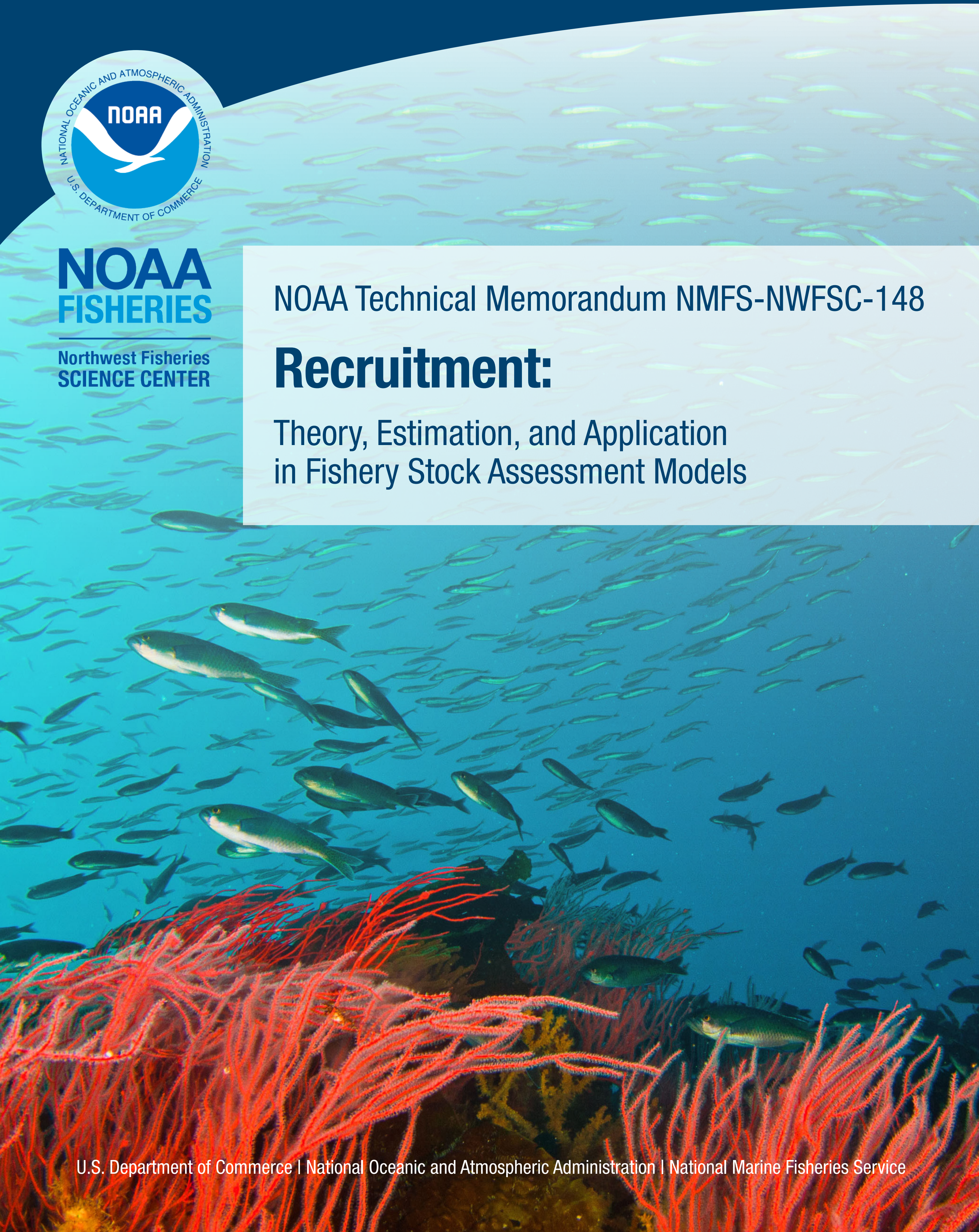

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Recruitment:

Theory, Estimation, and Application in Fishery Stock Assessment Models

U.S. Department of Commerce | National Oceanic and Atmospheric Administration | National Marine Fisheries Service

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https://doi.org/10.25923/1r2p-hs38

Edited by Rishi Sharma,[1] Clay E. Porch,[2] Elizabeth A. Babcock,[3] Mark Maunder,[4] and André E. Punt[5]

Conservation Biology Division
[1]Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

Sustainable Fisheries Division
[2]Southeast Fisheries Science Center
75 Virginia Beach Drive
Miami, Florida 33149

Rosenstiel School of Marine and Atmospheric Science
[3]University of Miami
4600 Rickenbaker Causeway
Miami, Florida 33149

Inter-American Tropical Tuna Commission
[4]8901 La Jolla Shores Drive
La Jolla, California 92037

School of Aquatic and Fishery Sciences
[5]University of Washington
1122 Northeast Boat Street
Seattle, Washington 98195

March 2019

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Northwest Fisheries Science Center
https://www.nwfsc.noaa.gov/index.cfm

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Cover image: Fish schooling near Catalina Island, Southern California. Photograph by A. Obaza, NMFS/WCR.

Reference this document as follows:

Sharma, R., C. E. Porch, E. A. Babcock, M. Maunder, and A. E. Punt, editors. 2019. Recruitment: Theory, Estimation, and Application in Fishery Stock Assessment Models. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-148. https://doi.org/10.25923/1r2p-hs38

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Executive Summary

The Center for the Advancement of Population Assessment Methodology (CAPAM) hosted a technical workshop on Recruitment: theory, estimation, and application in fishery stock assessment models in Miami, Florida, USA, from 30 October to 3 November 2017. The recruitment workshop was the fourth in a series organized by CAPAM as part of its Good Practices in Stock Assessment Modeling Program for improving fishery stock assessments. The workshop was sponsored by NOAA and the University of Miami via the Cooperative Institute for Marine and Atmospheric Science (CIMAS).

The primary goal of the workshop was to provide advice and guidance on practices for modeling recruitment in fishery assessments. The focus was on model specification, parameter estimation, and management consequences. The five-day forum included an interactive modeling session, six keynote addresses, and 30 research presentations; discussions focused on major topics, from describing mechanistic properties of recruitment to time series modeling and management implications. Ninety-five attendees registered, and an average of 20 people were online at any given time. A special issue in the journal *Fisheries Research* finalized in March 2019 features articles from the workshop.

This report summarizes the presentations and discussions made during the workshop. As such, it represents the general views of the editors, rather than any achieved consensus set of recommendations. Several important research topics on recruitment are identified to guide further research, along with recommended practices to consider when developing stock assessment models.

Some of the key recommendations discussed at the workshop were:

1. It is important to have good fishery-independent recruitment information, not only for improving assessment models, but also as the basis for an early warning sign. A series of low recruitments is often the first indication that a stock is in trouble. Waiting until the signal is observed in the catch data (if the data are good enough to show it) can be too late.
2. Each assessment should describe the recruitment process, and evaluate alternative hypotheses and what they imply about the stock–recruitment relationship.
3. In cases where the parameters of the stock–recruitment relationship are considered estimable, log-likelihood profiles and other diagnostic tools should be examined to determine how reliable the estimates are. A useful diagnostic, when possible, is to compare the average recruitment (or bias-adjusted deviates, if using a stock–recruitment relationship) over a period where recruitment is considered likely to fluctuate about R_0.
4. Random effects models should improve the estimability of the parameters of the stock–recruitment relationship and σ_r in principle, but will not resolve the problem if the data are not informative.
5. Include and estimate autocorrelation about the stock–recruitment relationship within the assessment. Autocorrelation reduces short-term uncertainty, but increases uncertainty in long-term projections.

6. The effects of assuming alternative stock–recruitment models should be evaluated, unless there is clear reason to expect that the chosen model is correct.
7. In many cases, it will be more cost-effective to develop management procedures and harvest control rules that are robust to recruitment uncertainty, rather than attempting to incorporate that uncertainty into assessment models.
8. Continued research on environmental drivers and spatial dynamics influencing recruitment should be encouraged.

Introduction

In the opening keynote address to this workshop, Kenneth Rose described understanding recruitment as the Holy Grail of fisheries science. Indeed, the processes controlling recruitment have important implications for defining management quantities such as the maximum sustainable yield and for predicting the response of populations to proposed management actions. However, for most species, future recruitment remains essentially unpredictable. At some level, of course, recruitment must depend on the number of spawners, but the nature of that relationship is seldom obvious from the available data. Typically, spawners and recruits are not observed directly and must be inferred from models that use other sources of data, such as the age or size composition of fishery catches. Estimation is, therefore, confounded by observation errors in the data and possible misspecifications of fishery selectivity, growth, and other key model parameters. Moreover, the mechanisms that control recruitment may change through time, further complicating estimation and adding uncertainty to long-term predictions.

Three general approaches for dealing with recruitment uncertainty have emerged. The most common has been to model annual recruitment variation as a random deviate from a stationary functional relationship between spawners and subsequent recruitment. Typically, however, the data are insufficient to reliably estimate the shape of the spawner–recruit relationship. In such cases, the usual recourse has been to adopt one of several time-honored models (usually the Beverton–Holt, Ricker, or hockey stick functions), and then to fix or impose informative priors for parameters (e.g., steepness) that do not appear to be well estimated.

The second approach has been to explicitly link recruitment variation to underlying environmental drivers. In some examples, the stock–recruitment relationship has been assumed to be stationary, and the annual deviates are modeled as functions of environmental covariates. In other examples, the parameters of the stock–recruitment relationship themselves have been allowed to vary over time, either discretely in time (regime shifts) or as functions of covariates. This approach could, in principle, allow for more adaptive management that is responsive to climate change and other factors. However, it requires a great deal more information than the first approach, and several studies have suggested it may not perform as well in practice as might be expected.

