0.1647	0.22964	0.287	0.20939	0.30728	0.17494	0.3417	6	0	All
Fort Ross2013	0.3333	0.05774	0.1732	0.29439	0.3723	0.26692	0.39975	0.22017	0.4465	6	0	All

Fort Ross2014	0.5028	0.17097	0.34	0.38746	0.6181	0.30611	0.69945	0.16769	0.8379	6	0	All
Fort Ross2015	0.7361	0.11389	0.1547	0.65929	0.8129	0.6051	0.86712	0.51289	0.9593	6	0	All
Fort Ross2016	0.3389	0.04648	0.1372	0.30754	0.3702	0.28542	0.39236	0.24779	0.43	6	0	All
Fort Ross2017	0.1139	0.03533	0.3102	0.09006	0.1377	0.07324	0.15453	0.04464	0.1831	6	0	All
Glass Beach2015	0.7222	0.17388	0.2408	0.60494	0.8395	0.5222	0.92225	0.38142	1.063	6	0	All
Mendocino Headlands2007	1.3417	0.17093	0.1274	1.22638	1.457	1.14504	1.5383	1.00665	1.6767	6	0	All
Mendocino Headlands2008	0.725	0.12418	0.1713	0.64124	0.8088	0.58215	0.86785	0.48161	0.9684	6	0	All
Mendocino Headlands2009	0.75	0.03496	0.0466	0.72642	0.7736	0.70978	0.79022	0.68148	0.8185	6	0	All
Mendocino Headlands2010	0.75	0.03522	0.047	0.72624	0.7738	0.70948	0.79052	0.68096	0.819	6	0	All
Mendocino Headlands2011	0.9417	0.20551	0.2182	0.80305	1.0803	0.70525	1.17808	0.53887	1.3445	6	1	All
Mendocino Headlands2012	1.4222	0.12734	0.0895	1.33633	1.5081	1.27573	1.56871	1.17264	1.6718	6	0	All
Mendocino Headlands2014	0.7889	0.06096	0.0773	0.74777	0.83	0.71876	0.85901	0.66941	0.9084	6	0	All
Mendocino Headlands2015	0.6417	0.08507	0.1326	0.58429	0.699	0.54381	0.73952	0.47494	0.8084	6	0	All
Mendocino Headlands2016	0.3833	0.1221	0.3185	0.30098	0.4657	0.24288	0.52379	0.14403	0.6226	7	0	All
Mendocino Headlands2017	0.2583	0.18628	0.7211	0.13269	0.384	0.04405	0.47262	-0.1068	0.6234	6	0	All
Ocean Cove2007	0.2528	0.11991	0.4744	0.1719	0.3337	0.11484	0.39071	0.01776	0.4878	6	0	All
Ocean Cove2008	0.2667	0.10417	0.3906	0.1964	0.3369	0.14683	0.3865	0.06249	0.4708	6	1	All
Ocean Cove2009	0.4417	0.09601	0.2174	0.37691	0.5064	0.33122	0.55211	0.25349	0.6298	6	0	All
Ocean Cove2011	0.4333	0.08682	0.2003	0.37478	0.4919	0.33346	0.5332	0.26318	0.6035	6	0	All
Ocean Cove2012	0.3833	0.06555	0.171	0.33912	0.4275	0.30793	0.45873	0.25487	0.5118	6	0	All
Ocean Cove2013	0.6417	0.09848	0.1535	0.57524	0.7081	0.52838	0.75496	0.44864	0.8347	6	0	All
Ocean Cove2014	0.5861	0.13246	0.226	0.49677	0.6755	0.43374	0.73848	0.3265	0.8457	6	1	All
Ocean Cove2015	0.5306	0.11654	0.2197	0.45195	0.6092	0.39649	0.66462	0.30214	0.759	6	0	All
Ocean Cove2016	0.1472	0.03977	0.2701	0.1204	0.174	0.10147	0.19297	0.06927	0.2252	6	1	All
Point Arena Lighthouse2011	0.0472	0.01576	0.3338	0.03659	0.0579	0.02909	0.06535	0.01633	0.0781	6	1	All
Point Arena Lighthouse2012	0.5167	0.12649	0.2448	0.43135	0.602	0.37116	0.66218	0.26875	0.7646	6	0	All
Point Arena Lighthouse2013	0.05	0.02509	0.5018	0.03308	0.0669	0.02113	0.07887	0.00082	0.0992	6	3	All
Russian Gulch2014	0.4583	0.16232	0.3541	0.34885	0.5678	0.27161	0.64506	0.1402	0.7765	6	0	All
Russian Gulch2015	0.6639	0.10813	0.1629	0.59095	0.7368	0.5395	0.78828	0.45195	0.8758	6	0	All

Russian Gulch2016	0.7611	0.15139	0.1989	0.659	0.8632	0.58696	0.93527	0.46439	1.0578	6	0	All
Russian Gulch2017	0.8556	0.22214	0.2596	0.70573	1.0054	0.60002	1.11109	0.42017	1.2909	6	0	All
Salt Point2007	0.6	0.12531	0.2089	0.51548	0.6845	0.45584	0.74416	0.35439	0.8456	6	0	All
Salt Point2008	0.3833	0.04615	0.1204	0.35221	0.4145	0.33025	0.43642	0.29289	0.4738	6	0	All
Salt Point2009	0.2583	0.06719	0.2601	0.21302	0.3036	0.18105	0.33562	0.12665	0.39	6	0	All
Salt Point2010	0.5222	0.13093	0.2507	0.43391	0.6105	0.37161	0.67283	0.26561	0.7788	6	0	All
Salt Point2011	0.6111	0.08972	0.1468	0.5506	0.6716	0.5079	0.71432	0.43527	0.787	6	0	All
Salt Point2012	0.5333	0.06777	0.1271	0.48762	0.579	0.45538	0.61129	0.40051	0.6662	6	0	All
Salt Point2013	0.1944	0.02344	0.1205	0.17864	0.2103	0.16748	0.22141	0.14851	0.2404	6	0	All
Salt Point2014	0.4833	0.06206	0.1284	0.44147	0.5252	0.41194	0.55473	0.36169	0.605	6	0	All
Salt Point2015	1.1944	0.08396	0.0703	1.13781	1.2511	1.09786	1.29103	1.02989	1.359	6	0	All
Salt Point2016	0.3361	0.04952	0.1473	0.30271	0.3695	0.27915	0.39308	0.23906	0.4332	6	0	All
Salt Point2017	0.1	0.01427	0.1427	0.09037	0.1096	0.08358	0.11642	0.07203	0.128	6	0	All
Sea Ranch2015	0.2444	0.05067	0.2073	0.21027	0.2786	0.18615	0.30274	0.14512	0.3438	6	0	All
Sea Ranch2016	0.3222	0.17356	0.5386	0.20516	0.4393	0.12257	0.52188	-0.018	0.6624	6	0	All
Sea Ranch2017	0.0972	0.09722		0.03165	0.1628	-0.0146	0.20906	-0.0933	0.2878	6	5	
Stillwater Cove2007	0.3417	0.03915	0.1146	0.31526	0.3681	0.29664	0.3867	0.26494	0.4184	6	0	All
Stillwater Cove2008	0.4444	0.09885	0.2224	0.37777	0.5111	0.33073	0.55816	0.2507	0.6382	6	0	All
Stillwater Cove2009	0.3722	0.05386	0.1447	0.33589	0.4086	0.31026	0.43418	0.26665	0.4778	6	0	All
Stillwater Cove2010	0.9722	0.08462	0.087	0.91515	1.0293	0.87488	1.06956	0.80637	1.1381	6	0	All
Stillwater Cove2011	0.3472	0.07631	0.2198	0.29575	0.3987	0.25944	0.435	0.19767	0.4968	6	0	All
Stillwater Cove2012	0.6361	0.06546	0.1029	0.59196	0.6803	0.5608	0.71142	0.5078	0.7644	6	0	All
Stillwater Cove2013	0.25	0.03305	0.1322	0.22771	0.2723	0.21198	0.28802	0.18521	0.3148	6	0	All
Stillwater Cove2014	0.7056	0.05816	0.0824	0.66633	0.7448	0.63865	0.77246	0.59156	0.8195	6	0	All
Stillwater Cove2015	0.425	0.06607	0.1555	0.38043	0.4696	0.34899	0.50101	0.2955	0.5545	6	0	All
Stillwater Cove2016	0.2278	0.0959	0.421	0.16309	0.2925	0.11745	0.3381	0.03981	0.4157	6	0	All
Stillwater Cove2017	0.0389	0.02304	0.5925	0.02335	0.0544	0.01238	0.06539	-0.0063	0.084	6	2	All
Van Damme2007	0.7583	0.08679	0.1144	0.69979	0.8169	0.6585	0.85817	0.58823	0.9284	6	0	All
Van Damme2008	0.3111	0.06349	0.2041	0.26829	0.3539	0.23808	0.38415	0.18668	0.4355	6	0	All

Van Damme2009	0.8806	0.12542	0.1424	0.79596	0.9651	0.73628	1.02483	0.63474	1.1264	6	0	All
Van Damme2010	0.45	0.10844	0.241	0.37686	0.5231	0.32526	0.57474	0.23746	0.6625	6	0	All
Van Damme2011	0.8056	0.15897	0.1973	0.69833	0.9128	0.62268	0.98843	0.49398	1.1171	6	0	All
Van Damme2012	0.4639	0.1159	0.2499	0.38571	0.5421	0.33056	0.59722	0.23672	0.6911	6	0	All
Van Damme2013	0.5833	0.09477	0.1625	0.51941	0.6473	0.47431	0.69235	0.39759	0.7691	6	0	All
Van Damme2014	0.5444	0.12771	0.2346	0.45831	0.6306	0.39754	0.69135	0.29415	0.7947	6	0	All
Van Damme2015	0.4222	0.09336	0.2211	0.35925	0.4852	0.31483	0.52962	0.23924	0.6052	6	0	All
Van Damme2016	0.0694	0.03662	0.5273	0.04474	0.0941	0.02732	0.11157	-0.0023	0.1412	6	0	All

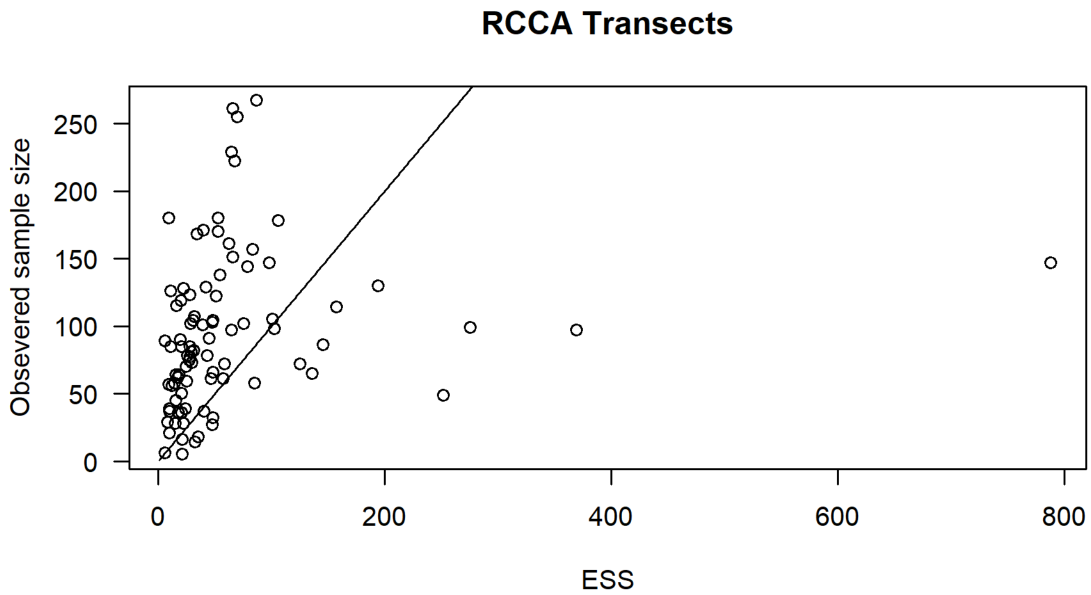
Table A1.8. delta-lognormal confidence intervals of density estimates for RCCA site visits. p is probability of zero count transect (i.e., Binomial component of delta-lognormal model), n is number of transects, n zero is zero count transects, CV is coefficient of variation, CI is confidence interval of the mean (L is lower value and U is upper value).

Site	Mean of lognormal part	CV of lognormal part	p	Overall Mean	50% CI of mean		75% CI of mean		95% CI of man		n	n zero	Depth type
					L	U	L	U	L	U			
Arena Cove2007	0.50	0.65	0.00	0.50	0.39	0.61	0.30	0.71	0.08	0.92	6	0	All
Arena Cove2010	0.29	0.58	0.00	0.29	0.23	0.34	0.19	0.39	0.08	0.50	6	0	All
Arena Cove2013	0.24	1.00	0.33	0.16	0.06	0.26	0.00	0.35	0.00	0.55	6	2	All
Bodega Head2007	0.22	0.99	0.00	0.22	0.13	0.31	0.06	0.38	0.00	0.56	6	0	All
Bodega Head2008	0.23	0.47	0.33	0.15	0.11	0.20	0.07	0.23	0.00	0.32	6	2	All
Bodega Head2009	0.90	0.82	0.00	0.90	0.63	1.18	0.40	1.41	0.00	1.94	6	0	All
Bodega Head2010	0.43	0.53	0.33	0.29	0.20	0.38	0.12	0.45	0.00	0.63	6	2	All
Bodega Head2011	0.25	1.46	0.00	0.25	0.04	0.45	0.00	0.62	0.00	1.02	6	0	All
Bodega Head2012	0.45	1.02	0.00	0.45	0.25	0.64	0.10	0.79	0.00	1.16	6	0	All
Bodega Head2014	0.25	0.82	0.17	0.21	0.13	0.29	0.07	0.36	0.00	0.51	6	1	All
Bodega Head2017	0.77	1.48	0.00	0.77	0.10	1.44	0.00	1.99	0.00	3.29	6	0	All
Caspar2008	0.11	0.78	0.00	0.11	0.08	0.14	0.05	0.17	0.00	0.23	6	0	All
Caspar2010	0.27	0.26	0.00	0.27	0.25	0.29	0.23	0.31	0.19	0.35	6	0	All
Caspar2014	0.39	1.43	0.00	0.39	0.28	0.49	0.21	0.56	0.07	0.70	18	0	All
Caspar2015	0.46	0.86	0.00	0.46	0.39	0.53	0.34	0.58	0.25	0.68	18	0	All
Caspar2016	0.07	1.11	0.00	0.07	0.06	0.09	0.04	0.10	0.02	0.12	16	0	All
Caspar2017	0.14	0.98	0.00	0.14	0.08	0.19	0.04	0.24	0.00	0.34	6	0	All
Fort Ross2007	0.25	0.91	0.00	0.25	0.16	0.33	0.09	0.41	0.00	0.58	6	0	All
Fort Ross2008	0.28	1.38	0.00	0.28	0.07	0.50	0.00	0.67	0.00	1.09	6	0	All
Fort Ross2009	0.30	0.64	0.00	0.30	0.23	0.36	0.18	0.42	0.05	0.54	6	0	All
Fort Ross2010	0.26	0.58	0.00	0.26	0.21	0.32	0.17	0.36	0.07	0.46	6	0	All
Fort Ross2011	0.36	0.22	0.00	0.36	0.34	0.39	0.32	0.41	0.27	0.45	6	0	All
Fort Ross2012	0.26	0.49	0.00	0.26	0.22	0.30	0.19	0.34	0.11	0.42	6	0	All
Fort Ross2013	0.33	0.41	0.00	0.33	0.29	0.38	0.25	0.41	0.17	0.50	6	0	All