A third approach, management strategy evaluation (MSE), has also been used in recent years. Here, simulations conditioned on the available data are used to identify management procedures that perform well over a plausible range of recruitment processes and other sources of uncertainty. MSE may incorporate many of the elements of the first two approaches above, but does not necessarily use recruitment models in a predictive capacity within the management procedure.

Each of the three approaches has its own merits, and there is little consensus on the circumstances when one might be most appropriate. Certainly, the choice will depend on the legislative and management systems in place, which may not be easy to change. The aim of this workshop was therefore to help direct research in some common areas that will better inform the debate and, eventually, lead to best-practice guidance. To achieve this, the workshop was divided into five sessions covering: 1) processes driving recruitment, 2) stock and recruitment models, 3) time-varying processes, 4) spatial considerations of recruitment dynamics, and 5) management implications. Each session started with a keynote address followed by a series of contributed presentations, and then finished with a 30-minute group discussion. The end of the workshop was dedicated to discussing a series of focus questions designed to highlight some of the major issues identified during the course of the workshop.

Ninety-five scientists registered for the workshop, including an average of about 20 who participated online. Accordingly, this report summarizes the presentations and discussions from the point of view of the editors alone. It is not intended to reflect a consensus set of recommendations.

Workshop Session Summaries

Session 1: Processes Driving Recruitment

The recruitment of young animals to a population is controlled by many factors operating over a wide range of spatial and temporal scales. Some of the control mechanisms are abiotic, such as temperature or oxygen, while others are biotic (e.g., predators and prey). The biotic controls can depend on the density of recruits or be independent of it. Density-dependent controls can be compensatory, such as cannibalism or intraspecific competition, or depensatory, such as intensified predation at low densities or a reduced ability to find a mate. Understanding the roles that all of these processes play is daunting, even in the simplest of systems. In some cases, however, it may be possible to reduce the dimensionality of the problem to a few key drivers and develop models that can deliver useful predictions of recruitment.

Rose (Presentation 1) showed how mechanistic and individual-based models (IBMs) developed during the last few decades have been used to capture the complexities of recruitment in a dynamic environment and improve our understanding of the underlying processes. He provided examples from the California Current ecosystem for sardine (*Sardinops sagax caerulea*) and anchovy (*Engraulis mordax*), and in the Gulf of Mexico for spiny lobster (*Panulirus argus*). While the latter used an IBM with rule-based systems for recruitment, the former used an integrated ecosystem approach based on a physical oceanographic model to assess dynamic changes in the systems and tie them to key processes in the life histories of sardine and anchovy.

Ehrhardt (Presentation 2) pointed out that understanding surplus production is complicated by the fact that density-dependent processes operate at several life stages between spawning and recruitment. He discussed the example of Caribbean spiny lobster (*Panulirus argus*), where most countries have assumed that recruitment to their waters is largely independent of the local spawning stock owing to the extended duration of the larval phase. Consequently, the landings of most spiny lobster fisheries are not regulated based on concepts of surplus production, but on the assumption that they are recruitment-driven, with little or no fishing mortality controls and limited stock assessment initiatives. Recent evidence, however, has suggested that local retention of spiny lobster larvae may be more important than previously thought. This has to some extent reopened the debate over how best to manage spiny lobster fisheries, but better data on spawning and recruitment are needed to adequately understand the density-dependent factors that contribute to surplus production.

In the third presentation, authors Lorenzen and Camp highlighted the tendency in fisheries to divide the life cycle of exploited fish and invertebrates into a pre-recruit phase (from spawning to an advanced juvenile stage) and a subsequent recruited phase (during which the animals mature, spawn, and are fished). Most age-structured fisheries models assume that density-dependent processes operate primarily during the pre-recruit phase, but are negligible after recruitment. The authors showed that surplus production can be influenced by patterns of density-dependence throughout the life cycle, and that ignoring post-recruitment density-dependence can have profound implications for stock assessment practice. They also suggested that the age at recruitment, rather than arbitrarily being set to age-0 or -1, should be set at the age where the growth pattern is consistent with that of older fish (perhaps 20% of L_∞). This would avoid the need to model the complex density-dependent and environmental interactions that affect the growth and survival of the early life stages—although it is not always clear when density-dependent survival ends or if it occurs only as the population gets close to its carrying capacity.

During the discussion session, it was pointed out that time series observations of spawners and recruits can often be fit equally well by spawner–recruit relationships with different functional forms and very different implications for management. Accordingly, there was some agreement that process studies are needed to better inform the choice of the spawner–recruit relationship. However, such studies require a great deal more information on the effect the environment has on survival and other processes affecting different life stages (e.g., eggs, larvae, juveniles, and recruits to the fishery). Some participants suggested that it is vital to have this information, while others noted that the value of many fisheries may not justify the cost. Several participants cited recent work suggesting that recruitment determines spawning stock more than the reverse, in which case it may be more cost-effective to simply have a survey of recruits that can be included in the stock assessment and management rules. The survey would have to occur at a life stage after the main factors that influence recruitment strength have occurred, but before recruitment to the fishery.

Any investigation of recruitment processes should keep in mind its purpose. For example, attention should focus on identifying important environmental drivers, if the goal is to improve short-term catch predictions. On the other hand, gaining an understanding of density-dependent factors that determine the stock–recruitment relationship is paramount if the purpose is to optimize long-term yield. Alternatively, the purpose may just be understanding causal factors without having predictive ability, or identifying and mitigating catastrophic recruitment failures.

Possible research areas identified during the session include:

1. Quantify the tradeoffs between developing complex models that explicitly model specific processes affecting recruitment (e.g., IBMs) and using simpler spawner–recruit models that implicitly include those processes, including from the point of view of ecosystem-based fisheries management.
2. Develop recruitment indices for use in assessments that can collapse complex data on multiple spatial and temporal scales to levels relevant to stock assessments (e.g., integrating a larval survey over space and time to get an index of the whole stock's annual deviation).
3. Identify rules of thumb for determining the life stage when density-dependent effects are no longer important (e.g., 20% of L_∞).
4. Develop nonparametric techniques for modeling recruitment and nonstationary processes.
5. Understand the indirect effects of fishing on recruitment, such as changing the average size of spawners or removing spawners from areas with locally high recruitment success rates.
6. Prioritize projects to improve management in the face of shrinking budgets.

Session 2: The Stock–Recruitment Relationship

It is obvious that the number of recruits depends in some way on the number of spawners. Unfortunately, the exact nature of the relationship between spawners and recruits is usually unclear, owing to considerable variability in recruitment caused by factors other than spawner abundance (Walters and Ludwig 1981) and observation errors in the data. Moreover, most of the available data are collected from fisheries, often after the stock has been exploited for some time. Thus, the data are prone to a variety of potential biases and may not cover enough of a range in spawning stock size to discern a trend of recruitment with spawners. Nevertheless, the profound implications of different spawner–recruit relationships for surplus production and management have made the stock–recruitment relationship one of the most researched processes in fisheries. Rose (Presentation 1) and Maunder (Presentation 4) paralleled the search for the stock–recruitment relationship with the search for the Holy Grail: Everyone believes that a relationship between spawners and recruits exists, but no one can find it.

Less fecund species such as marine mammals often exhibit a near-linear relationship between adults and offspring until the population increases above a certain threshold, when pregnancy rates and juvenile survival may decrease due to density-dependent factors (e.g., reduced resources and increased disease). Depensatory mechanisms at very low abundance levels (e.g., failure to find a mate) may cause recruitment to decline faster than the number of adults (Liermann and Hilborn 1997). Most fisheries, however, are based on more fecund species, where the dependence of offspring (recruits) on adults (spawners) is highly nonlinear, and for which recruitment appears independent of spawners over much of the observable range. The Beverton–Holt stock recruitment curve, which is most commonly used in fisheries stock assessment, assumes that juvenile mortality is a linear function of the number of individuals in a cohort (e.g., due to competition; Beverton and Holt 1957). The Ricker model (Ricker 1975), more commonly used for modeling salmon population dynamics, assumes juvenile mortality increases with cohort abundance at an increasing rate (e.g., due to cannibalism or competition and destruction of nest sites). Other, more general models have also been developed. For example, Deriso's (1980) model has the Ricker and Beverton–Holt models as special cases. Often these functions are reparameterized—in terms of quantities such as maximum recruits per spawner or steepness (fraction of recruitment from an unfished population obtained when the spawners are at 20% of the unfished level)—to facilitate interspecific comparisons.

The parameters of the stock–recruitment relationship can be estimated inside or outside the stock assessment model. The latter approach may suffer bias because both variables (spawners and recruits) are observed with error (the errors-in-variables problem, Kendall and Stuart 1977), and is particularly problematic when the "observations" of the spawners and recruits are themselves derived quantities with an unknown error structure and implicit time-series bias (as spawners are computed from recruits). The former approach, estimation within the assessment model, adds structure to the assessment model and, in principle, mitigates the errors-in-variables problem. However, while the added structure can improve the precision of the model estimates, it comes at the expense of potentially biasing the assessment if the functional form of the stock–recruit relationship is misspecified.

There are numerous issues associated with estimating the stock–recruitment relationship. For example, Brooks (Presentation 5) showed that there is bias toward estimating a dome-shaped stock–recruitment relationship even if it does not exist, and that multiple sequential density-dependent survival factors can make the apparent stock–recruitment relationship flat. He et al. (Presentation 6) found that higher recruitment variability, as represented by the standard deviation of the lognormal recruitment deviates about the stock–recruitment relationship, leads to higher bias and variability in estimates of the steepness of the Beverton–Holt stock–recruitment relationship. They also showed that steepness is often estimated close to its bounds (0.2 and 1), but this is reduced when there is more contrast in the spawner abundance levels. Their findings are consistent with those of several studies using penalized likelihood (Thorson, Presentation 7). It has been conjectured that using a more statistically rigorous random-effects or Bayesian approach that integrates over the recruitment deviates may reduce this problem, but simulation analysis discussed by Eveson (Presentation 36) found that this was not necessarily the case. The magnitude of the standard deviation used in the distributional assumption (σ_r) may also impact the estimates of steepness if it is estimated within the assessment.

Ovoviviparous and viviparous species such as sharks would seem likely to have a clearer relationship between spawners and recruits than highly fecund species that broadcast their eggs at the mercy of the environment. The stock–recruitment relationship for these species has been modeled in terms of density-dependent survival using a three-parameter model that takes into account demographic information on the average number of offspring per female. Nevertheless, the data are insufficient to reliably estimate all three parameters in most, if not all, assessments that have used three-parameter stock–recruitment relationships. Carvalho et al. (Presentation 8) illustrated the sensitivity of model results to different parameter values, and discussed how life history characteristics could be used to determine the values of some of the parameters.

As noted previously, the choice of spawner–recruit models can have large impacts on the assessment results and management advice. Brodziak and Brooks (Presentation 9) described how ensemble modeling can be used to address uncertainty in the form of the stock–recruitment relationship. This could be done by examining alternative structural models for stock and recruit, process error formulations, steepness assumptions, and σ_r.

These and other issues concerning stock and recruit models and their utility were further debated during the second discussion session, particularly the issue of whether the uncertainty in these relationships could be adequately characterized for use in stock assessments and management advice. Most of the views expressed aligned with one of three philosophical camps: pro-steepness, post-steepness, and steepness-agnostic. The pro-steepness camp essentially reduces the apparent uncertainty by assuming a specific functional form of the spawner–recruit relationship (usually Beverton and Holt), and then fixing or imposing an informative prior on its steepness. The post-steepness camp places more emphasis on understanding and modeling the specific processes that contribute to recruitment uncertainty, making it potentially useful for predicting long-term changes in surplus production that might occur with changes in climate. This approach, however, is far more expensive and time-consuming than the first, and may not be cost-effective for many fisheries. The third camp, steepness-agnostic, represents those who believe it is impractical to determine the appropriate functional relationship between spawners and recruits, and that even where it can be done, it may change in unpredictable ways. Some in this camp proposed relying on short-term advice that implicitly assumes recruits are independent of the number of spawners. Others questioned how one would evaluate recovery/rebuilding without an assumption regarding the form of the stock–recruitment relationship. In response, some proposed a "dynamic B_0" approach that sets reference points based on recent levels of recruitment. Others in the agnostic camp supported the management strategy evaluation (MSE) approach, where empirical or model-based harvest control rules are selected based on their performance in simulation tests with a variety of plausible spawner–recruit models.

The discussion also covered reference points that are less dependent on assumptions about the stock–recruitment relationship, such as the "pretty good yield target" (e.g., 90% $YPR_{F_{max}}$) or SPR proxies used by most councils in the United States.[1] Finally, the ability to forecast recruitments was important, and, in this context, process error should be assumed to be autocorrelated.

Session 3: Time-Varying Issues with Stock and Recruit

The recruitment of young animals to the exploitable population is highly variable for most marine species. For a few populations, good progress has been made toward identifying the primary environmental drivers, and mechanistic models have been developed that appear to have reasonable predictive power, at least to the extent the environmental drivers themselves can be predicted (Rose, Presentation 1, and Karnauskas, Presentation 13). More typically, however, the sources of variability are not sufficiently understood to develop mechanistic models, and temporal variation is either ignored (as in many production models) or treated as some form of random variable (Maunder and Thorson, Keynote Address 3).

Virtual population analysis (VPA) infers recruitment strength by adding up the fishery removals from a cohort over time. It makes no assumptions about the recruitment process at all, but at the expense of assuming the catches and natural mortality rate are well known. In contrast, many contemporary stock assessment models estimate recruitment using statistical models, in some cases as free parameters (unconstrained random variables) and in others as random deviates from an underlying stock–recruitment relationship. Often the stock–recruitment relationship is assumed to be stationary, and the annual deviations are treated as uncorrelated "white noise." Typically, these white-noise deviates are assumed to be lognormally distributed, in which case a bias-correction factor is needed to make the recruitments mean-unbiased. One way this has been dealt with is to include the bias correction factor $-0.5\ \sigma_r^2$ directly into the likelihood expression. However, this approach is statistically inconsistent unless the true value of σ_r^2 is known.

Bias-correction is further complicated in stock assessments that use a penalized likelihood framework, because the recruitment deviates are not equally informed by the data in every year. This is especially true for deviates for earlier years, where there are no age- or length-composition data, and for later years (including forecasts), where the recruits have yet to enter the fishery (or survey). Accordingly, the bias-correction factor should depend on time. No closed-form analytical solution for such a graduated bias-correction has been found, but several empirically based approximations have been suggested (e.g., Methot and Taylor 2012, Thorson et al 2015). Even so, these approximations can exhibit some unexpected behaviors over the range of potential values

[1] YPR = yield per recruit; SPR = spawner per recruit; F_{max} = maximum fishing mortality.

of σ_r^2; in some cases, with the maximum likelihood estimate corresponding to $\sigma_r^2 = 0$ (Thorson, Presentation 7, and Maunder, Keynote Address 2b). Marsh (Presentation 16) described an approach where the year–class strength scaler was normalized to average zero over a given period, which avoids the bias-correction problem but complicates the meaning of the penalty on the recruitment deviates. Alternatively, modern computing power has made it possible to implement computationally intensive random effects or Bayesian methods that integrate across the uncertainty in the random deviates and potentially eliminate the need for ad hoc bias-correction factors.

It has long been recognized that some stocks exhibit large changes in recruitment that are correlated in time (but apparently unrelated to stock size). The correlations can persist for several years, perhaps reflecting a regime-shift in productivity (Mantua et. al. 1997, Hare et. al. 1999), or they can be highly episodic, as is the case for Antarctic krill (*Euphausia superba*; Kinsey, Presentation 18). As mentioned above, the processes that underlie these correlations could potentially be explained and modeled mechanistically, but the resources required to do so are often prohibitive. Moreover, apparently good mechanistic explanations may break down if the environment changes sufficiently. For example, studies suggest Antarctic krill follow a cycle of two years of high recruitment and three or four years of low recruitment, but the climate around Antarctica is changing rapidly and it is unclear whether the mechanisms that cause this pattern will persist into the future (Kinsey, Presentation 18).

Increasingly, the annual deviates, and sometimes the spawner–recruit parameters themselves, have been modeled as functions of environmental covariates (Punt et al. 2016). For example, Fitchett (Presentation 15) showed that catch rates of fully recruited Indo-Pacific sailfish (*Istiophorus platypterus*) and black marlin (*Istiompax indica*) correspond statistically with the seasonal intensities of five-year delayed Northern Equatorial Current (NEC) and Equatorial Counter-Current (ECC) indices, which may indicate large-scale ocean circulation effects that are conducive to eddy formations that increase larval fish retention and food sources and, hence, survivorship. Similarly, catches of blue marlin (*Makaira nigricans*) in high-seas fleets correspond to delayed Atlantic Multidecadal Oscillation (AMO) climatology indices. These findings underscore the importance of incorporating trends in oceanographic and climatology statistical signals in stock assessments.

Crone et al. (Presentation 34) evaluated two methods for incorporating environmental information pertaining to the recruitment of Pacific sardine: 1) using an environmental covariate as an additional parameter inside the stock–recruitment function, and 2) using an environmental covariate as an index (proxy for survey-based recruitment time series) outside the stock–recruitment function. Model performance was examined statistically with respect to the quality (bias and precision) of critical estimated parameters of the stock–recruitment relationship (e.g., virgin recruitment) and derived quantities useful to management (e.g., terminal-year stock biomass). The traditional practice of using an environmental covariate as an index (proxy for survey-based recruitment time series) outside the stock–recruitment function generally performed with less bias or relative error (in terms of estimating R_0 and spawning stock biomass [SSB]) than those models using an environmental covariate as an additional parameter inside the stock–recruitment function modeled as penalties in the likelihood.

Hypothesis tests can be used to determine if a covariate significantly explains variation in recruitment or other measures of abundance. However, preliminary simulation results presented by Weston (Presentation 11) suggest that hypothesis testing may not identify the correct model consistently. There is also the usual caveat that correlation does not imply causation. In addition, significant relationships between recruitment and environmental variables have often been published in the literature, only to break down a few years later. For example, Zwolinski (Presentation 35) discussed the case of a northern subpopulation of Pacific sardine in the northeastern Pacific, where an index of coastal sea surface temperature (SST) measured at the Scripps Institution of Oceanography pier was used in the harvest control rule for U.S. fisheries. This measure was replaced by another index of oceanic SST measured quarterly off Southern California that better fit the data. More recent analyses found that recruitment to the northern subpopulation of Pacific sardine no longer correlates as well with this index as it does to an environmental index derived from a combination of summer and spring Pacific Decadal Oscillation (PDO) values.