Fort Ross2014	0.52	1.03	0.00	0.52	0.30	0.75	0.11	0.93	0.00	1.37	6	0	All
Fort Ross2015	0.78	0.66	0.00	0.78	0.60	0.96	0.45	1.10	0.10	1.45	6	0	All
Fort Ross2016	0.34	0.37	0.00	0.34	0.30	0.38	0.27	0.41	0.19	0.49	6	0	All
Fort Ross2017	0.12	0.93	0.00	0.12	0.08	0.16	0.04	0.20	0.00	0.29	6	0	All
Glass Beach2015	0.71	0.49	0.00	0.71	0.60	0.83	0.50	0.92	0.28	1.14	6	0	All
Mendocino Headlands2007	1.36	0.42	0.00	1.36	1.18	1.54	1.03	1.69	0.67	2.05	6	0	All
Mendocino Headlands2008	0.75	0.60	0.00	0.75	0.60	0.90	0.47	1.03	0.17	1.32	6	0	All
Mendocino Headlands2009	0.75	0.12	0.00	0.75	0.72	0.78	0.70	0.80	0.65	0.85	6	0	All
Mendocino Headlands2010	0.75	0.13	0.00	0.75	0.72	0.78	0.70	0.80	0.64	0.86	6	0	All
Mendocino Headlands2011	1.13	0.23	0.17	0.94	0.80	1.09	0.67	1.21	0.39	1.50	6	1	All
Mendocino Headlands2012	1.42	0.24	0.00	1.42	1.32	1.53	1.23	1.62	1.02	1.82	6	0	All
Mendocino Headlands2014	0.79	0.22	0.00	0.79	0.74	0.84	0.69	0.89	0.59	0.99	6	0	All
Mendocino Headlands2015	0.65	0.39	0.00	0.65	0.57	0.73	0.50	0.79	0.35	0.95	6	0	All
Mendocino Headlands2016	0.38	0.89	0.00	0.38	0.27	0.50	0.17	0.59	0.00	0.79	7	0	All
Mendocino Headlands2017	0.20	1.40	0.00	0.20	0.05	0.36	0.00	0.48	0.00	0.78	6	0	All
Ocean Cove2007	0.24	1.09	0.00	0.24	0.12	0.35	0.03	0.45	0.00	0.67	6	0	All
Ocean Cove2008	0.31	0.61	0.17	0.26	0.19	0.33	0.13	0.39	0.00	0.53	6	1	All
Ocean Cove2009	0.44	0.57	0.00	0.44	0.36	0.53	0.29	0.60	0.12	0.76	6	0	All
Ocean Cove2011	0.45	0.69	0.00	0.45	0.34	0.56	0.25	0.65	0.04	0.86	6	0	All
Ocean Cove2012	0.40	0.62	0.00	0.40	0.31	0.48	0.24	0.55	0.08	0.72	6	0	All
Ocean Cove2013	0.66	0.58	0.00	0.66	0.53	0.79	0.43	0.90	0.18	1.14	6	0	All
Ocean Cove2014	0.70	0.24	0.17	0.59	0.49	0.68	0.42	0.75	0.24	0.93	6	1	All
Ocean Cove2015	0.54	0.65	0.00	0.54	0.42	0.66	0.32	0.76	0.08	1.00	6	0	All
Ocean Cove2016	0.18	0.46	0.17	0.15	0.12	0.18	0.09	0.21	0.03	0.27	6	1	All
Point Arena Lighthouse2011	0.06	0.71	0.17	0.05	0.03	0.06	0.02	0.08	0.00	0.11	6	1	All
Point Arena Lighthouse2012	0.54	0.80	0.00	0.54	0.38	0.70	0.25	0.83	0.00	1.14	6	0	All
Point Arena Lighthouse2013	0.10	0.41	0.50	0.05	0.03	0.07	0.02	0.08	0.00	0.12	6	3	All
Russian Gulch2014	0.60	1.45	0.00	0.60	0.10	1.10	0.00	1.50	0.00	2.47	6	0	All
Russian Gulch2015	0.68	0.57	0.00	0.68	0.55	0.81	0.44	0.92	0.19	1.18	6	0	All

Russian Gulch2016	0.78	0.65	0.00	0.78	0.61	0.96	0.47	1.10	0.13	1.44	6	0	All
Russian Gulch2017	0.93	0.96	0.00	0.93	0.57	1.29	0.28	1.58	0.00	2.27	6	0	All
Salt Point2007	0.61	0.59	0.00	0.61	0.49	0.73	0.39	0.83	0.15	1.06	6	0	All
Salt Point2008	0.38	0.32	0.00	0.38	0.35	0.42	0.31	0.45	0.24	0.53	6	0	All
Salt Point2009	0.26	0.70	0.00	0.26	0.20	0.33	0.14	0.38	0.02	0.51	6	0	All
Salt Point2010	0.52	0.57	0.00	0.52	0.42	0.62	0.34	0.70	0.14	0.89	6	0	All
Salt Point2011	0.62	0.47	0.00	0.62	0.53	0.71	0.45	0.79	0.27	0.97	6	0	All
Salt Point2012	0.54	0.42	0.00	0.54	0.47	0.61	0.41	0.67	0.26	0.82	6	0	All
Salt Point2013	0.19	0.27	0.00	0.19	0.18	0.21	0.16	0.22	0.13	0.25	6	0	All
Salt Point2014	0.48	0.32	0.00	0.48	0.44	0.53	0.40	0.57	0.30	0.66	6	0	All
Salt Point2015	1.20	0.19	0.00	1.20	1.13	1.27	1.07	1.32	0.93	1.46	6	0	All
Salt Point2016	0.34	0.36	0.00	0.34	0.30	0.37	0.27	0.40	0.19	0.48	6	0	All
Salt Point2017	0.10	0.38	0.00	0.10	0.09	0.11	0.08	0.12	0.05	0.15	6	0	All
Sea Ranch2015	0.25	0.60	0.00	0.25	0.20	0.30	0.16	0.34	0.06	0.44	6	0	All
Sea Ranch2016	0.29	1.02	0.00	0.29	0.17	0.42	0.07	0.52	0.00	0.76	6	0	All
Stillwater Cove2007	0.34	0.35	0.00	0.34	0.31	0.38	0.28	0.41	0.20	0.49	6	0	All
Stillwater Cove2008	0.54	1.14	0.00	0.54	0.26	0.82	0.03	1.04	0.00	1.58	6	0	All
Stillwater Cove2009	0.38	0.49	0.00	0.38	0.32	0.44	0.27	0.49	0.15	0.61	6	0	All
Stillwater Cove2010	0.97	0.21	0.00	0.97	0.91	1.03	0.86	1.09	0.74	1.21	6	0	All
Stillwater Cove2011	0.35	0.54	0.00	0.35	0.28	0.41	0.23	0.46	0.11	0.58	6	0	All
Stillwater Cove2012	0.64	0.31	0.00	0.64	0.58	0.70	0.53	0.75	0.41	0.87	6	0	All
Stillwater Cove2013	0.25	0.33	0.00	0.25	0.22	0.28	0.20	0.30	0.15	0.35	6	0	All
Stillwater Cove2014	0.71	0.21	0.00	0.71	0.66	0.75	0.62	0.79	0.53	0.88	6	0	All
Stillwater Cove2015	0.42	0.35	0.00	0.42	0.38	0.47	0.34	0.51	0.25	0.60	6	0	All
Stillwater Cove2016	0.22	1.06	0.00	0.22	0.12	0.32	0.04	0.40	0.00	0.60	6	0	All
Stillwater Cove2017	0.06	0.87	0.33	0.04	0.02	0.06	0.00	0.07	0.00	0.11	6	2	All
Van Damme2007	0.76	0.34	0.00	0.76	0.68	0.85	0.61	0.91	0.45	1.07	6	0	All
Van Damme2008	0.31	0.43	0.00	0.31	0.27	0.35	0.23	0.39	0.15	0.47	6	0	All
Van Damme2009	0.89	0.41	0.00	0.89	0.77	1.00	0.68	1.10	0.46	1.32	6	0	All

Van Damme2010	0.46	0.69	0.00	0.46	0.35	0.57	0.25	0.66	0.04	0.88	6	0	All
Van Damme2011	0.83	0.63	0.00	0.83	0.65	1.00	0.50	1.15	0.16	1.49	6	0	All
Van Damme2012	0.49	0.85	0.00	0.49	0.33	0.64	0.20	0.77	0.00	1.07	6	0	All
Van Damme2013	0.59	0.48	0.00	0.59	0.50	0.68	0.42	0.75	0.25	0.93	6	0	All
Van Damme2014	0.57	0.78	0.00	0.57	0.40	0.73	0.27	0.87	0.00	1.18	6	0	All
Van Damme2015	0.42	0.50	0.00	0.42	0.35	0.49	0.29	0.55	0.16	0.68	6	0	All
Van Damme2016	0.06	1.00	0.00	0.06	0.04	0.09	0.02	0.11	0.00	0.16	6	0	All



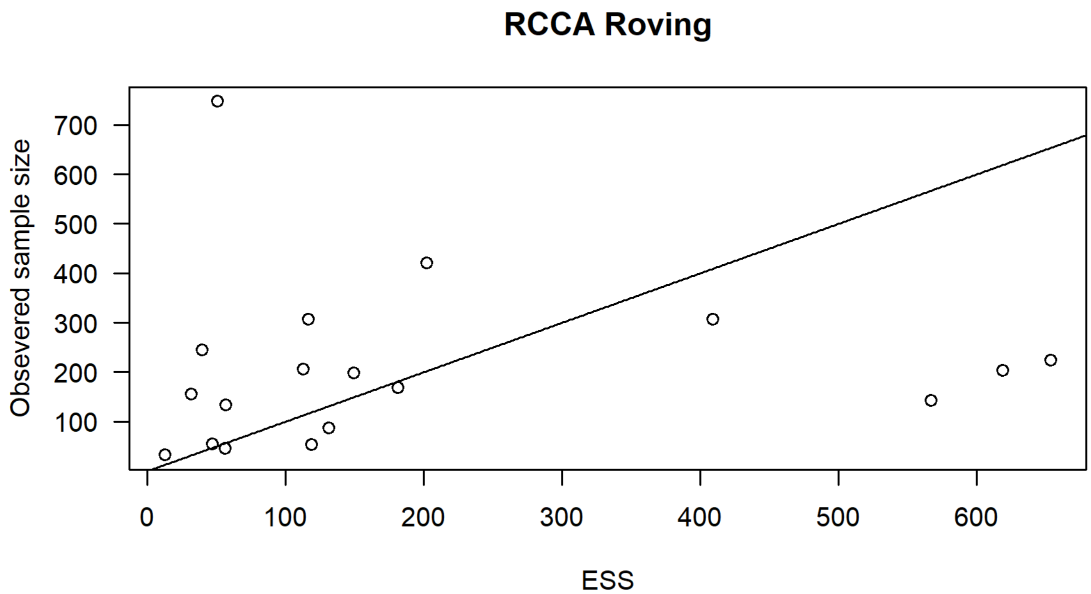
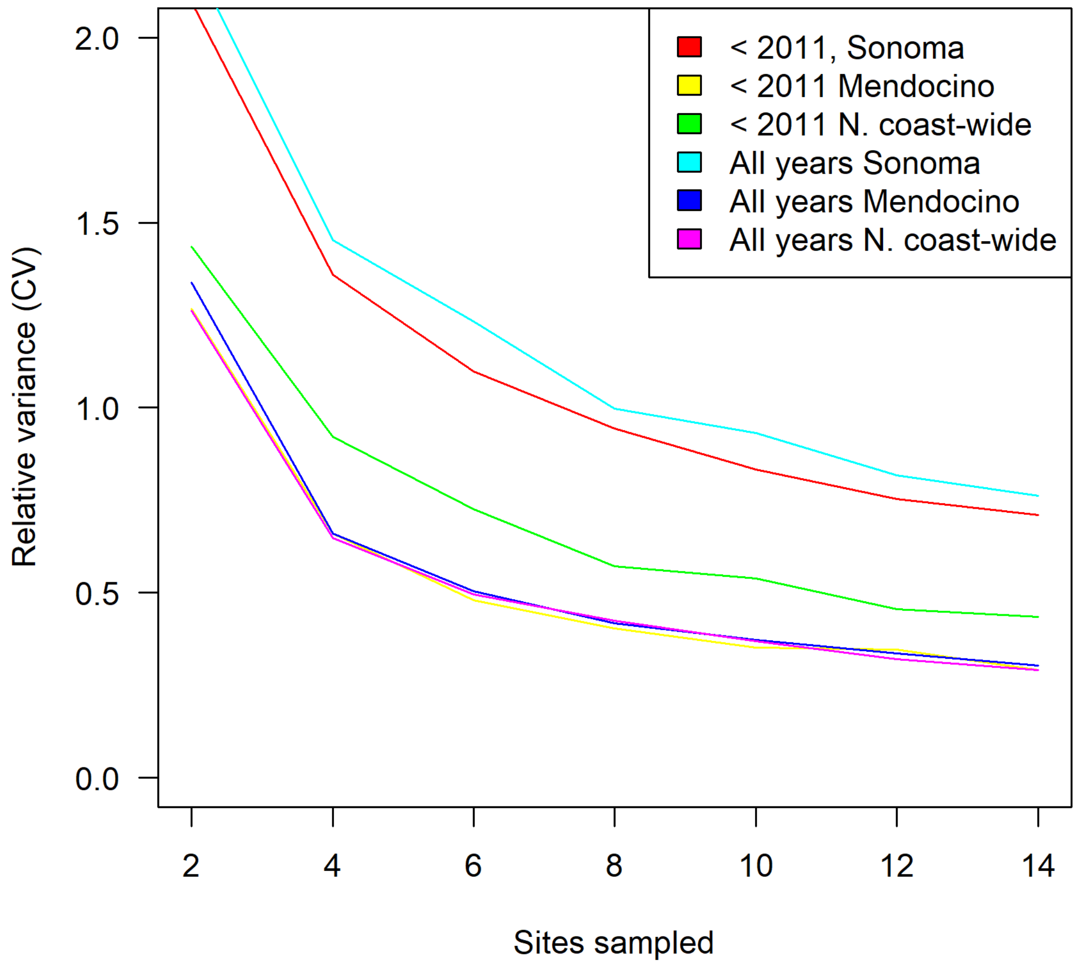


Figure A1.1. RCCA length frequency sampling of the exploited phase (>178 mm shell length). Comparison of observed sample sizes and corresponding sampling precision, measured as effective sample size (ESS).