As Hilborn and Walters (1992) warn, "… it is almost impossible to make sure that the apparent correlation is not spurious." Accordingly, it is preferable to identify theoretical models of how various oceanographic and other environmental drivers affect recruitment, and then apply statistical tests to examine whether the use of those drivers explains a significant fraction of the variance. Karnauskas (Presentation 13) presented an example of this approach, where a biophysical model was used to predict larval recruitment strength for Gulf of Mexico red snapper (*Lutjanus campechanus*). The model used output from the hydrodynamic model to track the three-dimensional movements of advection-based particles through time, given a specified set of release points and particle behaviors and traits that may change with ontogeny and environmental variables. A good correlation was found between the indices and the estimates of recruits from the corresponding stock assessment model, which formed the basis for a discussion on how valuable recruitment predictions from a hydrodynamic model could be in forecasting short-term fluctuations in stock size.

Another approach to modeling recruitments that appear to be correlated in time is to assume an autocorrelated correlated error structure (e.g., autoregressive moving average [ARIMA] models). These models can be used with or without explicit linkages to environmental drivers, and may be especially useful where the mechanisms driving recruitment variation are not well understood. They can potentially reduce the uncertainty of short-term projections and increase uncertainty in longer-term projections. However, as Johnson (Presentation 26) showed, when the degree of autocorrelation (correlation coefficient) is estimated within the assessment model, the estimated values tend to be biased toward extreme values and are confounded with estimates of the steepness of the stock–recruitment relationship.

The presentations by Minte-Vera (Presentation 12) and Hamel (Presentation 20) highlighted some of the challenges associated with the use of fisheries data to estimate annual recruitment strength. Minte-Vera pointed out that the information on recruitment often comes mainly from catch-composition data and is particularly sensitive to model misspecification. Minte-Vera hypothesized that in some cases the influence of misspecification of the asymptotic length on absolute biomass could be minimized—without influencing the estimates of recruitment—by grouping the large fish into a single length bin. Hamel (Presentation 20) described how aging error, if not taken into consideration, can reduce the estimated size of strong cohorts and increase the estimated sizes of neighboring cohorts. Aging error may also negatively bias the estimates of the standard deviation of σ_r and positively bias the estimates of autocorrelation. Trijoulet (Presentation 17) described how sporadic large recruitments can be modeled by treating such recruitments as independent parameters, but noted that sporadic large recruitments influence the estimates of the steepness of the stock–recruitment relationship and complicate the standard approaches for calculating reference points. Recruitment could also occur throughout the year, but have some seasonal pattern. Canales (Presentation 14) described various approaches to modeling seasonal recruitment, including separating the variation into an annual effect and a seasonal effect. This approach allows a seasonal pattern even in years where there is no seasonal information in the data. McGarvey et al. (Presentation 18) presented a computationally efficient "slice-partition" approach to separate harvestable-size fish from prerecruits based on their length. They showed that this approach can eliminate bias in growth estimation by dynamically accounting for the earlier removals of faster-growing fish in each cohort, and provide accurate predictions for fitting to length in fishery samples when the cohort is partially recruited.

The discussion session touched on many areas related to estimating the parameters of the stock–recruitment relationship. There seemed to be a near consensus on some recommendations for best practice guidance, including:

1. Autocorrelation is typical of most recruitment time series and should be explored in most, if not all, stock assessments.
2. ARIMA 1 models with lags longer than one should be considered in analysis of stock and recruitment estimates, and these lags could be environmentally driven (correlation anomalies).
3. A useful diagnostic would be to check if the average recruitment is close to R_0 during years where fishing is known to have been low for a considerable period of time.
4. Time-varying and density-dependent processes that affect the later stages of a species also have large implications for assessment outcomes (e.g., resonant cohort effects; Bjornstad et. al. 2004) and, if ignored, can bias the perception of the stock–recruit relationship.
5. The standard deviation of the recruitment deviates (σ_r) should be estimated (preferably using a random effects or Bayesian approach rather than penalized likelihood) when the parameters of the stock–recruitment relationship are being estimated.

Other points brought up in discussion included:

1. The metric used to characterize the spawning capacity of the stock can affect perceptions of the stock–recruit relationship (fecundity may not be proportional to weight, spawning frequencies may vary with age, etc.).
2. Model selection diagnostics should be based on residual plots (or other measures), and not on standard statistical criteria (e.g., the Akaike information criterion [AIC] and the Bayesian information criterion [BIC]), as these methods assume that the data are correctly weighted, which is seldom the case.
3. Munch's (2017) work on examining the Meyers legacy database identified possible mechanisms for stock and recruitment that work on temporal lags (i.e., a substantial fraction of the variation in recruitment can be accounted for using time lags). However, using three parameter stock–recruitment relationships or alternative forms provided no real benefit versus current procedure.

4. A decision tree or a flow chart using life history (ecological) principles could be identified and used to assess the correct temporal and spatial resolution for management.
5. Exploratory data analysis examining maternal effects or environmental effects can identify the mechanisms, and then subsequent analysis in the assessment can be pursued. This would also identify possible data gaps, and prioritize where data should be collected in time and space that relate to recruitment. It would also help in identifying the sampling domain and help define the unit of the stock.
6. Retrospective analysis should be used to examine how often stocks collapsed and whether collapses were caused primarily by overfishing or by recruitment failure, or both. These dynamics could possibly be explained by larger-dimension ecosystem models and processes. Indicators from these large-scale models could then be developed and examined for possible use in a predictive sense for management.

Session 4: Spatial Issues and Recruitment Modeling

Most stocks of fish and invertebrates are not homogeneously distributed across their range owing to spatial variation in the quality of habitat, nonrandom migration patterns, differential exploitation rates, and the existence of multiple substocks. In principle, assessments for such stocks should be based on population dynamics models that are spatially explicit. However, this presents challenges with respect to how recruitment and movement are modeled. Most of the spatially explicit models to date have focused more on movement than on recruitment, but the two processes are linked. Thus, assumptions made about stock structure and movement will affect perceptions of recruitment. For example, Contreras and Quiroz (Presentation 25) found that a two-area spatial model for pink cusk-eel (*Genypterus blacodes*) estimated a more productive stock than the corresponding single-area model.

The added complexity of spatial models poses considerable challenges on several levels. Nevertheless, their use is on the rise, both in stock assessments and as the operating models for management strategy evaluations. Punt (Keynote Address 4) reviewed how recruitment has been modeled in existing spatially structured stock assessments, and presented a simulation evaluation of several alternative modeling approaches. He reported that most of the estimation models tested produced biased results and performed especially poorly when the natural mortality rate differs among areas (interestingly, estimating movement actually reduced bias in this case). Estimating movement was also found to be more important than estimating spatial variation in recruitment.

Cadrin et al. (Presentation 23) showed that incorporating stock structure and stock mixing into existing assessment models changed the perception of recruitment events for yellowtail flounder (*Pleuronectes ferruginea*), Atlantic bluefin tuna (*Thunnus thynnus*), and the northern stock of black sea bass (*Centropristis striata*). Simulation testing conditioned on these case studies suggested that correct identification of stock structure improves model performance, but accounting for movement does not always improve model performance. Misspecifying stock structure and mixing can produce misleading estimates of spawning stock biomass, recruitment, and the stock–recruitment relationship, as well as inaccurate estimates of reference points for overfishing or rebuilding. Bosley et al. (Presentation 24) similarly used a spatially explicit, tag-integrated assessment model that directly estimates movement in a simulation framework to compare bias in recruitment estimates when population structure is correctly or incorrectly specified for both spatially explicit and spatially aggregated assessment methods. They found that recruitment and movement are estimated with low bias when the underlying population structure is correctly specified. However, the resulting biases can be equivalent to or worse than assuming a panmictic population when misspecification in the population structure is assumed.

Notwithstanding the caveats above, spatial models have the advantage of providing outputs on scales that can better inform fine-scale spatial management. For example, McGilliard et al. (Presentation 26) used spatial models to examine the hypothesis that marine reserves are needed to ensure sufficient older females survive to sustain rockfish populations over the long term. They modeled two mechanisms by which reduced numbers of older fish were thought to influence sustainability, one where mothers of different ages spawned in different times or locations with local environmental conditions, and another where older mothers produced larger offspring that were less likely to starve compared to offspring from younger mothers. Both hypotheses can be seen as "portfolio effects," whereby risk of recruitment failure is spread over a portfolio of maternal ages. Their results indicated that populations with sedentary adults, and sedentary or mobile larvae, that are managed under a constant fishing mortality rate strategy would not benefit further from marine reserves in terms of long-term catch, the probability of falling below a biomass threshold, or recruitment variability over a range of exploitation rates.

Much of the discussion session focused on the observation that spatial and temporal variation in natural mortality, movement, and other life history parameters have similar effects to, and can masquerade as, recruitment variation. Several simulation studies suggest that including movement in assessment models can help compensate for some of this, but other simulations indicate that misspecification of the movement model can create more problems than it solves, especially when auxiliary information (such as tagging data) is biased. There was consequently general agreement that it is as important to get the geographic stock structure right, and to account for how it may change over time (e.g., due to climate change), as it is to estimate movement.

Another issue to resolve is how to specify the stock–recruitment relationship for multiple populations: Is density-dependence a function of the global population, or is it area-specific? In some cases, stocks may share feeding areas, but migrate to different spawning areas, further complicating the development of stock assessments and the estimation of model parameters. Inclusion of area-specific stock–recruitment relationships complicates the calculation of initial conditions and reference points, as there is no general closed-form solution for equilibrium conditions in multiple areas.

Other recommendations that arose during the discussion included:

1. A tagging study should be initiated as a first step to parameterize movement and area resolution (natural mortality, fishing mortality, and movement are confounded and, hence, difficult to parameterize).
2. Catchability and selectivity should be time-varying to better reflect spatial dynamics.
3. There is a need to identify stocks for which spatial structure is likely to be relevant for assessment and management, and to determine both which data are available and which data are needed to parameterize spatial models, if necessary (i.e., data gap analysis).
4. The life stages (larvae, yearlings, etc.) that will be the focus for spatial assessments should be identified early and used to prioritize data collection.

5. Assessments (e.g., Stock Synthesis [SS]) should include area-specific density-dependence options to model recruitment and other processes, although issues with finding closed-form solutions for equilibrium numbers-at-age remain (in addition, most stocks don't have the data to be used at this resolution).
6. What happens when boundaries between spatial areas are incorrectly set should be explored using simulations.
7. The consequences of bias-correction for recruitment deviations in a spatial modeling context need to be explored.
8. An attempt should be made to find a general recruitment model that includes those already included in the various integrated models (CASAL [C++ Algorithmic Stock Assessment Laboratory], SS, and MULTIFAN [the length-based multi-fishery and age and spatially structured model]). There are some advantages to having models deal with spatial assumptions differently, but it makes comparisons among assessments based on different platforms harder.

Session 5: Management Implications

The goal of assessment models is to provide the scientific basis for management measures to maintain healthy fisheries and the stocks they depend on. Understanding and predicting recruitment is an important factor in providing this advice. Estimates of future biomass and catch depend on predictions of the number of recruits entering the fishery, and traditional reference points based on sustainable yield depend on the nature of the stock–recruitment relationship. Plagányi (Keynote Address 5) reviewed several examples exploring the implications of various recruitment processes for management, including alternative ways to parameterize the stock–recruitment relationship, sporadic recruitment, Allee effects, shared stocks and artificial stock boundaries, coupling models with environmental drivers, and multispecies/ecosystem models. Eveson (Keynote Address 6) reviewed the approaches and challenges in monitoring and estimating recruitment for the tuna species managed by five Regional Fisheries Management Organizations (tRFMOs), including overviews of fisheries-independent recruitment monitoring successes, recruitment estimation methods, and the role of recruitment estimates and uncertainty in traditional stock assessment and simulation-tested management procedures. Several general conclusions emerged from these two reviews, which are reflected in the discussion at the end of this section.

De Moor and Butterworth (Presentation 29) showed that multiple stock–recruitment relationships can fit the data for South African sardine (*Sardinops ocellatus*) equally well, but with very different implications for maximum sustainable yield (MSY) and equilibrium unfished biomass (B_0). Moreover, the estimate of B_0 appeared to change over time. Berger (Presentation 30) suggested that dynamic reference points, e.g., dynamic B_0, could be used where temporal shifts in the underlying productivity of the population appear likely, but careful consideration of the recruitment dynamics is warranted to ensure that management benchmarks are informed by current productivity potential, not cyclical, white-noise, or other process-error-driven factors. Dynamic reference points may be particularly inappropriate if the steepness of the stock–recruitment relationship is misspecified (biased high), as management action might then simply follow the recruitment down as the spawning biomass decreases. Dynamic reference points may not be appropriate for biomass limit reference points in cases where recruitment collapse may occur when the stock falls below a certain threshold (Allee effect).

Sharma (Presentation 31) indicated that limit reference points are more important for management than targets for tuna species, and that stocks will remain resilient over the longer term if limit reference points are precautionary in nature (e.g., 0.25 B_0). Modeling key processes that account for temporal autocorrelation in recruitment (resonant cohort effects) and having a precautionary limit reference point reduces the probability of the stock being severely overfished. Assessments for several tuna stocks in the Indian and Atlantic Oceans illustrated a risk-based approach that balances the risk of failing to detect overfishing and unnecessarily penalizing a fishery when it was not needed.

Haltuch et al. (Presentation 32) reviewed progress toward including environmental factors in stock–recruitment projections and MSEs. They concluded that the inclusion of such factors into assessment and forecasting was most likely to be successful for species with short prerecruit survival windows (e.g., squid, sardine) and for those species that have bottlenecks in their life history during which the environment can exert a well defined pressure (e.g., anadromous fishes). The effects of the environment are more difficult to quantify for species with a longer prerecruit survival window and, in those cases, research should focus on developing a more mechanistic understanding. Denson et al. (Presentation 33) proposed a strategy for evaluating whether to include or exclude the environment from a stock assessment. Preliminary results suggest that excluding environmental indices when there is a relationship between the recruitment and the environment results in biased estimates of productivity.

The discussion session started with a question: Can we identify, measure, and predict the dominant drivers of productivity well enough to derive useful quantitative scientific advice? All agreed with Plagányi's (Keynote Address 5) call for more work developing theoretical underpinnings, validating models, and understanding the extent to which model outcomes are predetermined by model assumptions. Many underscored the need to continue advancing progress in explicitly linking recruitment variation to underlying environmental drivers in light of the increasing need for adaptive management that is responsive to climate change. Beyond that, the responses to the question were as diverse as the literature on the topic.

Much of the remaining discussion was centered on how to pursue the development of management advice in cases where recruitment remains largely unpredictable. Several participants (the post-steepness camp) advocated dedicating the resources to developing mechanistic models of recruitment along the lines of the apparently successful examples presented earlier by several of the workshop participants. It was recognized that it would be impractical (if not impossible) to explicitly model each of the multitude of interacting factors that determine recruitment success (Figure 1).

Accordingly, a key to the success of this approach is to reduce complexity by identifying the dominant factors influencing recruitment and the spatial and temporal scales over which they operate (consider, for example, the Models of Intermediate Complexity for Ecosystem assessments [MICE] approach discussed by Plagányi in Keynote Address 5). The results of these "mechanistic" models can be designed to provide an index of recruitment for a stock assessment model, which in turn could be tested against the stock assessment model's estimates of recruitment (however, correlating one model output to another model output is problematic and the caveat "correlation does not imply causation" is important to remember). This allows consideration of the complex spatial dynamics of oceanography without overly complicating the stock assessment model.

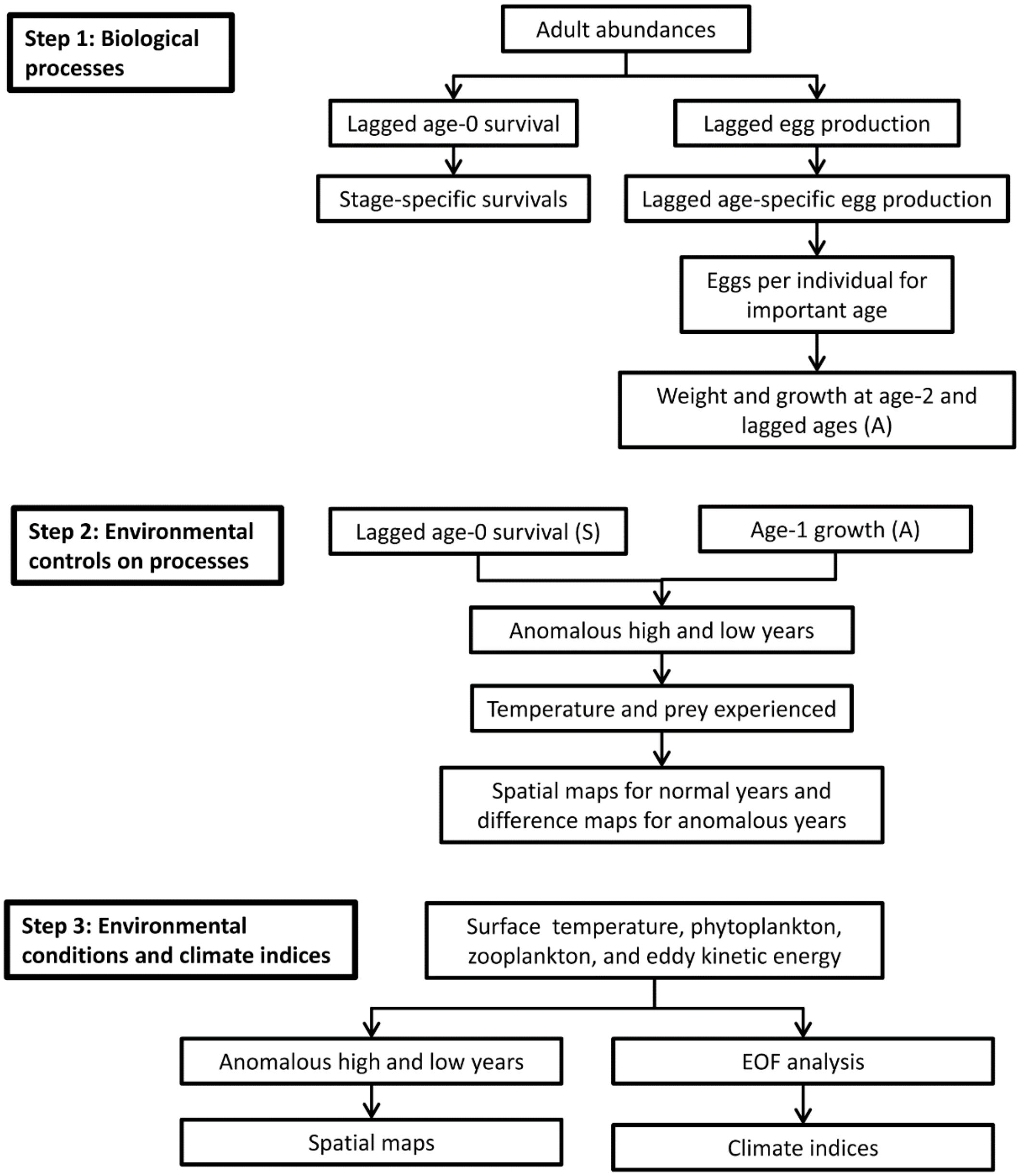

Figure 1. Forensics that outlay multiple processes that may drive recruitment success for anchovies or sardine in the California Current ecosystem (Rose et al. 2015). Key: *EOF* = empirical orthogonal function.