FigureA1.2 Bootstrapped estimates of relative variance in SPR estimates among sites, calculated according to number of sites visited in characterizing a defined geographic area and period of time.

Technical appendix 2. Operating model – base model configuration

Population dynamics of red abalone

Simulations were implemented in the R statistical computing environment (R Development Core Team 2012). A spatially-explicit simulation model was constructed with red abalone distributed along a 1-dimensional array consisting of 56 red abalone report card sites, each of which corresponded to a recreational fishing location that spans a total distance of approximately 540 km (334 miles) from San Francisco to the California-Oregon border. We did not model site connectivity because short larval durations of abalone species typically act to minimize dispersal distances from 10s to 100s of meters (Prince et al. 1987, McShane et al. 1988, Shepherd and Brown 1993, Leighton 2000, Temby et al. 2007, Gruenthal et al. 2007, Saunders et al. 2008). Adult movement over various time scales is also thought to be limited to 100s of meters (Ault and Demartini 1987, Coates et al. 2013). Change in abundance and growth through time were formulated using a length-transition probability model (Breen et al. 2003, Haddon 2011). The red abalone stock was initialized for the year 2002 in a state that was consistent with catch, length frequency, and density data (Technical Appendix 3).

Numbers of red abalone were assigned to length classes from 5 mm to 320 mm, with bin sizes increasing in 5 mm increments. For a given site *l* and simulation replicate *k*, the matrix algebra involved in calculating the progression of individuals between length bins, according to an annual time step, *j*, was (for brevity *k* and *l* subscripts are omitted):

$$\mathbf{N_{j+1}} = \mathbf{G_j}\left(\mathbf{S_j}\mathbf{N_j}\right) + \mathbf{R_j}, \tag{1}$$

where **N** is the abundance vector of length classes, **G** is the square growth transition matrix with upper triangle of zeros preventing negative growth in length, **S** is a diagonal matrix representing survival at length, and **R** is the recruitment vector.

Life history is described with subscript j to indicate parameters that are time-varying. The growth matrix specified how numbers-at-length would transition probabilistically into other length classes based on a Gaussian probability density function with expected growth increments obtained from a von Bertalanffy function (i.e., expected growth increment is $\Delta L_{i,j,k,l} = \left(L\infty_{j,k,l} - L_{\mathrm{bin},i}\right)\left(1-\exp(-K_{k,l})\right)$, where K is Brody growth coefficient, $L\infty$ is average maximum size, and L_{bin} is the lower bound of each length bin, i. Logistic maturity ($\mathrm{Mat}_{i,k,l}$) was parameterized based on average maximum size ($\bar{L}\infty_{k,l}$) and the following life history relationships: $L50_{k,l} = \bar{L}\infty_{k,l} \times 0.512$ and $L95_{k,l} = L50_{k,l} \times 1.15$, where *L50* and *L95* are the lengths associated with 50% and 95% probabilities of maturity, respectively (Jensen 1996, Prince et al. 2015). The quantities $\bar{L}\infty_{k,l}$ and the average Brody growth coefficient, $\bar{K}_{k,l}$, were 254 mm and 0.108 year^{-1}, respectively (Rogers-Bennett et al. 2007). The ratio $L50/L\infty = 0.512$ was obtained from life history and histological studies of California red abalone, noting that histological studies provide similar of *L50* of approximately 120 mm to 130 mm (Giorgi and DeMartini 1977, Rogers-Bennett et al. 2004, 2007). *L95* was specified as $L95/L50$=1.15, which is consistent with histological studies of red abalone maturity (Rogers-Bennett et al. 2004). Eggs-per-female was an exponential function of length ($\mathrm{fec}_i = exp(-10.434) L_{\mathrm{mids},i}^{4.701}$; L_{mids} is mid-point of each length bin), with parameter estimates obtained by fitting the exponential function to digitized length-fecundity data from Rogers-Bennett et al. (2004).

Survival (S) consisted of natural mortality (M) and fishing mortality (F) and was calculated at the beginning of each time step:

$$S_{i,j,k,l} = \exp\left(-M_{i,j,k,l} - \mathrm{sel}_{i,j} F_{j,k,l}\right), \tag{2}$$

where *sel* is selectivity and is specified as knife-edge at the minimum harvest size of 178 mm shell length. For a given *l* and *k*, $S_{i,j}$ populates the diagonal of the corresponding survival matrix ($\mathbf{S_j}$). Leaf et al. (2007) conducted analysis of mark-recapture data from northern California red abalone, from which mortality of red abalone < 100 mm was estimated at 0.65 year^{-1} (0.56 – 0.75 year^{-1}, mean ± 1 standard error). Leaf et al. (2007) also estimated mortality for larger size classes, however, considerable uncertainty in mortality rates for individuals 100 mm to 178 mm was reported with site-specific estimates ranging from 0.34 y^{-1} (0.28–0.40 y^{-1}, mean ± standard error) to 0.75 y^{-1} (0.65–0.87 y^{-1}, mean ± standard error). For red abalone in the exploited phase (i.e., > 178 mm), estimates from Point Cabrillo South Cove were of interest because this location is not subject to fishing. But likely owing to exceptionally few individuals comprising the mark and recapture dataset in the exploited phase at Point Cabrillo South Cove, the resulting mortality estimate had a coefficient of variation of 1.8 (0.0 – 0.14 year^{-1}, mean ± 1 standard error), mean value of 0.05 year^{-1}. Thus, we defined natural mortality-at-length ($\overline{M}_i$) as follows. For length classes < 100 mm, natural mortality of 0.65 year^{-1} was specified from Leaf et al. (2007). For length bins from 100 mm to 130 mm (i.e., *L50*) natural mortality followed a linearly decreasing function from 0.65 year^{-1} to 0.097 year^{-1}. For mature individuals, natural mortality was 0.097 year^{-1}. The value of 0.097 year^{-1} was selected to be consistent with evidence from life-history theory, mark-recapture from Point Cabrillo South Cove, and *M/K* ratios reported for abalone species (Leaf et al. 2007, Rogers-Bennett et al. 2007, Prince 2016). Catch in numbers (C^N) is calculated:

$$C^N_{i,j,k,l} = \frac{\mathrm{sel}_{i,j} F_{j,k,l}}{\left(M_{i,j,k,l} + \mathrm{sel}_{i,j} F_{j,k,l}\right)} \left(1 - S_{i,j,k,l}\right) N_{i,j,k,l}, \tag{3}$$

And catches in weight (C^B; kg) is:

$$C^{B}_{i,j,k,l} = C^{N}_{i,j,k,l} W_i . \tag{4}$$

Age-one numbers of recruits at each site were calculated according to the Beverton and Holt (1957) stock-recruitment function that was re-parameterized using steepness (*h*):

$$R_{j,k,l} = \left(\frac{0.8 R_{0,k,l} h B_{j-1,k,l}}{0.2 B_{0,k,l} (1-h) + (h-0.2) B_{j-1,k,l}} \right) \exp\left(d_{j,k,l} - \sigma^2 / 2 \right), \tag{5}$$

where *d* is a recruitment deviation for each combination of year, site, and simulation replicate, which is specified to have a normal distribution with mean zero and with standard deviation σ of 0.2. B_0 is unfished egg production, and *B* is a measure of reproductive output summed across length bins, *i*, in year *j-1*:

$$B_{j-1,k,l} = \sum_i \mathrm{Mat}_{i,k,l} \times \mathrm{fec}_i \times N_{i,j-1,k,l} \tag{6}$$

Steepness was specified as 0.7, as abalone species tend to display weaker compensatory recruitment at low stock size and this value is the approximate mid-point of values that have been specified in abalone stock assessments (Rose et al. 2001, Gorfine et al. 2005, Fu 2014). The Allee effect has been suggested as being an important limitation to reproduction at low density of red abalone, although exact reproductive thresholds are difficult to identify (Tegner et al. 1989b, Shepherd and Brown 1993, Catton et al. 2016). In our stock-recruitment simulations, we forced complete recruitment failure to occur when reproductive output fell below 1% of unfished reproductive output (i.e., egg production). Age-1 recruits ($R_{i,j}$) populated length bins of the recruitment matrix ($\mathbf{R_j}$) according to the Gaussian probability density function with von Bertalanffy parameters $\overline{L}\infty_{k,l}$ and $\overline{K}_{k,l}$.

Spatial and temporal variation in growth and natural mortality

Spatial variation in growth was simulated by specifying mean asymptotic length ($\overline{L}\infty_{k,l}$) and mean Brody growth coefficient ($\overline{K}_{k,l}$) for each site-simulation replicate. Spatial variation across simulation runs was generated according to a multivariate Gaussian distribution ($\mathrm{MVN}(\mu,\Sigma)$) with $\mu = \left(\overline{L}\infty = 254, \overline{K} = 0.108\right)$ and using a coefficient of variation of 4% on asymptotic length and a coefficient of variation of 3% on the Brody growth coefficient, based on reported inter-site variation in growth parameter estimates (Geibel et al. 2010), with a correlation coefficient of 0.6 to obtain the variance-covariance matrix, Σ. Truncation was introduced, preventing asymptotic growth from being specified below 234 mm or above 274 mm, reflecting ± 2 standard deviations in asymptotic length variability around our chosen mean of 254 mm. Spatial variability in $\overline{L}\infty_{k,l}$ and $\overline{K}_{k,l}$ is incorporated into maturity-at-length functions, thus enabling growth and maturity characteristics to co-vary at each site (Prince et al. 2015).

The life history parameters asymptotic length and natural mortality were time-varying and were correlated with an index of the El Nino Southern Oscillation (ENSO) known as the Ocean Nino Index, which measures surface temperature anomalies (NOAA 2017). This index was not considered to be an exhaustive environmental driver of red abalone dynamics, but was thought to have reasonable statistical properties of temporal climate fluctuations. Laboratory and observational studies have shown water temperature to negatively affect red abalone gamete production, body condition, survival rates, and somatic growth (Vilchis et al. 2005, Perez 2010, Jiao et al. 2010, Moore et al. 2011). Likewise, trends in food availability, especially related to climate- and storm-induced variability in kelp biomass (e.g., *Nereocystis luetkeana*), have been implicated in changes to red abalone survival and growth (Tegner and Dayton 1987, Tegner et al.

2001, Cavanaugh et al. 2011, Rogers-Bennett et al. 2011). During the time period of 2002 to 2016, actual ENSO autumn season means (i.e., the September through November average) were used in constructing historical stock dynamics. Then, to produce forecasts, we randomly selected toroidal-like segments of the autumn season ENSO index from the time period of 1950 to 2017 in an effort to preserve temporal autocorrelation. Given generation of an ENSO time series, corresponding time series of $L\infty$ were generated using a Cholesky transformation (Fig. A2.1). We opted to link $L\infty_{j,k,l}$ with the ENSO index using a negative correlation of 0.5 and $L\infty_{j,k,l}$ varied in magnitude based on a Gaussian CV of 0.05 around the corresponding parameter $\bar{L}\infty_{k,l}$ (Jiao et al. 2010). Correlation strength reflected observational studies that have demonstrated statistically significant correlations between climate signals and red abalone growth parameters (Jiao et al. 2010) or kelp biomass (Cavanaugh et al. 2011), albeit, reported correlation strengths varied considerably among studies.

To link time-varying natural mortality events to the ENSO index, we again generated a time series of standardized (i.e., standard deviation of 1.0) environmental fluctuations using a Cholesky transformation with correlation of 0.5 (Fig. A2.2). An additive mortality term was triggered when environmental fluctuations equaled or exceeded a value 1.5, mimicking the onset of el Nino conditions. This trigger was selected by identifying the timing of reported effects of climate on abalone (in both northern and southern California), noting that events in 1957-1959, 1982-1984, 1997-98, and 2014 align with high ENSO index values (using the September through November average) of 1.5 or greater (Tegner et al. 2001, Rogers-Bennett et al. 2019). The magnitude of this additional natural mortality term was calculated:

$$S_{j,k,l} = \begin{cases} 1 & \text{if env}_{j,k,l} < 1.5 \\ 1 - env_{j,k,l} 0.05 & 1.5 \le \text{env}_{j,k,l} < 2.0 \\ 0.9 & \text{otherwise} \end{cases} \tag{7}$$

$$M_{i,j,k,l} = \overline{M}_i - \log\left(S_{j,k,l}\right) \tag{8}$$

This configuration imposes an additional 7.5% mortality rate on all size classes under an event with ENSO index value of 1.5, and an additional 10% mortality above ENSO index values of 2 or greater. Experimental evidence clearly identifies that red abalone are susceptible to environmentally-induced fluctuations in temperature, although the magnitudes of associated mortality rates vary considerably, perhaps reflective of differences in experimental conditions (Vilchis et al. 2005, Rogers-Bennett et al. 2010, Moore et al. 2011). Experiment durations where, for example, extreme temperatures are held for approximately one year, have resulted in 20% to 60% adult mortality (Vilchis et al. 2005). But in situ temperature profiles suggest that even during extreme of el Nino years, red abalone appear to be subject to temperature extremes, like those applied in experiments, for a lower fraction of the year (Tegner et al. 2001, Rogers-Bennett et al. 2010). Rogers-Bennett et al. (2010) exposed red abalone to warm water for 26 weeks (1/2 year), while feeding liberally, noting that 6% died during this treatment. Moore et al. (2011) reported 17% mortality through one year under ambient conditions, and 31% mortality from partial annual exposure to warm water, with the mortality difference of 14% presumably reflecting warm water exposure. Experimental feeding of kelp has also produced variable effect size relative to feed quantity and quality, with variation in quality producing 5% to 10% mortality, while complete starvation can produce upwards of 30% mortality over the course of approximately one year (Vilchis et al. 2005, Rogers-Bennett et al. 2010). Thus, the simulated magnitude of environmentally-induced mortality was specified to vary with ENSO anomaly severity, but also in a manner that reflects those experimental results that we expected to be most reflective of in situ conditions. Furthermore, simulated environmentally-induced mortality events can produce multi-year die-offs that are reflective of the temporal correlation in ENSO anomalies.

Fishery behavior

Regional TACs were removed (harvested) without error. We utilized a spatial effort allocation model that increased or decreased regional effort as necessary to achieve removal of the regional TAC, while maintaining the relative spatial distribution of effort commensurate with the simulated 2017 effort distribution (i.e., the final year of the historical time period). This effort allocation model reflected the idea that each site would continue to maintain its relative popularity with fishers into the foreseeable future, despite local red abalone abundance changes.

Observation model

Field sampling conducted by Reef Check California (RCCA) and by California Department of Fish and Wildlife (CDFW) were separately and concurrently represented in the operating model. In the simulating site selection for data collection, 9 of 14 abalone report-card sites monitored by RCCA were randomly chosen annually (since the time of report preparation, Reef Check California may have expanded site selection). Likewise, of the 10 sites sampled historically by CDFW, 3 sites were randomly chosen annually to be sampled. In each case, visiting the specified subset of total sites reflects the typical annual sampling effort deployed by each organization. Site selection is not coordinated between these two organizations, and was not coordinated in our simulations. In the instance where the same site was sampled in the same year by both organizations, quantities obtained from CDFW sampling were used by default.