Several participants pointed out that we are very far from achieving workable MICE-style models for most of our fisheries, and that, in many cases, the fisheries are simply not valuable enough to justify the expense. While it was recognized that some synergies might be gained by working in a multispecies ecosystem context, many agreed that more practical alternatives will be needed. In that regard, the approaches advocated by the participants echoed those that have emerged in practice where the harvest strategies are based on 1) traditional, stationary stock–recruitment models, 2) empirically derived, nonstationary stock–recruitment models, and/or 3) harvest control rules designed to be robust to recruitment uncertainty. There is, of course, considerable overlap among these approaches, but the distinctions were clear enough to provide a convenient way to facilitate discussion.

The first approach (referred to earlier in the workshop as pro-steepness) focuses on modeling annual recruitment variation as a random deviate from a stationary stock–recruitment relationship (usually one of the time-honored models such as the Beverton–Holt, Ricker, or hockey-stick functions). As the data are usually insufficient to reliably estimate the parameters of those functions (e.g., steepness), the usual recourse has been to fix them to predetermined values or impose informative priors based on meta-analysis. A problem with this approach is that there is every reason to expect that the stock–recruitment relationship may change over time owing to climate change, coastal development, exploitation of prey species, and other factors. Moreover, the basis for selecting the functions and their parameter values is always subject to uncertainty, and the choices often change with the membership of the assessment team. Objective quantitative criteria on parameter choice and influence on model fits are often ignored due to the poor fit to stock and recruitment data in general (Mangel et al. 2010), but, eventually, informed stakeholders often come to question the basis for those decisions. As one workshop participant put it, "How can we explain to stakeholders with a straight face that the stock–recruitment relationship is Beverton–Holt with a steepness of 0.8 when what they see is a stock–recruitment plot that looks like a shotgun blast and any curve will do?"

The second approach focuses on how best to explicitly accommodate systematic temporal variation in recruitment (e.g., regime shifts) within the context of the traditional stock–recruitment constructs (and in that sense is a variant of the pro-steepness school). Here, empirical, nonmechanistic approaches are used to model and predict trends in recruitment. Several participants suggested that establishing statistical correlations between recruitment and environmental covariates did not have a reliable enough track record to form the basis for management decision-making (e.g., due to the potential for spurious correlations). Either the amount of annual variation in recruitment explained is low, or the relationship fails over time. There appeared to be more support for the inclusion of autocorrelation models (e.g., ARIMA) in stock assessments. It was noted that the use of autocorrelation models can reduce short-term uncertainty, but increase uncertainty in long-term projections (this is the correct way to model long-term projections, and admitting to the larger uncertainty in general). Autocorrelation is probably more important than the stock–recruitment relationship in short-term projections, while the stock–recruitment relationship is more important in long-term projections and equilibrium calculations (e.g., reference points).

The third approach is to develop management procedures and harvest control rules that are robust to perceived uncertainties about recruitment. While the mechanisms that determine the recruitment of a particular species may not be understood well enough to use in a predictive capacity, the collective understanding gained from other species should allow the construction of simulation models that can bracket the potential range of uncertainty. An MSE can then be used to test the performances of candidate management procedures to that uncertainty. In this context, the group discussed several avenues that could be taken. Some participants argued that empirical harvest control rules might be most cost-effective for many species, where catch or other management measures are adjusted according to trends in direct measures of stock abundance or mortality rates, such as an annual survey of recruitment (e.g., southern bluefin tuna). Empirical harvest control rules have the advantage of being model-free and more easily understood by stakeholders, but at the expense of a reduced capacity to learn about the stock–recruitment relationship and with no explicit linkage to other factors that influence stock productivity, such as selection.

Other participants suggested that the relationship between recruitment and spawners is likely to remain obscure for many species, particularly when biomass levels are managed to stay near target reference points, and therefore, that harvest control rules and target reference points should be based on constant fishing mortality strategies, perhaps based on YPR or SPR considerations. These strategies are implicitly dynamic, as the corresponding equilibrium reference points will change with the productivity of the stock. It was pointed out that the maximum YPR corresponds to the maximum sustainable yield when recruitment is independent of spawners (steepness = 1 for the Beverton–Holt relationship), but otherwise may lead to biomass levels that are considerably lower than that which would support MSY (e.g., in cases where recruitment follows a Beverton and Holt relationship with steepness <1). In response, recommendations included more conservative reference points such as $F_{0.1}$ and the fishing mortality that produces 90% of the maximum YPR, particularly for species that do not have some unusual reproductive behavior (e.g., guarding their young). Another recommendation was to use economic-based reference points such as maximum economic yield, which are generally more precautionary than those based on MSY and which maximize benefits to some user groups. This may be a less-palatable approach for recreational fisheries, however, where fishing opportunities are more important than profits.

There was discussion of the utility of explicitly dynamic reference points such as dynamic B_0, where the unfished biomass (or spawners) is recalculated every year based on the estimates of recruitment for the cohorts to constitute biomass in that year (and other model parameters). The alternative, or the "moving-window approach," is where biomass reference points such as B_0 or B_{MSY} are calculated assuming that the average recruitment estimated over the last *n* years will persist into the foreseeable future. These approaches allow the estimates of B_0 to vary in time regardless of the perceived cause, and in principle could accommodate systematic environmental changes.

There was general agreement regarding the need for continued development of fisheries-independent recruitment monitoring methods (e.g., exploring new technologies such as mark-recapture based on genotyping of individuals, or monitoring of tropical tuna abundance from a network of acoustic fish aggregating devices [FADs]). The group also agreed that the management paradigm should be designed to be robust to future recruitment uncertainties (e.g., recognize that recruitment compensation might be much lower than model-based estimates, and be prepared for an appropriate response to large, correlated recruitment deviations, e.g., regime shifts).

Overall Conclusions

The workshop was a good avenue to discuss work in progress and provided an update on the state of the art in recruitment modeling. The discussion periods following each session were productive, with many participants contributing actively to the debate. At the end of the meeting, a series of focus questions was used to facilitate the discussion of potential "best-practice" recommendations. While this was useful, future workshops should consider using the focus questions immediately after each session rather than all together at the end.

Several key areas of research were identified, and an initial attempt was made to develop best-practice guidance. In particular, the group recommended the following:

- It is important to have good fishery-independent recruitment information, not only for improving the assessment models, but also as the basis for an early-warning sign. A series of low recruitments is often the first indication that a stock is in trouble. Waiting until the signal is seen in the catch data (if the data are good enough to show it) can be too late.
- Each assessment should describe the recruitment process and evaluate any alternative hypotheses and what they imply about the stock–recruitment relationship.
- In cases where the parameters of the stock–recruitment relationship are considered estimable, examine log-likelihood profiles and other diagnostic tools to determine how reliable the estimates are. A useful diagnostic, when possible, is to compare the average recruitment (or bias-adjusted deviates if using a stock–recruitment relationship) over a period where recruitment is considered likely to fluctuate about R_0.
- Random effects models should improve the estimability of the parameters of the stock–recruitment relationship and σ_r in principle, but will not resolve the problem if the data are not informative.
- Include and estimate autocorrelation about the stock–recruitment relationship within the assessment. Autocorrelation reduces short-term uncertainty, but increases uncertainty in long-term projections.
- Covariates should be developed based on an understanding of the processes that affect recruitment for a particular stock (e.g., larval transport), rather than a search for statistically significant correlations.
- The effects of assuming alternative stock–recruitment models should be evaluated, unless there is clear reason to expect that the chosen model is correct.
- In many cases, it will be more cost-effective to develop management procedures and harvest control rules that are robust to recruitment uncertainty, rather than attempting to incorporate that uncertainty into assessment models.
- Less-conventional management strategies such as spatial rotation strategies for benthic invertebrates require less monitoring and, particularly if used in combination with a minimum size limit, can reduce risk and optimize returns even when there is considerable uncertainty in the underlying stock dynamics.

- The use of dynamic reference points is attractive, but requires more research.
- Stakeholder consultation can be useful in guiding choice of key environmental indices/relationships.
- Simulation models with detailed mechanistic processes (e.g., exploring the impact of spatial structure, complex larval settlement, and distribution) can be used to inform simpler proxy adjustments for stock assessments.
- Continued research on the environmental drivers and spatial dynamics influencing recruitment should be encouraged.