Simulation of emergent red abalone

Measurement of red abalone density and length-frequency distributions reflects observation of emergent abalone. Emergence is defined as the proportion of each length class that has undergone an ontogenetic shift from cryptic habitat, such as being hidden within crevices, to inhabiting exposed substrates. In the operating model, numbers of emergent abalone were calculated as the product of numbers-at-length and the proportion emerged-at-length:

$$N_{i,j,k,l}^{E} = N_{i,j,k,l}^{T} \times E_i, \tag{9}$$

where, for a given length bin, i, N^E is the number of emergent red abalone, N^T is total red abalone, and E is proportion emerged. Proportion emerged was specified as an exponential function:

$$E_i = \begin{cases} 1.0 & \text{if } Lmid_i > 178 \\ \alpha_E \left(\dfrac{Lmid_i}{178} \right)^{\beta_E} & \text{otherwise} \end{cases}, \tag{10}$$

with parameters $\alpha_E = 1$ and $\beta_E = 5.55$. The specified pattern of emergence was obtained from examining RCCA and CDFW observed length-frequency distributions. Observed length-frequencies reflect the outcomes of two processes: the numbers of red abalone in each length class (which is affected by survival rate) and the proportion emergent. Using the operating model, proportions of the population in size classes less than 178 mm (i.e., prior to entering the fishery) can be calculated, and thus, by contrasting relative population abundance within length bins against observed length-frequencies, the proportion emerged at length can be separated-out

(Fig. A2.3). This was done using the exponential model described in Equation (10), and accordingly, parameters α_E and β_E were estimated. Emergence should be thought of as a heuristic means to impose a pattern reflective of observed data, and not as a mechanistic model of emergence (Fig. A2.4).

Simulation of length-frequency sampling and SPR estimation

Simulated length frequency distributions were sampled from emergent red abalone-at-length as a multinomial process with an effective sample size of 100 individuals, which is consistent with the measured precision of Reef Check California field sampling (Technical Appendix 1). It was assumed that precision of length frequency sampling was equivalent between RCCA and CDFW. Given a simulated observation of length frequency, SPR is calculated according to the length-based SPR method (Hordyk et al. 2015). The maximum likelihood LB-SPR estimation routine requires input parameters of *M/K*, asymptotic length, coefficient of variation of asymptotic length, exponential parameter for fecundity, and a logistic maturity curve (Hordyk et al. 2015). *M/K* was specified as 0.9, obtained from life history information of California red abalone, and consistent with life history of abalone species (Leaf et al. 2007, Rogers-Bennett et al. 2007, Prince 2016). Length at 50% maturity (*L50*) was obtained from the operating model, but was subject to observation error of up to 5%. Observation error was specified as a normally distributed with mean one and standard deviation 0.025, with the error terms specified as a multiplier of the ‘true’ *L50*. This approach was intended to reflect the attainment of site-specific *L50* from evaluation of red abalone length frequency distribution as they undergo an ontogenetic shift from cryptic juveniles, hidden in crevices, to mature adults that inhabit exposed substrates (Prince 2016). Asymptotic length was calculated using the ratio $L50/L\infty$ = 0.512 and *L95* was assumed to follow the approximate value of $L95/L50$=1.15. Coefficient of variation of asymptotic length is specified at 0.1, but was allowed to systematically increase up to 0.3 in instances were statistical convergence could not be obtained. The fecundity exponent was 4.7 (Rogers-Bennett et al. 2004).

Simulation of emergent density

Observation of emergent density was determined according to the statistical sampling distributions and related properties that were most consistent with CDFW and RCCA sampling (Technical Appendix 1). Observation of density required specifying the statistical sampling distribution of transect data. Given the right-skewed and zero-inflated nature of density observations (Technical Appendix 1), a zero-inflated lognormal distribution was specified (Lo et al. 1992, Hall 2000, Warton 2005). The zero-inflated lognormal distribution can be thought of a two-part distribution, with mean overall density specified:

$$D_{j,k,l} = q_l \sum N^{E}_{i,j,k,l}, \tag{11}$$

and the density of the positive log-normal (non-zero) portion of the distribution specified as:

$$\theta_{j,k,l} = \frac{D_{j,k,l}}{(1-\rho)} \tag{12}$$

where the catchability coefficient, q, is estimated as a site-specific quantity as part of model tuning (Technical Appendix 3) and ρ indicating the probability of a zero density observation. Sampling from the zero-inflated lognormal distribution was carried out using the R library EnvStats (Millard 2013). To generate transect-level density observations using EnvStats, also required specifying the coefficients of variation of the lognormal part of the distribution. For RCCA sampling, ρ was set at 0.05 and the coefficients of variation of the lognormal part of the distribution was set at 0.65 and density observations for 6 transects were made for each site visit.

For CDFW sampling, ρ was set at 0.2 and the coefficients of variation of the lognormal part of the distribution was set at 1.73 and density observations for 36 transects were made for each site visit. In each case, the chosen sampling properties reflect those estimated values from CDFW and RCCA sampling (Technical Appendix 1). Given specification of the sampling distribution, simulated observation of transects are used to calculate a confidence interval of the mean observed density, which is calculated using the EnvStats R library.

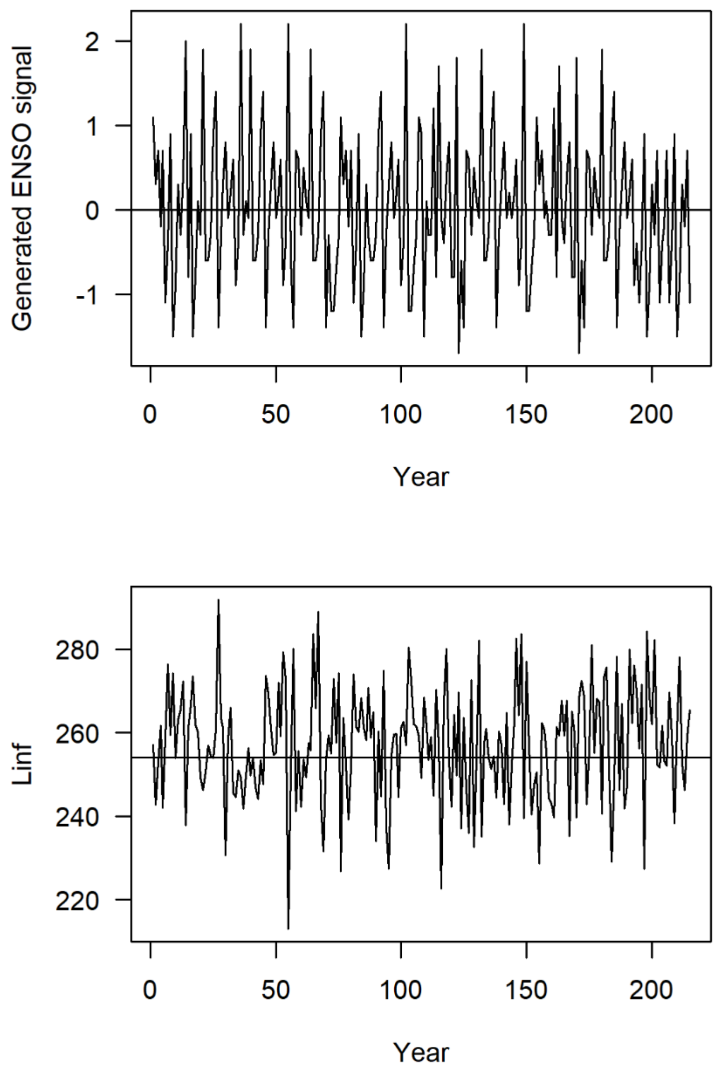


Figure A2.1. Example of time-varying pattern in asymptotic length (Linf; lower panel), illustrating negative correlation of 0.5 with generated ENSO signal (upper panel).

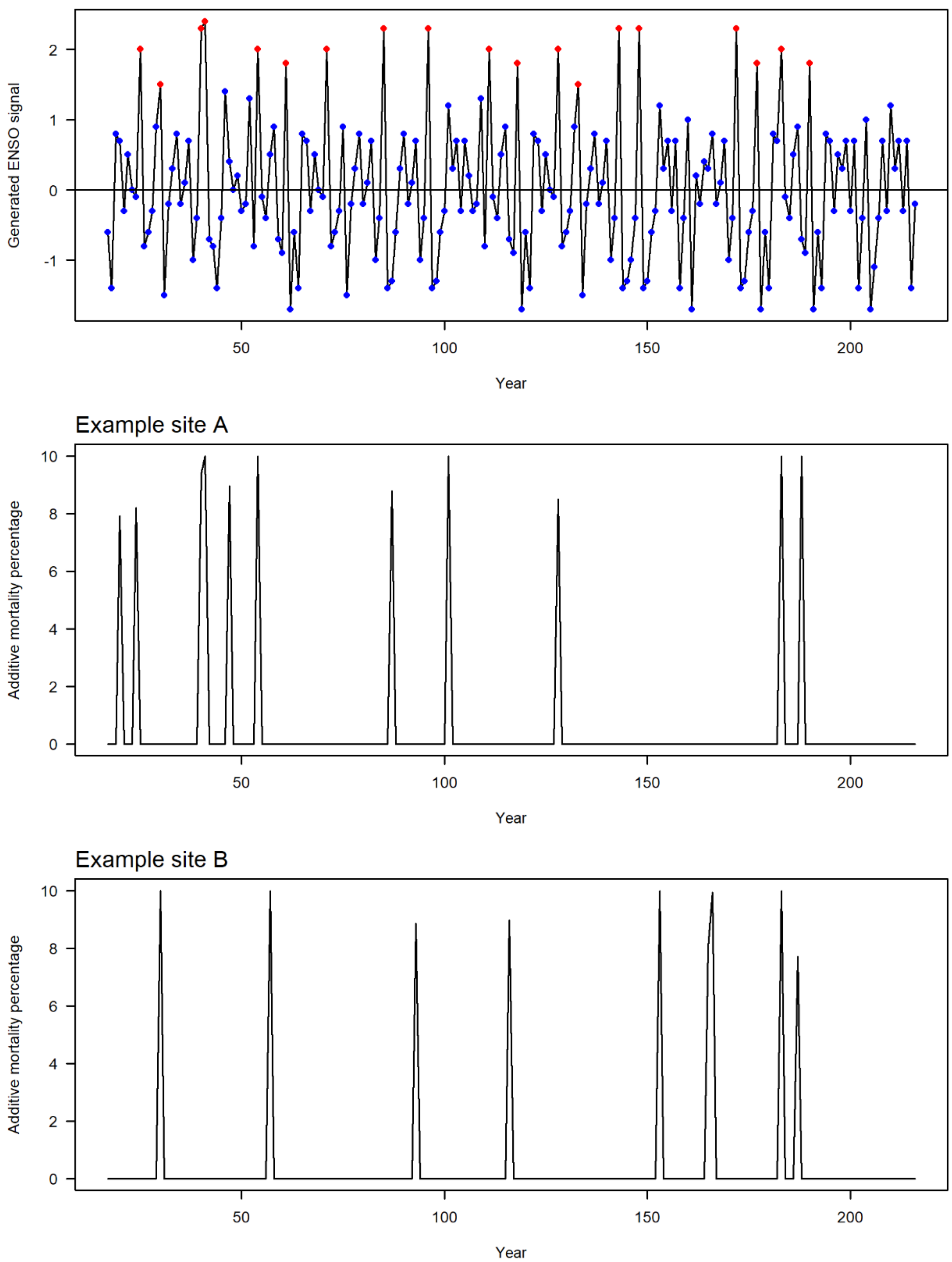


Figure A2.2. Example of time-varying pattern in natural mortality in relation to generated ENSO signal (upper panel; red circles highlight ENSO signals equal to or exceeding a value 1.5). Cholesky transformation is used to generate an intermediate signal (not shown) with a positive correlation of 0.5 with ENSO signal, then additive environmental M (lower two panels) are triggered according to the intermediate signal (see Equations 7 & 8). This approach results in occurrence of site-specific additive environmental M that are correlated across sites (lower two panels show two different sites A and B) and with the original ENSO signal.

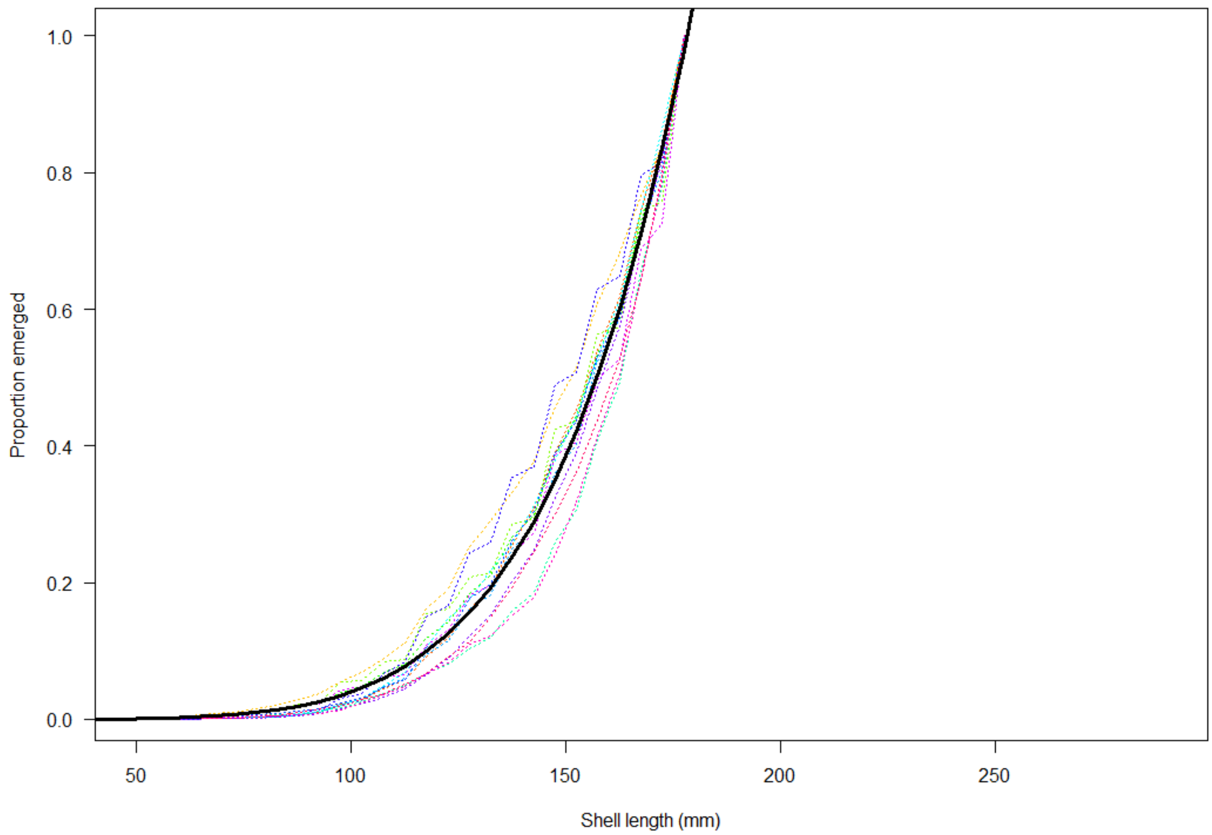


Figure A2.3. Proportion emerged-at-length (solid line) estimated using as an exponential function against empirical emergence patterns obtained from CDFW and RCCA length frequency sampling (dotted lines; each line is a different site: Caspar Cove, Russian Gulch, Mendocino Hdlnds, Van Damme, Arena Cove, Sea Ranch, Salt Point State Park, Ocean Cove, Stillwater Cove, Fort Ross, Bodega Head, Todd's Point, Timber Cove).

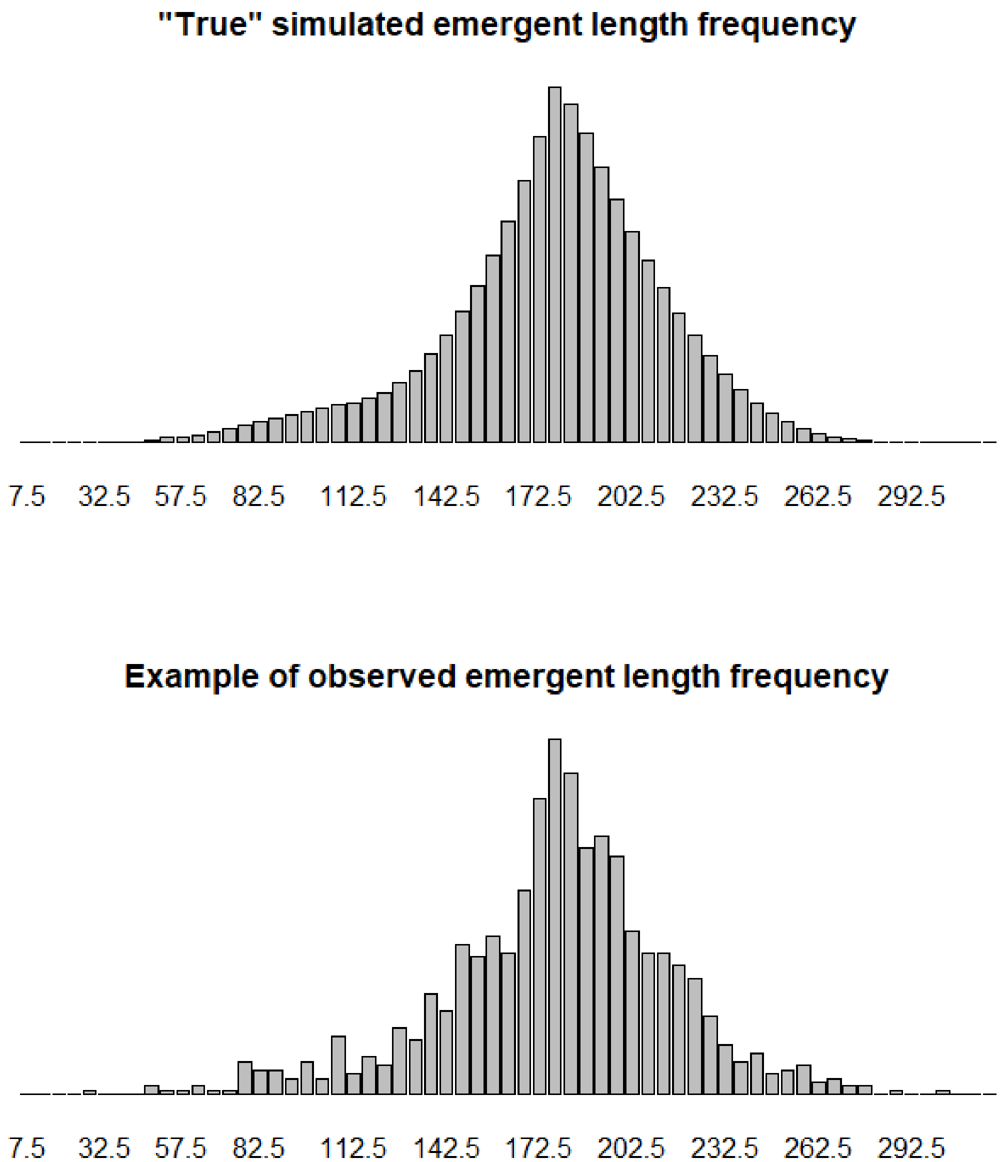


Figure A2.4. Example of emergent length frequency distribution obtained from the operating model (upper), and the same example observed through the lens of sampling of length-frequencies (lower). The right-side of the length frequency distribution (i.e., > 178 mm) includes effect fishing and the stock is depleted to 30% of its unfished level.

Technical appendix 3. Operating model – specifying historical trends

Like other data-limited fisheries, historical trends in abundance are not well established for red abalone. Historical trends are used to initialize the simulation prior to the application of a management strategy. A scenario is re-constructed about red abalone stock dynamics from 2002 to 2017. Reconstruction was based on fishery-independent data sets from California Department of Fish and Wildlife (CDFW), Reef Check California (RCCA) and the catch history from the fishery. Tuning is a coarse visual process, with the goal of approximately reproducing historical patterns. This is carried out by modifying site-specific unfished recruitment (R_0), initial depletion, and magnitude of known mass mortality events during 2002 to 2017. This appendix is structured as follows. First, data-limited assessment methods are described that were used to gain insight into historical stock size and depletion. Second, the process of model tuning is described in relation to quantities obtained from data-limited assessment and from information about mass mortality events. Finally, a summary of how the historical dynamics are generated during each simulation run is provided.

Derived quantities used in model tuning

Measuring relative stock status

In model tuning, estimates of spawning potential ratio (SPR) are used as a measure of relative stock status. Full details regarding calculation of density estimates can be found in Technical Appendix 1. In brief, SPR was estimated using the LB-SPR approach, consistent with the approaches Hordyk et al. (2015) and Prince (2016).

Scaling stock size using maximum sustainable yield estimates

The operating model requires use of site-specific unfished recruitment (R_0) that scales relative abundance trends to absolute stock size at each site. This parameter was estimated using two data-limited assessment methods, each of which provides a site-specific estimate of maximum sustainable yield (MSY; in numbers of red abalone). After obtaining MSY, the operating model was tuned so that site-specific R_0 produced the corresponding estimate of MSY. Estimates of MSY were obtained using observed site-specific catch histories and the data-limited methods known as DB-SRA and catch-MSY. Ultimately, R_0 was tuned using MSY estimates from DB-SRA because this model accounts for skewness of the surplus production curve (i.e., the quantity *Bmsy/K*), which is fixed at 0.5 in Schaefer form of surplus production used by catch-MSY. However, catch-MSY was useful as a comparison and MSY estimates were similar between approaches (Fig. A3.1).

DB-SRA is implemented by specifying a catch history, priors for depletion during in the initial and a reference year, a prior for *Bmsy/K*, natural mortality, and age-at-50% maturity. The latter two quantities were specified as 0.09 year^{-1} and 7 years. A uniform prior for *Bmsy/K* was specified with a range of 0.3 to 0.6. Priors for depletion were specified in two parts. In the first part, MSY was estimated for sites that have SPR estimates. It was assumed that depletion was relatively stable prior to 2011, thus for each site with SPR estimates available between 2002 and 2010, the minimum and maximum values ±0.1 were used as an uncertainty range. SPR was converted to depletion as:

$$D = \left(4hSPR + h - 1\right) / \left(5h - 1\right), \tag{13}$$

where h is steepness and a value of 0.7 was used. If a site had only one SPR estimate between 2002 and 2010, its value ±0.2 was used. The specified prior was used for both depletion during in the initial and a reference year, which was specified for 2005. In the second part, MSY was estimated for the remaining sites. After estimating MSY for sites with SPR, the posterior distribution obtained from DB-SRA for the reference depletion year (pooled estimates across sites with SPR estimates) was applied to all other sites.

Catch-MSY is a numerical routine that identifies plausible combinations of intrinsic rate of increase r and unfished vulnerable stock size $B0$, given the site-specific input of a catch history. Given these outputs, MSY is calculated as $rK/4$. The estimation routine proceeds by drawing samples from specified prior distributions for r and $B0$. Using the Schaefer surplus production model, re-constructed stock size trends are compared against plausible benchmarks for depletion in the initial year and final year of the time series. Parameter combinations of r and $B0$ that satisfy plausibility criteria about stock depletion are retained. Plausible parameter ranges for depletion in the initial year and final year are required as uniform priors. These priors were specified similar to the approach used in DB-SRA, where site-specific uncertainty ranges were specified for sites with SPR estimates. The remaining sites were assigned a uniform prior as the centered 95% of all available SPR estimates (converted to depletion via Equation (1)). MSY was initially calculated separately for each site, and then re-calculated using an informative prior on r. Given that red abalone catches were available for 56 sites, we leveraged information across sites to develop an informative prior for r, which occurred in two steps. First, 10,000 draws of r from a diffuse prior (Uniform[0.05, 0.15]) were made and identically applied to each site. Second, the subset of those 10,000 draws that satisfied the plausibility criteria for at least 25% of sites were retained and the remaining r values were discarded. The retained r values were used as an informative prior and re-applied to each site, producing final estimates of MSY. This approach gleans information about r from sites where catch histories are informative about this quantity, and then leverages this information to produce derived quantities for each site.

Density estimates

Red abalone density estimates were used in model tuning. Full details regarding calculation of density estimates can be found in Technical Appendix 1. In brief, density estimates were obtained based on a model selection exercise to evaluate the right-skewed and zero-inflated nature of these data, to determine the best approximating sampling distribution(s). Statistical distributions of the forms normal, log-normal, Poisson, zero-inflated Poisson, and zero-inflated log-normal were fit to count data for each survey (for each site and year combination) and Akaike Information Criteria was used to identify the 'best approximating model'. Density estimates were obtained using a zero-inflated log-normal approach (Lo et al. 1992, Hall 2000, Warton 2005).

Model tuning process

Model tuning was initiated by determining site-specific unfished recruitment (R_0) that produced MSY estimates obtained from DB-SRA. Tuning to time-series information was carried out using RCCA data for years 2007 to 2017 and CDFW data for years 2002 to 2017. Initial depletion was adjusted in a manner that produced relative stock status that was reflective of estimates of spawning potential ratio (SPR) (Fig A3.2). In addition, initial depletion at sites where SPR estimates were not available were tuned so that (1) SPR of these sites was reasonably consistent with other sites in the same region, (2) catches were reproducible, and (3) fishing mortality was approximately reflective to the magnitude of historical catches at a given site in relation to other sites in the region (Figs. A3.3 & A3.4). Tuning of historical dynamics also required accounting for anomalous mass mortality events. These events were specified in addition to ENSO-driven increases in natural mortality, which occur throughout the time series (i.e., both historical time period and forward forecast time period). Rogers-Bennett et al. (2019)

report an average reduction in density of 35% during 2011 resulting from a harmful algal bloom occurring close to Sonoma county. We translated this quantity into an additional instantaneous mortality rate of 0.43 $year^{-1}$ and applied this quantity to all size classes in 2011. In addition, RCCA and CDFW density estimates for 2015 through 2017 indicated a downward trend, which could be a result of unfavorable environmental conditions. We addressed this trend by imposing an additional instantaneous mortality rate of 0.3 $year^{-1}$, which through visual tuning, caused density trends in the operating model to approximately reflect those observed in RCCA and CDFW data (Fig. A3.5). Thus, the overall process of tuning resulted in reproduction of historical catches, depletion levels that were consistent with expectations about SPR, and relative abundance trends consistent with observed red abalone density d (Fig. A3.2, A3.5, A3.6, A3.9). Parameters related to initial conditions can be found in Table A3.1.

Simulation of historical dynamics

The operating model contains three time-varying stochastic components: recruitment variation, and growth (asymptotic length) and natural mortality. These stochastic components are generated during all time steps, including during the historical dynamics. Thus, each run produces a slightly different historical pattern (Fig. A3.7). For contrast, a deterministic recovery is also shown (Fig. A3.8).

Given that each run is dynamic, simulating the correspondence between historical density and historical emergent abundance requires that the catchability coefficient, q, is calculated at the end of historical time period during each run. This is done by calculating q as a proportionality constant using an intercept-only linear model. Catchability is calculated separately for each site where sampling occurs. This is a form of dynamic tuning that ensures that simulated density is scaled relative to historical observations.

Table A3.1. Parameter values related to initial model conditions. Average exploitable abundance and average fishing mortality (F) are presented as averages since these quantities varying slightly according to stochastic elements of each simulation run. R0 is unfished recruitment; Req is equilibrium recruitment in the initial year; average exploitable abundance refers to equilibrium abundance in the initial year; average initial F is equilibrium F in initial year.

Report card site	Initial depletion	R0	Req	Average exploitable abundance	Average initial F
Crescent_City	0.8	51075.44	49743.04	6698.871	0.01
Other_Del_Norte	0.6	18349.02	17125.75	1951.266	0.04
Patricks_Pt	0.6	166051.6	154981.53	19034.725	0.04
Trinidad	0.6	94047.33	87777.5	9762.927	0.04
Punta_Gorda	0.8	237671.8	231471.67	31613.907	0.01
Shelter_Cove	0.6	847219.8	790738.46	90427.816	0.04
Other_Humboldt	0.8	182927.2	178155.22	24204.855	0.01
Bear_Harbor	0.9	115627.8	114267.42	17168.074	0.01
Usal	0.8	73938	72009.18	9477.985	0.01
Hardy_Creek	0.6	400499.9	373799.9	42890.996	0.04
Abalone_Point	0.5	857394.2	774420.59	78880.178	0.06
Westport	0.7	509128.3	486776.32	62762.646	0.03
Bruhel_Point	0.7	185626.5	177477.08	22992.587	0.03
Kibesillah	0.7	182546.2	174531.98	21940.9	0.03
MacKerricher	0.4	1311233	1129677.44	101708.509	0.08
Glass_Beach	0.6	1653458	1543227.29	180121.875	0.04
Georgia_Pacific	0.4	1947910	1678199.26	154377.284	0.08
Todds_Point	0.15	3922100	2440417.7	115740.876	0.33
Hare_Creek	0.4	1389545	1197146.09	111595.77	0.08
Mitchell_Creek	0.6	790831.5	738109.42	83451.97	0.04
Jughandle	0.4	1577187	1358807.24	123965.787	0.08
Caspar_Cove	0.35	1733380	1445712.63	121444.128	0.10
Russian_Gulch	0.7	1821390	1741426.47	216093.999	0.03
Jack_Peters_Gulch	0.6	1190762	1111377.54	125715.684	0.04
Mendocino_Hdlnds	0.6	2023789	1888869.91	224907.353	0.04
Gordon_Lane	0.5	966936.8	873362.29	93286.5	0.06
Van_Damme	0.7	2857860	2732393.15	347222.38	0.03
Dark_Gulch	0.5	1327024	1198602.38	120239.408	0.06
Albion_Cove	0.4	2074026	1786853.16	161396.98	0.08
Salmon_Creek	0.7	455490.5	435493.31	54741.681	0.03