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Appendix A: Agenda for CAPAM Meeting, 30 October–3 November 2017

DAY 1 (10/30)

Demo Session: Hands-On Workshop

	10:00	R. Methot	Overview of new features of Stock Synthesis (SS) version 3.30
	12:00	Lunch	
	1:00	I. Taylor	Demo of SS recruitment dynamics
	3:30	Coffee Break	
	4:00	C. Marsh	Demo of C++ Algorithmic Stock Assessment Laboratory (CASAL)

DAY 2 (10/31)

	9:00	R. Sharma, C. Porch	Introduction and Logistics

Session 1: Processes Driving Recruitment

No.	*Time*	*Speaker(s)*	*Title*
1	9:10	K. Rose	**Keynote Address 1:** Recruitment is the Holy Grail in Fisheries Science, and Why We Should Keep On Searching
2	10:10	N. Ehrhardt	Stock Assessment Modeling and the Conundrum of Multiple Life Stage Abundance Effects on Recruitment: The Caribbean Spiny Lobster, *Panulirus argus*, as an Example
3	10:40	K. Lorenzen	Patterns of density-dependent mortality in the life cycles of fishes: When is a recruit not a recruit?
	11:10	Coffee Break	
	11:30	**DISCUSSION ON SESSION 1**	

Session 2: The Stock–Recruitment Relationship

No.	*Time*	*Speaker(s)*	*Title*
4	12:00	T. Branch, M. Maunder[a]	**Keynote Address 2:** Population Dynamics and Stock and Recruitment[b]
	1:00	Lunch	
5	2:00	E. Brooks	Paulik revisited: Statistical framework and estimation performance of multistage recruitment functions
6	2:30	X. He	Effects of Recruitment Variability and Fishing History on Estimation of Stock–Recruitment Relationships: Two Case Studies from U.S. West Coast Fisheries
7	3:00	J. Thorson	Steepness for U.S. West Coast Rockfishes: Results from a Twelve-Year Experiment in Iterative Regional Meta-Analysis
	3:30	Coffee Break	
8	4:00	F. Carvalho[c]	Parameterizing the Low-Fecundity Stock–Recruitment Relationship (LFSR) for Pelagic Sharks in Stock Synthesis: Challenges and Results
9	4:30	J. Brodziak	Forecasting Recruitment Using Model Ensembles
	5:00	**DISCUSSION ON SESSION 2**	

[a] Presented by T. J. Quinn II.
[b] Title changed. See Appendix B.
[c] Presented by D. Courtney.

DAY 3 (11/01)

	Time	Speaker(s)	Title
	9:00	C. Porch	Overview of Day 2

Session 3: Time-Varying Issues with Stock and Recruit

No.	*Time*	*Speaker(s)*	*Title*
10	9:10	M. Maunder	**Keynote Address 3:** Modeling Recruitment Temporal Variation in Fisheries Stock Assessment: A Review of Theory and Practice
11	10:10	A. E. Weston	Evaluation of Model Selection Tools for Recruitment–Environmental Linkages in Stock Assessments
	10:40	Coffee Break	
12	11:00	C. Minte-Vera	Improving Estimates of Abundance Using Regional Recruitment Signals Derived from Meta-Analysis of Stock Assessments
13	11:30	M. Karnauskas	Use of a Biophysical Model to Estimate Recruitment Strength of Red Snapper in the Gulf of Mexico
14	12:00	C. Canales	Small Pelagics: Modeling Seasonality in Recruitments Using the Separability Assumption[a]
15	12:30	M. Fitchett	Recruitment Signals Commensurate to Ocean Circulation and Climatology
	1:00	Lunch	
16	2:00	C. Marsh	Reviewing Assumptions Surrounding Year Class Strengths in the Recruitment Dynamic
17	2:30	V. Trijoulet	Modeling Episodic Recruitment Events: Methods and Implications for Stock Assessment in the Presence of Occasional Very Large Year Classes
18	3:00	R. McGarvey	Modeling Gradual Recruitment to Legal Size by Dynamically Accounting for Both Age and Length: Slice Partition
	3:30	Coffee Break	
19	4:00	D. Kinzey	Recruitment in the Integrated Assessment for Antarctic Krill
20	4:30	O. Hamel	Addressing Cohort-Strength Correlated Ageing Error in Fishery Stock Assessment
21	5:00	I. Payá	Exploring Predictions of Recruitments Using Individual Mean Weight
	5:30	**DISCUSSION ON SESSION 3**	
	6:15	Social	

[a] Title changed. See Appendix B.

DAY 4 (11/02)

	9:00	C. Porch	Overview of Day 3

Session 4: Spatial Issues and Recruitment Modeling

No.	*Time*	*Speaker(s)*	*Title*
22	9:10	A. Punt	**Keynote Address 4:** Modeling Recruitment in a Spatial Context: A Review of Current Approaches, Simulation Evaluation of Options, and Suggestions for Best Practices
23	10:10	S. Cadrin	The Importance of Accurately Accounting for Geographic Stock Structure in Recruitment Estimation
24	10:40	K. Bosley	Estimating Recruitment in Spatially Explicit Stock Assessment Models: The Impact of Population Structure Assumptions on Recruitment Bias
	11:10	Coffee Break	
25	11:30	F. Contreras	Spatial Considerations for Assessment
26	12:00	K. Johnson	Recruitment Dynamics in a Changing Environment: Integrating Spatial and Temporal Variability into Stock Assessment and Management Strategies
27	12:30	C. McGilliard	Modeling the Impacts of Two Age-Related Portfolio Effects on Recruitment Variability with and without a Marine Reserve
	1:00	**DISCUSSION ON SESSION 4**	

	1:30	Lunch	

Session 5: Management Implications

No.	*Time*	*Speaker(s)*	*Title*
28	2:15	É. Plagányi	**Keynote Address 5:** Management Implications of Modeling Recruitment
29	3:15	C. L. de Moor	Letting the "Data" Speak for Themselves: The Use of Stock–Recruitment Relationships to Determine a Biomass Threshold above which Management Should Aim to Keep a Resource
	3:45	Coffee Break	
30	4:00	A. Berger	Shifts in Stock Productivity: Recruitment Potential and Static/Dynamic Reference Points
31	4:30	R. Sharma	A Simulation Approach Developed to Assess Resilience, Rebuilding Time as a Function of Steepness, and Perceived Risk to Reference Points on Indian and Atlantic Ocean Tuna and Tuna-Like Populations
32	5:00	M. Haltuch	Unraveling the Recruitment Problem: A Review of Environmentally Informed Forecasting
33	5:30	L. Denson	Strategy to Evaluate the Risks and Benefits of Including Environmental Predictors of Recruitment
	6:00	**DISCUSSION ON SESSION 5**	

Day 5 (11/03)

No.	*Time*	*Speaker(s)*	*Title*
34	9:00	P. Crone	Good Practices for Including Environmental Data to Model Spawner–Recruit Dynamics and Recruitment Variability in Integrated Stock Assessments: A Small Pelagic Species Case Study
35	9:30	J. Zwolinski	Environmental Dependence of Pacific Sardine Recruitment—Another Spurious Correlation?
36	10:00	D. Kolody, P. Eveson	**Keynote Address 6:** Recruitment in Tuna RFMO Assessment and Management: A Review of Recent Methods and Challenges
	11:00	Coffee Break	
	11:30	**DISCUSSION, FOCUS QUESTIONS, AND SUMMARY OF DAYS 2–5**	

Appendix B: Abstracts of Presentations

Keynote Addresses

Keynote Address 1 (Presentation 1)

Recruitment is the Holy Grail in Fisheries Science, and Why We Should Keep On Searching

K. Rose, T. Miller, M. Wilberg, and E. North

Abstract

Many authors have referred to the attempts to quantify spawner–recruit relationships with confidence as the Holy Grail of fisheries science. Sometimes new measurement technologies or modeling methods get us excited and optimism reigns, only to be put to the test of stock assessment and management decisions that show we were, at best, partially correct with improved forecasting. However, the improvements are fleeting and never long-lived, and often do not withstand the intense scrutiny when stakeholders and others win or lose with the resulting management decisions that depend on the spawner–recruit relationship. This has led scientists, managers, and stakeholders to call for giving up on understanding and predicting recruitment dynamics. I argue that while the study of recruitment may seem self-defeating, what we have learned has been underappreciated. I cover several topics that illustrate the usefulness of our quest for finding the Holy Grail, even if we never get to the ultimate endpoint of high predictability. Fisheries science and management benefit from our attempts.

Keynote Address 2 (Presentation 4)

Mathematical and Statistical Modeling of the Spawner–Recruit Relationship in Fish Populations: How to Unfailingly Make Fish Biologists Smirk

T. J. Quinn II

Abstract

The recruitment of juveniles into an adult fish population is one one most important population processes governing its sustainability. The high variability in recruitment has long been recognized and was a major consideration in the formation of the International Council for the Exploration of the Sea in 1902. Efforts in the early 20th century focused on the development of various hypotheses to explain recruitment fluctuations. Mathematical modeling of these hypotheses first occurred in seminal works by Ricker (1954) and Beverton and Holt (1957). The first key concept in the mathematical modeling of recruitment is the necessary existence of density-dependence, in which recruitment is a nonlinear function of egg production (or spawning stock), because a population cannot have infinite abundance. Two types of density dependence have been identified: 1) compensation, in which early life survival decreases as a function of egg production, and 2) depensation, in which early life survival increases as a function of egg production at low

population levels. However, identification of these processes remains elusive due to variability in measurement of recruitment and spawning stock and, in the process of recruitment, due to environmental and other unidentified factors. While additional spawner–recruit models have been developed, most assessment scientists continue to use the Ricker and Beverton–Holt models. Future research efforts appear to involve 1) the resolution of measurement and process error in a spawner–recruit model, 2) the use of spawner–recruit models in stock assessment, and 3) the use of spawner–recruit models for developing reference points for fishery management.