Navarro_River	0.4	989329.9	852345.76	73521.644	0.08
Elk	0.4	2213412	1906939.73	173092.732	0.08
Point_Arena_Lighthouse	0.2	2062054	1443437.49	77991.377	0.23
Arena_Cove	0.2	4165450	2915815.09	165072.625	0.22
Moat_Creek	0.4	3042642	2621352.88	233525.925	0.08
Schooner_Gulch	0.6	151847.3	141724.15	15635.604	0.04
Saunders_Landing	0.6	259938.8	242609.52	28660.791	0.04
Anchor_Bay	0.4	1361958	1173379.44	104545.877	0.08
Robinson_Pt	0.6	388723.3	362808.44	41180.9	0.04
Gualala_Point	0.8	241990.2	235677.45	32511.488	0.01
Sea_Ranch	0.55	2700395	2482750.79	268722.556	0.05
Black_Point	0.8	76659.24	74659.43	10286.587	0.01
Stewarts_Point	0.8	361065.6	351646.52	46769.56	0.01
Rocky_Point	0.6	87272.66	81454.48	9548.692	0.04
Horseshoe_Cove	0.8	389488.7	379328.12	52785.111	0.01
Fisk_Mill_Cove	0.4	1718311	1480390.83	129106.436	0.08
Salt_Point_State_Park	0.6	1579151	1473874.43	164879.166	0.04
Ocean_Cove	0.45	1377940	1218388.68	110907.403	0.07
Stillwater_Cove	0.35	1184985	988327.75	76098.165	0.10
Timber_Cove	0.65	1787663	1690153.96	201127.406	0.03
Fort_Ross_&_Reef_Campground	0.2	13478619	9435033.53	492294.534	0.23
Jenner	0.5	752933	680068.54	70501.968	0.06
Bodega_Head	0.8	168076.9	163692.27	22013.633	0.01
Tomales_Point	0.5	577906	521979.64	52859.527	0.06
Point_Reyes	0.9	91010.57	89939.86	13170.756	0.01
Other_Marin	0.8	130349.6	126949.2	17284.444	0.01

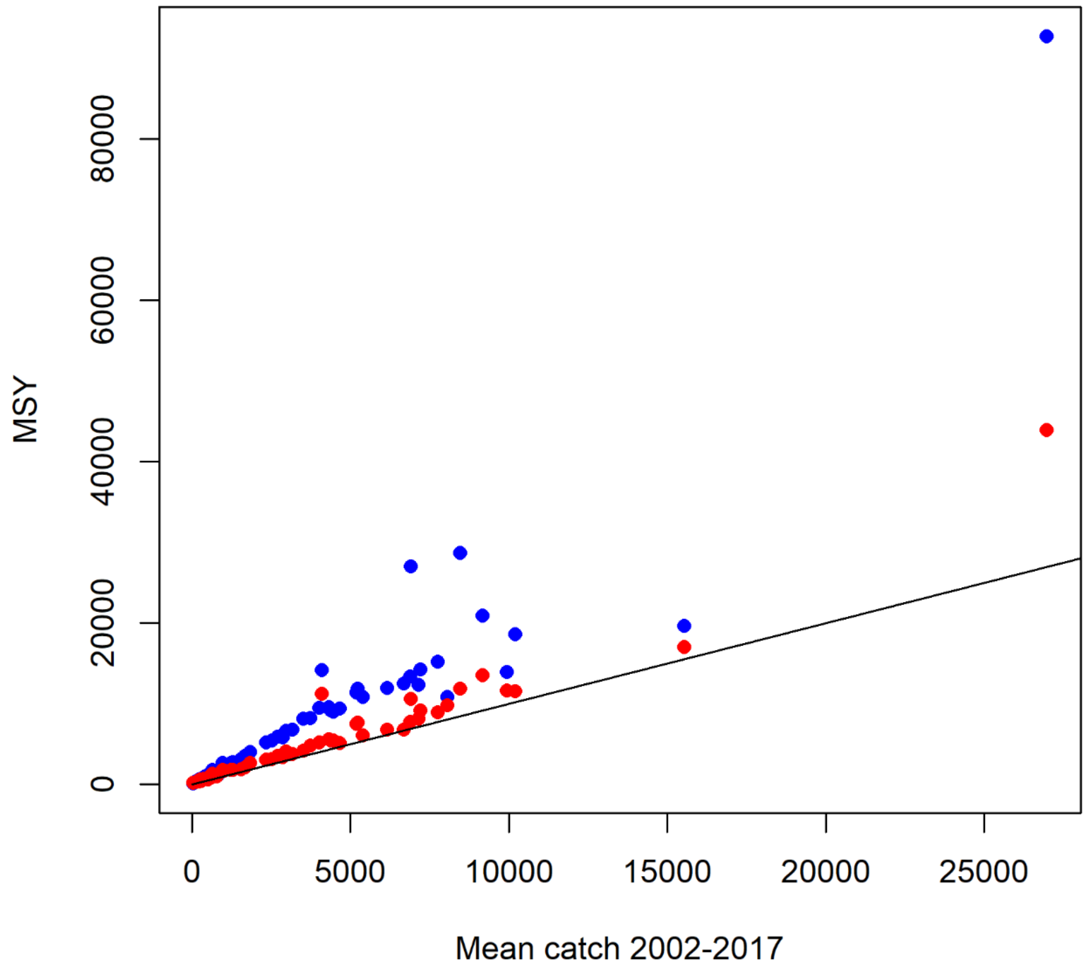


Figure A3.1. MSY estimates from DB-SRA (blue dots) and catch-MSY (red dots) against mean catch for each 56 sites.

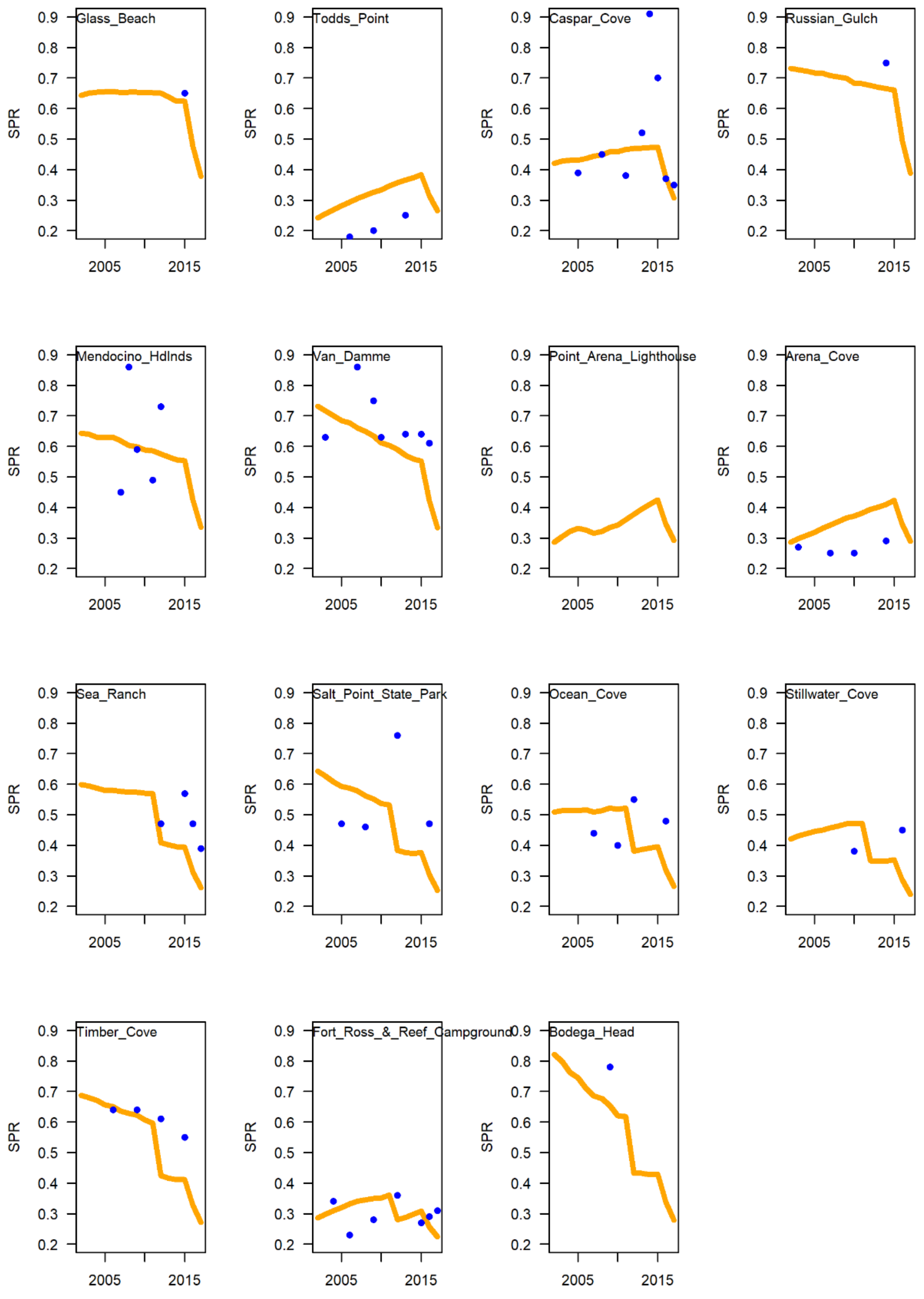


Figure A3.2. Simulated SPR (lines) and estimates of SPR from observed length frequency distributions (squares).

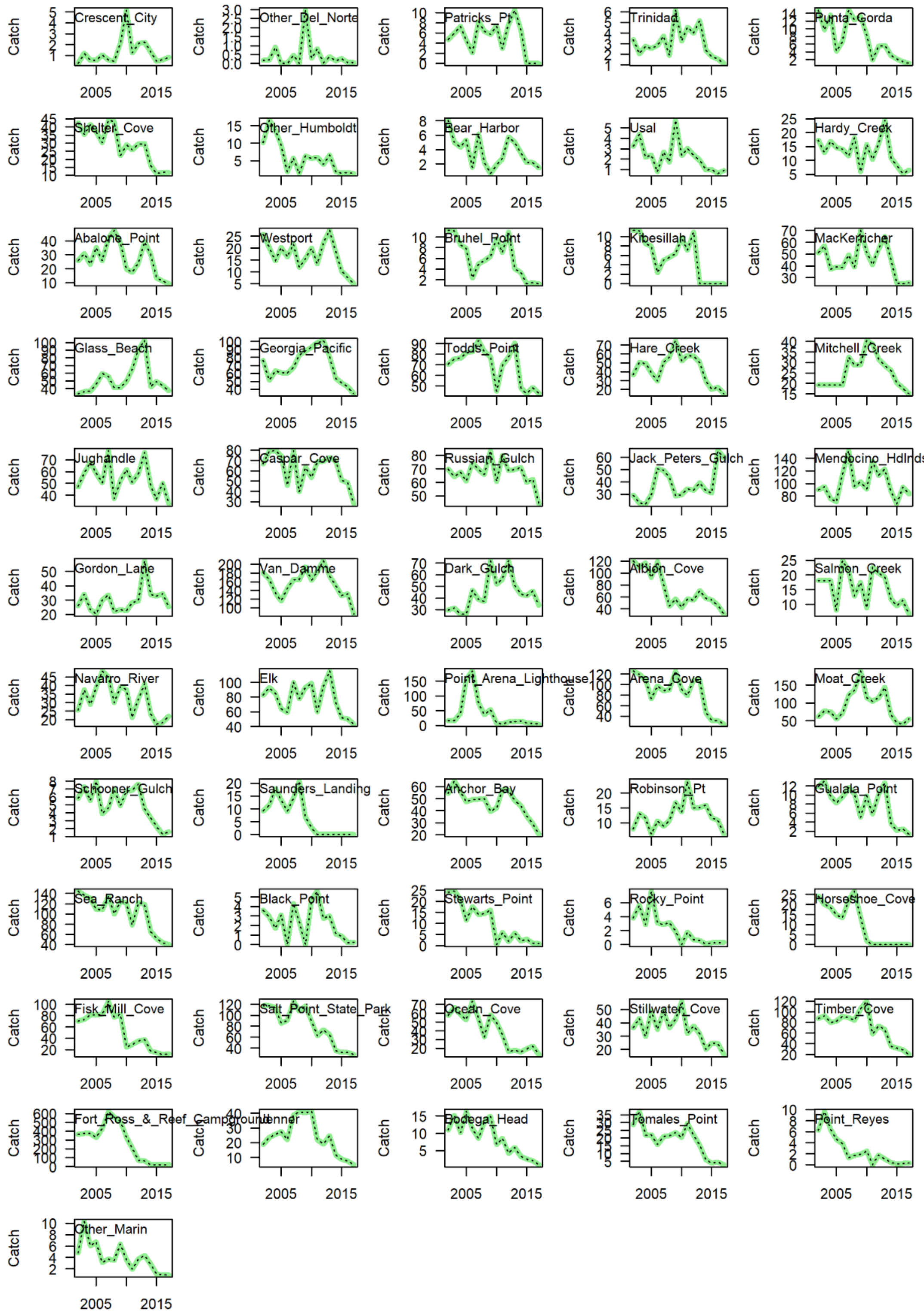


Figure A3.3. Reproduction of catches in simulations in numbers x 100 (solid lines) and observed catches during historical tuning time period (dotted lines).

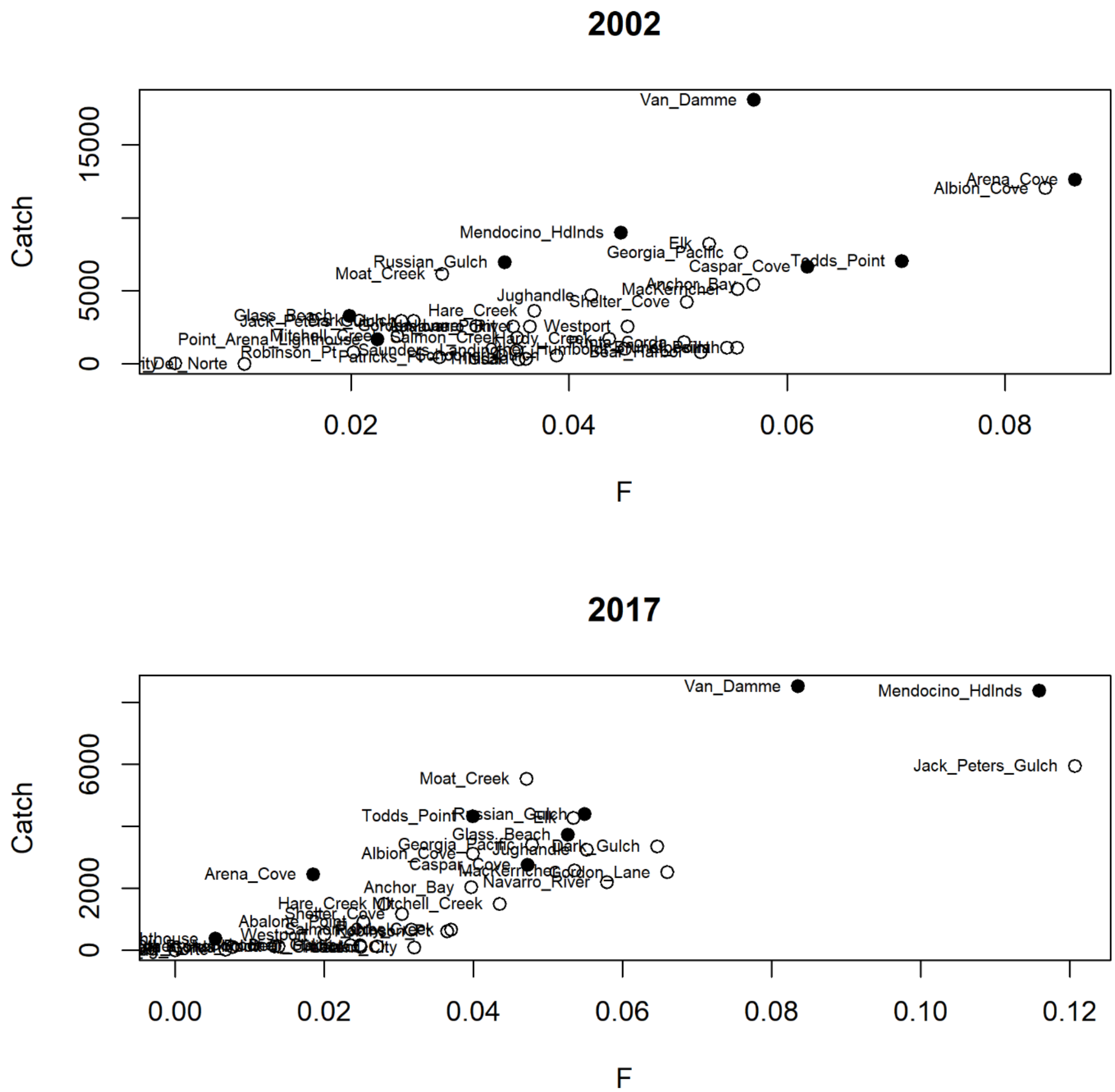


Figure A3.4. Mendocino and northward region. Initial (2002) and terminal (2017) fishing mortality estimates (F year^{-1}) of the historical time period resulting from model tuning. Fishing mortality plotted in relation to catch (numbers of red abalone) in the corresponding year. Closed circles are sites where sampling occurred by either RCCA or CDFW.

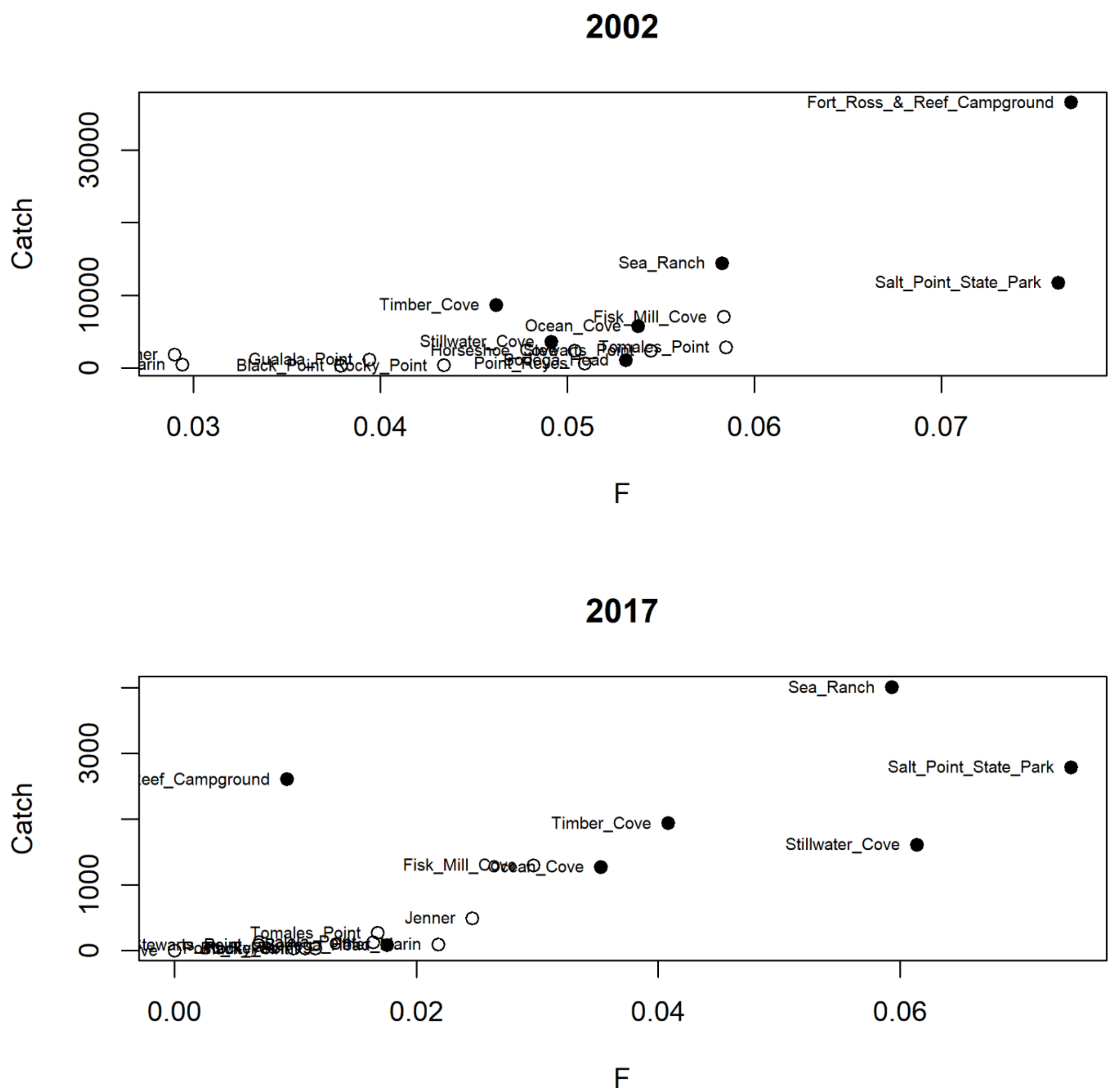


Figure A3.5. Sonoma and southward region. Initial (2002) and terminal (2017) fishing mortality estimates (F year^{-1}) of the historical time period resulting from model tuning. Fishing mortality plotted in relation to catch (numbers of red abalone) in the corresponding year. Closed circles are sites where sampling occurred by either RCCA or CDFW.

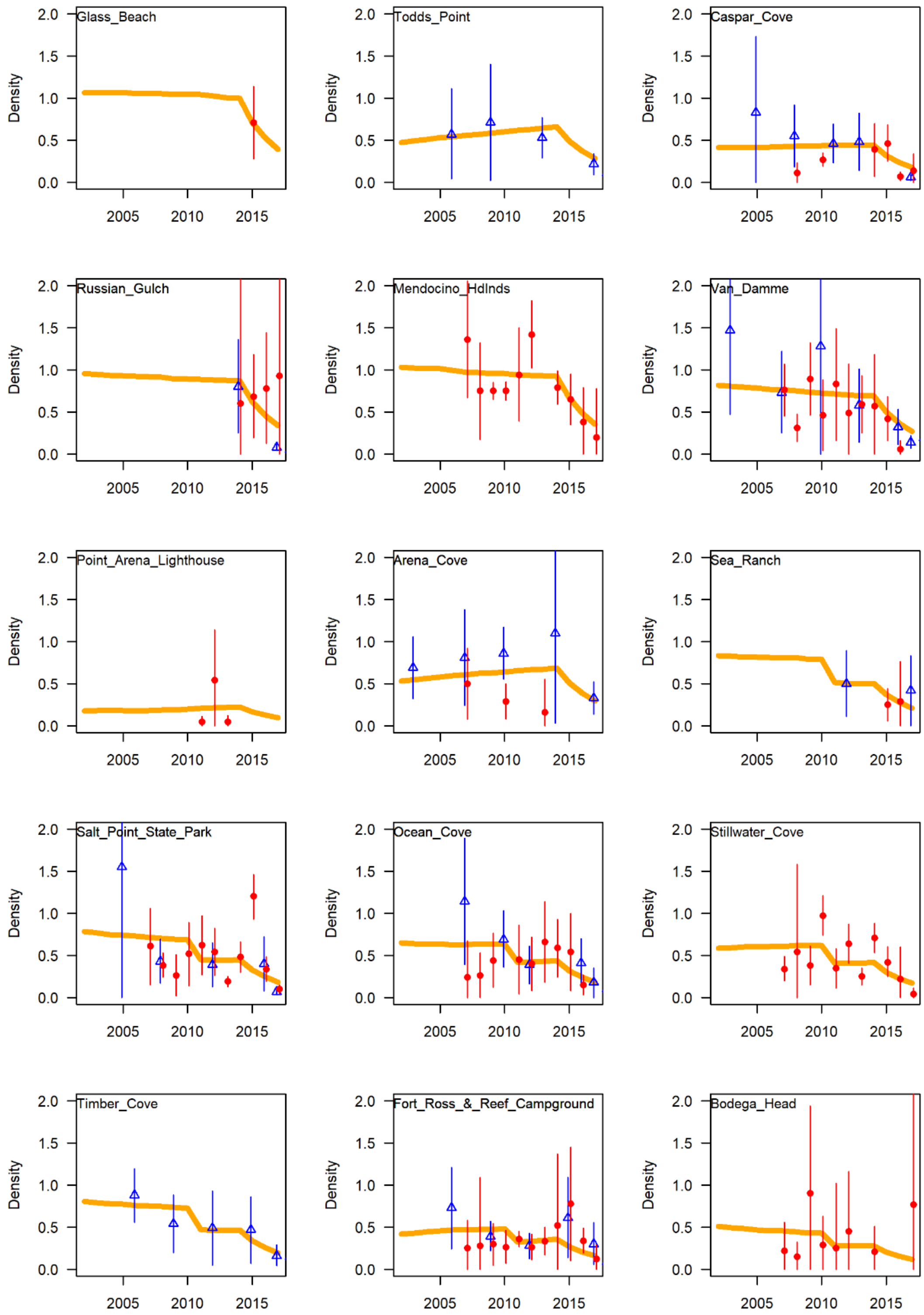


Figure A3.6. Simulated density (emergent abalone / m^2; lines) and density from CDFW (blue triangles with 95% confidence intervals) and Reef Check field sampling (red circles with 95% confidence intervals).

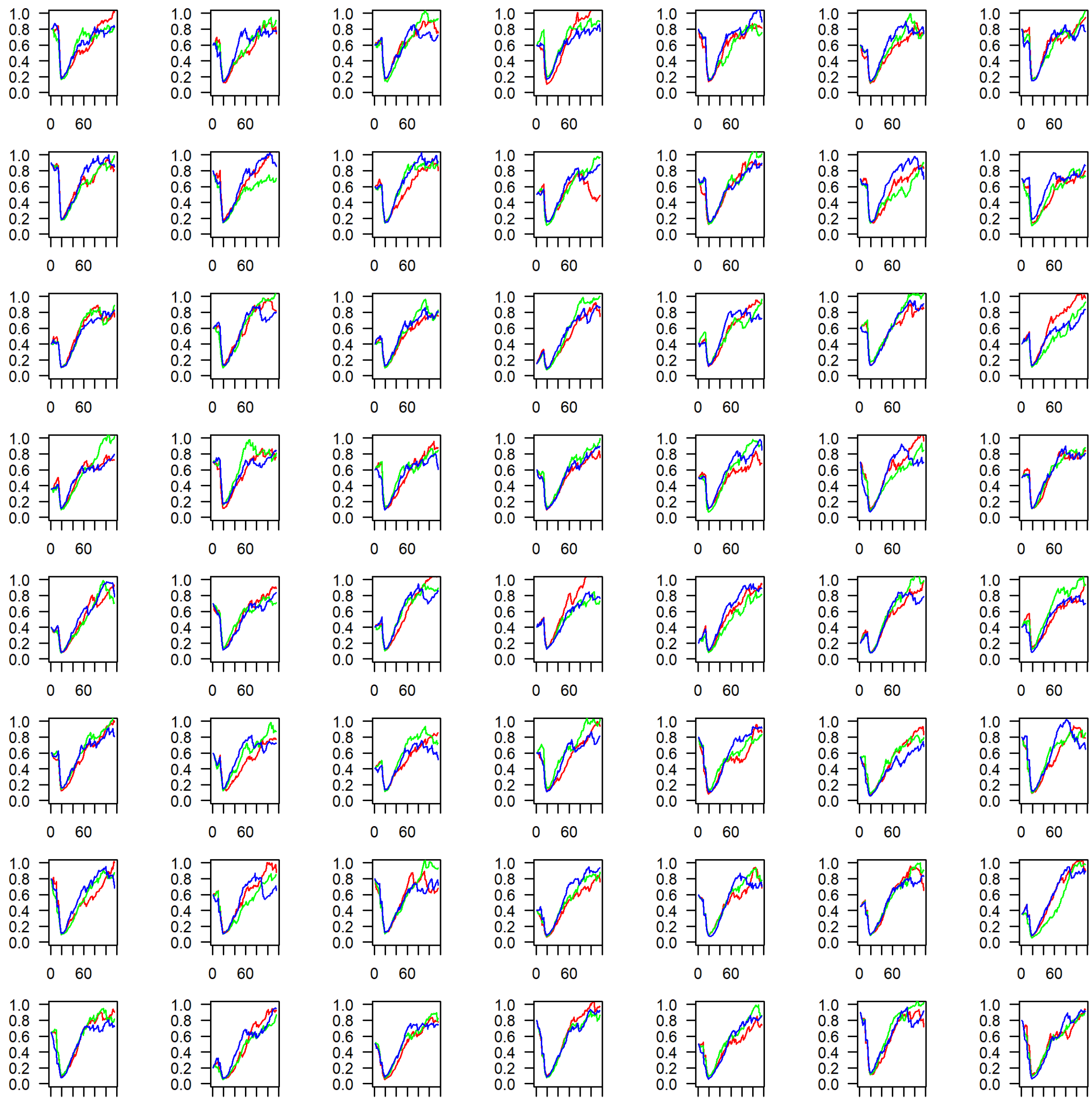


Figure A3.7. Cursory demonstration of stochastic nature of simulation runs. Each of the 56 plots is an abalone report card site. Y-axis is depletion, x-axis is year. Each simulation consists of a 16 historical time period, prior to forward forecast, three simulations are shown in each plot. In this example, there is no fishing during the forward forecast, thus the stock begins to return towards an unfished state.

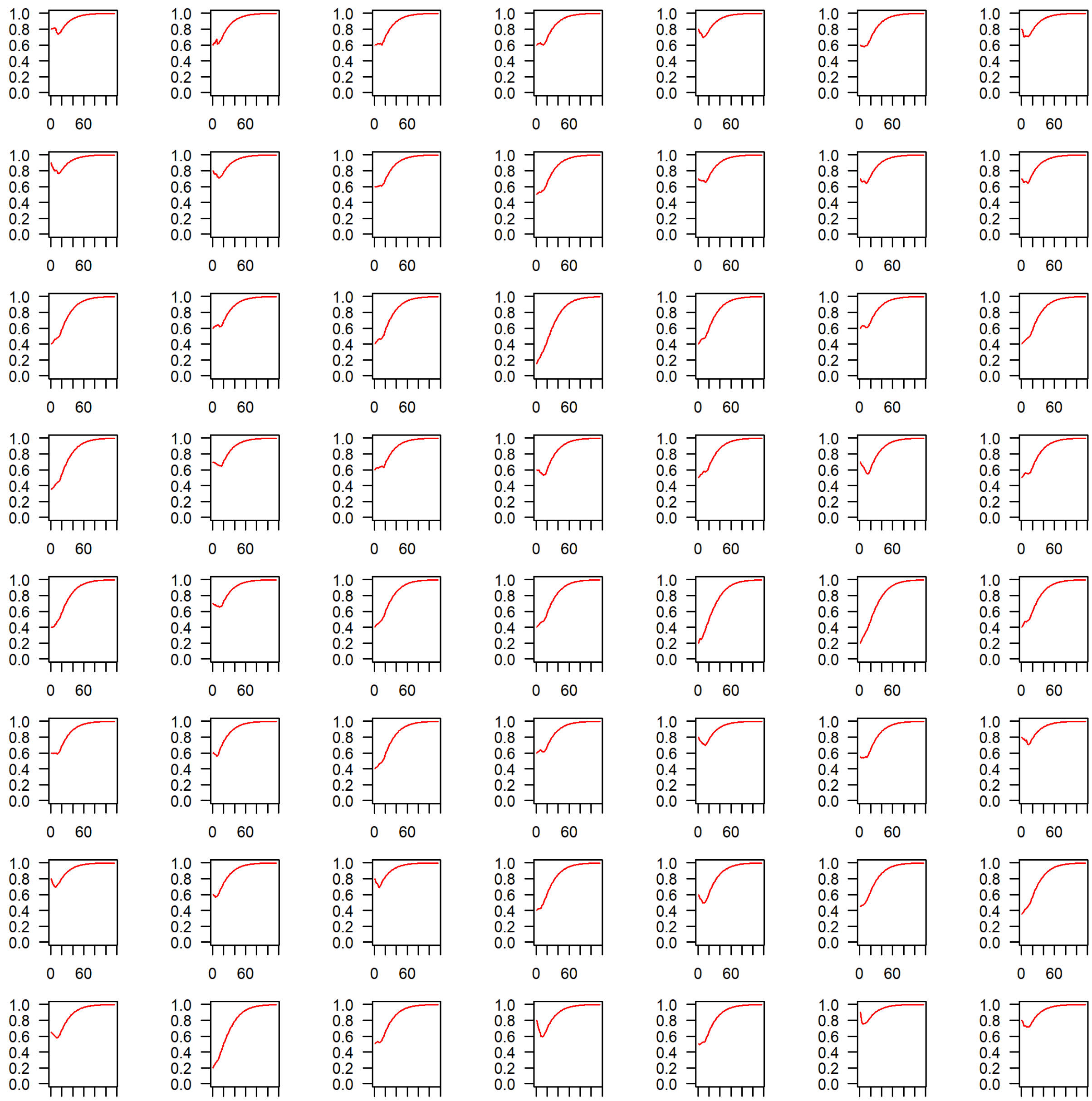


Figure A3.8. Demonstration of deterministic stock recovery. Each of the 56 plots is an abalone report card site. Y-axis is depletion, x-axis is year. Each simulation consists of a 16 historical time period, prior to forward forecast. In this example, there is no fishing during the forward forecast, thus the stock begins to return towards an unfished state.

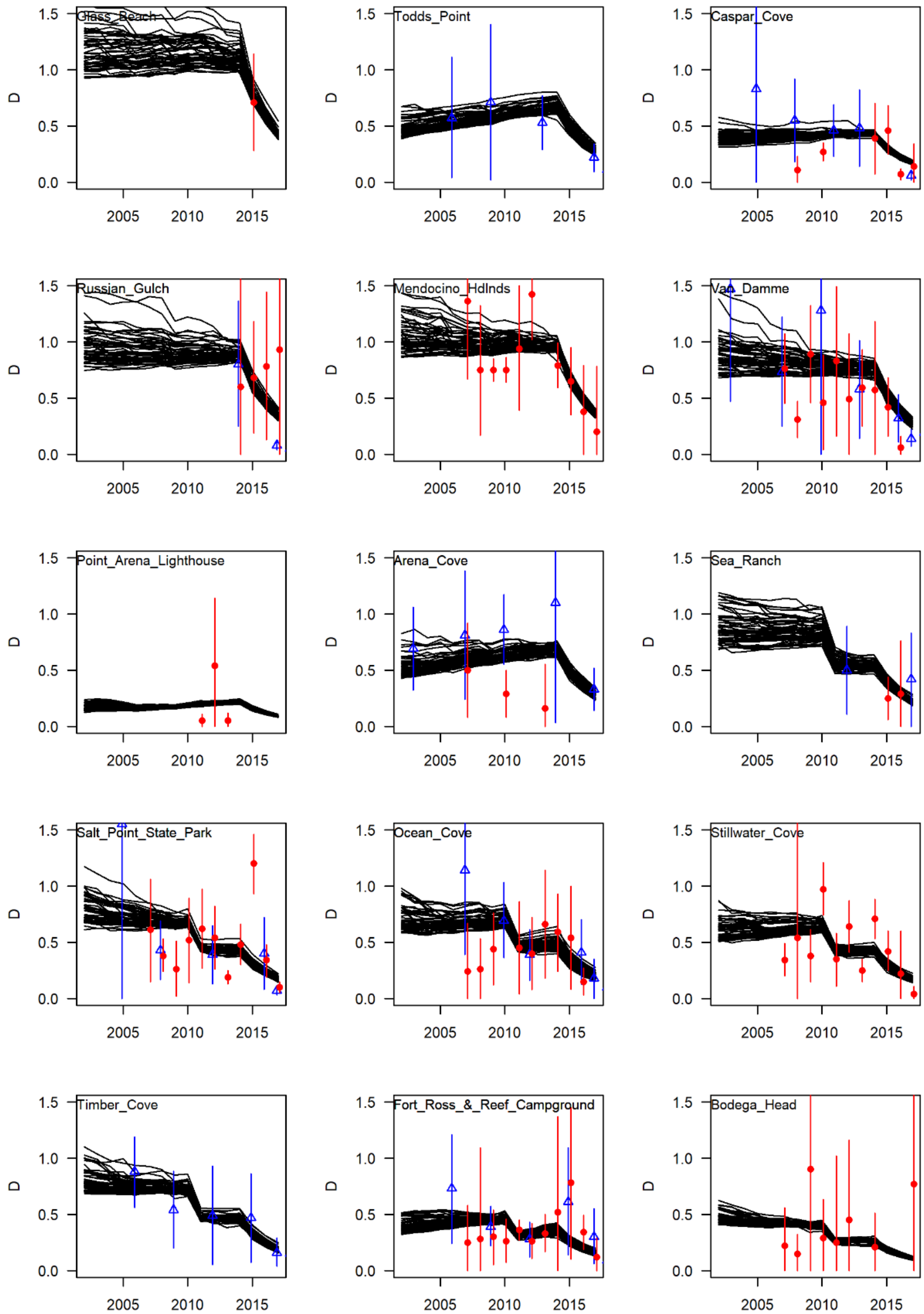
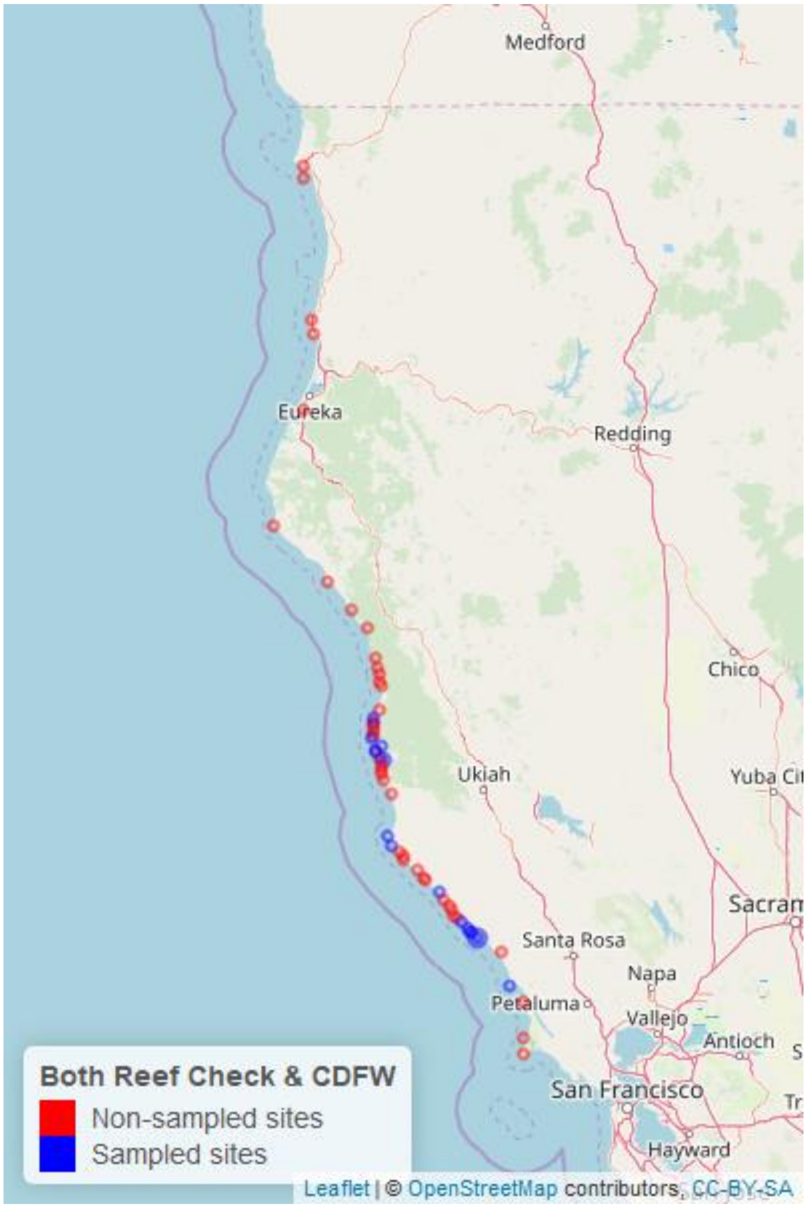


Figure A3.9. Stochastic historical trends used in MSE. Simulated density (emergent abalone / m^2; lines) and density from CDFW (blue triangles with 95% confidence intervals) and Reef Check field sampling (red circles with 95% confidence intervals). Shown are 50 simulation runs (black lines).

Technical appendix 4. Maps

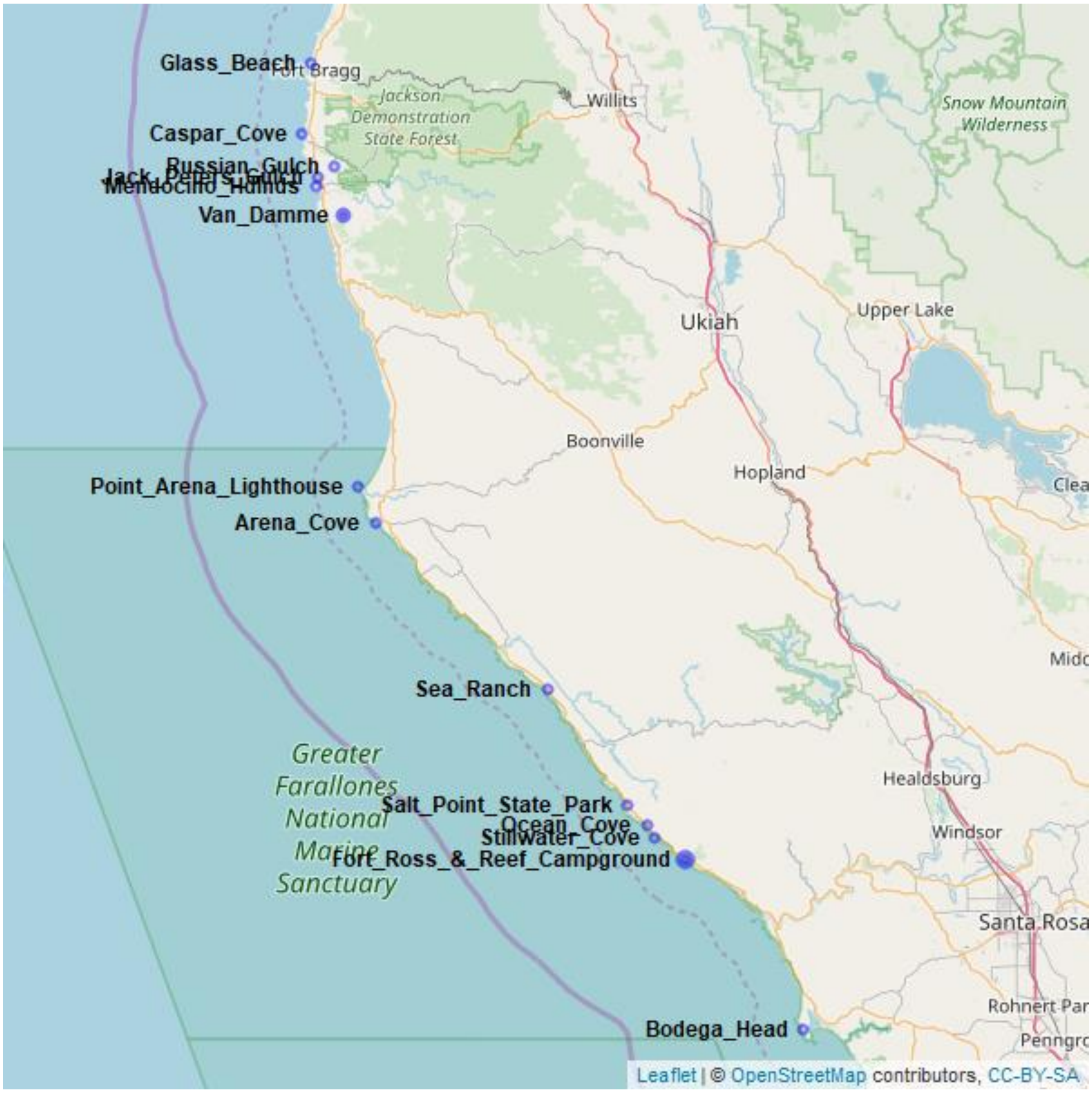
To aid in policy discussions, maps of approximate field sampling locations are provided. These maps show the approximate sampling locations of CDFW and Reef Check California as they were represented in the management strategy evaluation (MSE). Note that the terminal data year for data inputs to the MSE was 2017, thus only sites visited as of 2017 were included in the MSE (and are shown in the maps). Please note that Reef Check sometimes uses site naming conventions that differ from the red abalone report card sites. However, for purposes of conducting MSE, each Reef Check site was associated with a nearby report card site. The maps are presented using the report card site format.

Please note that a mapping website has also been created that allows users to zoom in/out and click on sites for identification. You may find that the website is more user friendly than the map images presented in this appendix.
https://harford.shinyapps.io/california_redabalone/



Map 1. Red abalone report card sites of the northern California coastline.

Map 2. Report card sites that are sampled by CDFW. These are known as index sites.



Map 3. Report card sites that are sampled by Reef Check California.