Keynote Address 3 (Presentation 10)

Modeling Recruitment Temporal Variation in Fisheries Stock Assessment: A Review of Theory and Practice

M. N. Maunder and J. T. Thorson

Abstract

Recruitment is one of the main biological processes driving fisheries population dynamics, and needs to be modeled adequately to provide reliable stock assessments and management advice. Temporal variation in recruitment can be substantial, and the characteristics and drivers of the variation differ among stocks. Therefore, understanding, describing (modeling), and predicting this variation are essential to assessment and management. Most modern stock assessments, particularly those that include composition data, estimate annual variation in recruitment. Changes over time are typically partitioned into those related to the spawning biomass and density dependence (the stock–recruitment relationship), and those related to other factors such as the environment. A variety of methods have been used to model recruitment inside stock assessment models; they differ by how recruitment is represented and how statistical inference is conducted. Recruitment has been modeled using a stock–recruitment relationship, autocorrelation, a function of covariates, regime shifts, or a combination of these. Statistical inference has been conducted using state-space models, Bayesian analysis, and penalized likelihood. All these methods have specific issues that need to be addressed, and there are tradeoffs in their use. Future temporal variation also needs to be considered when providing management advice. We review the theory and practice of modeling recruitment temporal variation in fisheries stock assessment, and provide advice on good practices and needed research.

Keynote Address 4 (Presentation 22)

Modeling Recruitment in a Spatial Context: A Review of Current Approaches, Simulation Evaluation of Options, and Suggestions for Best Practices

A. E. Punt

Abstract

Many, if not most, stocks of fish and invertebrates subject to commercial, recreational, or subsistence harvesting exhibit some degree of spatial heterogeneity. This can be due to a lack of complete movement within a single biological population, or due to the assessed region consisting of multiple substocks. In principle, assessments for stocks for which the assumption of homogeneity is violated should be based on population dynamics models that are spatially explicit. There are, however, relatively few stocks for which multistock/multi-area assessments are conducted. However, the number of assessments in which space is explicitly represented in the population dynamics model has been increasing in recent years, and such models are available for fish stocks such as New Zealand hoki (*Macruronus novaezelandiae*) and canary rockfish (*Sebastes pinniger*) off the U.S. West Coast, as well as invertebrates such as the rock lobsters (*Panulirus cygnus*) off southern Australia and New Zealand. A challenge within such spatially explicit assessments pertains to how recruitment and movement are modeled. This presentation reviews assessments for fish and invertebrate stocks that are based on spatially explicit models, identifying the challenges associated with modeling recruitment caused by increased model and parameter estimation complexity, and the available solutions. A set of illustrative simulations are undertaken, a) to evaluate the consequences of different assumptions regarding spatial recruitment and movement, and b) to develop some recommendations for best-practice guidelines.

Keynote Address 5 (Presentation 28)

Management Implications of Modeling Recruitment

É. Plagányi

Abstract

The representation and parameterization of the stock–recruitment relationship is highly influential in most fisheries stock assessments. This has important implications for management. This presentation uses an age-structured statistical population model to evaluate the implications of alternative choices for modeling recruitment. Results compare the implications for management when using alternative structural representations, as well as different choices of the variance parameter for representing the effects of environmental variation. The stock–recruitment steepness parameter, notoriously difficult to estimate, is highlighted as a major concern for reliably modeling and managing fish stocks. Its role in contributing to recruitment overfishing and collapse of some stocks is interrogated, and default parameterizations for long-lived versus short-lived highly variable stocks are queried. The need to continue advancing progress in explicitly linking recruitment variation to underlying environmental drivers is underscored given the increasing need for adaptive management that is responsive to climate change. Finally, a brief overview is provided of the implications of alternative representations of recruitment in ecosystem models.

Keynote Address 6 (Presentation 36)

Recruitment in Tuna RFMO Assessment and Management: A Review of Recent Methods and Challenges

P. Eveson, D. Kolody, A. Preece, C. Davies, and R. Hillary

Abstract

We review the approaches and challenges in monitoring and estimating recruitment for the main commercial species managed under the auspices of the five tuna Regional Fisheries Management Organizations (tRFMOs), including overviews of: 1) fisheries-independent recruitment monitoring successes, failures, and future options, 2) recruitment estimation methods within statistical population models, and 3) the role of recruitment estimates and uncertainty in traditional stock assessment and simulation-tested management procedures.

Despite the diversity in tuna populations and tRFMO scientific processes, there are many common recruitment issues, including: 1) fisheries-independent recruitment monitoring is difficult (despite various efforts, the aerial survey for juvenile southern bluefin tuna, *Thunnus maccoyi*, is the only continuous time series used in assessments), 2) most statistical models estimate stochastic recruitment deviations around a stationary Beverton–Holt relationship, 3) recruitment variability is high and the degree of compensation in the stock–recruit relationship is difficult to estimate ("steepness" is usually assumed to be 0.7–1.0), and 4) estimated recruitment time series often deviate systematically from the mean relationship, but it is unclear the extent to which this reflects reality (e.g., environmental change) or estimation artifacts (e.g., incorrect model assumptions or biased data).

Recommendations include: 1) continued development of fisheries-independent recruitment monitoring methods (e.g., exploring new technologies like mark-recapture based on genotyping of individuals, or monitoring of tropical tuna abundance from a network of acoustic FADs), and 2) the management paradigm should be designed to be robust to future recruitment uncertainties (e.g., it should recognize that recruitment compensation might be much lower than model-based estimates, and be prepared for an appropriate response to large, correlated recruitment deviations, e.g., regime shifts).

Speakers

Presentation 1

See Keynote Address 1.

Presentation 2

Stock Assessment Modeling and the Conundrum of Multiple Life Stage Abundance Effects on Recruitment: The Caribbean Spiny Lobster, Panulirus argus, as an Example

N. Ehrhardt

Abstract
Fishery management is widely recognized as important work in marine conservation. In this regard, dimensioning future surplus production is at the core of fishing mortality controls, and spawning and recruitment abundance information is considered pivotal regarding assessments of future stock potential yields. However, describing and objectively measuring the effects of fishery exploitation on future recruitment is difficult. The difficulty arises from assessing the abundance at several life stages between spawning and recruitment that often confound spawning stock density-dependent effects on recruitment.

Caribbean spiny lobster (*Panulirus argus*) stocks are heavily exploited and, as a result, landings are mostly recruitment-driven. Landings have experienced significant steady declines in several countries since 2000. This is cause for concern not only for economic reasons, but for issues of stock sustainability. Several hypotheses have been proposed about the most likely cause and effect of such declines. Despite the fact that some research results support the contention that local spawning populations are a significant contributing factor of local post-larval recruitment, the pan-Caribbean recruitment paradigm has prevailed. Consequently, most Caribbean spiny lobster fisheries are exploited with no fishing mortality controls and limited stock assessment initiatives. In this presentation, modeling the recruitment dynamics of *P. argus* in Florida with objectively collected information at the larval metamorphosis life stage shows that prerecruit cohort abundance may be fundamental to spawning stock assessment modeling, but with low statistical significance regarding transition to recruitment to the fishery. The conundrum is regarding the assessment of early life stages in the recruitment-to-the-fishery process such that integrated functional recruitment stages could provide the necessary information for stock assessment works.

Presentation 3

Patterns of Density-Dependent Mortality in the Life Cycles of Fishes: When is a Recruit Not a Recruit?

K. Lorenzen and E. Camp

Abstract
In fisheries ecology and assessment, the life cycle of exploited fish and invertebrates is divided into a prerecruit phase from spawning to the advanced juvenile stage, and a subsequent recruited phase during which the organisms mature and spawn, and are potentially fishable. Most age-structured fisheries models assume that compensatory density-dependence in mortality occurs during the prerecruit phase but is negligible after recruitment. It is therefore important to consider patterns of density-dependence throughout the life cycle when determining the age or size at which recruitment is assumed to occur in assessment models, and when assessing fishing activities that affect prerecruit stages (e.g., juvenile fish bycatch in shrimp trawls) or when using data series derived from such stages (e.g., young fish surveys). We review theoretical concepts and empirical information regarding patterns of density-dependent mortality in the life cycles of fishes and discuss their implications for stock assessment practice.

Presentation 4

See Keynote Address 2.

Presentation 5

Paulik Revisited: Statistical Framework and Estimation Performance of Multistage Recruitment Functions

E. Brooks, J. Thorson, K. Shertzer, R. Nash, J. Brodziak, K. Johnson, N. Klibansky, B. MacKenzie, M. Payne, B. Wells, and J. White

Abstract
A wide variety of processes act at different stages and intensities within the period between spawning and the age designated as “recruitment.” It is common practice to collapse this complex series of sequential stages into a single process between spawning stock size and resultant recruitment. Reasons for treating this as a single stage include lack of data on the intermediate stages, lack of understanding of the mechanisms and the functional form governing the intermediate stages, and lack of computational resources to model a multistage process in the appropriate statistical framework. Using a simulation study, we explore the estimation of multistage stock recruit functions in a state-space framework. Factors explored include the number of stages, the form of density dependence, the magnitude of measurement error

associated with each stage, and the magnitude of process error between stages. We summarize results in terms of parameter identifiability, bias, precision, and the ability of the model selection criteria to identify the correct underlying model. We also fit a single composite stock–recruitment function to the first and last simulated stages, the status quo practice, and compare the resulting inference about the shape of the stock–recruitment function (asymptotic or overcompensatory) and characterization of uncertainty. In addition to the simulation study, we illustrate the modeling framework using data on North Sea herring (*Clupea harengus*). We conclude with a discussion of general recommendations and management implications.

Presentation 6

Effects of Recruitment Variability and Fishing History on Estimation of Stock–Recruitment Relationships: Two Case Studies from U.S. West Coast Fisheries

X. He and J. C. Field

Abstract

The Beverton–Holt stock–recruitment (SR) relationship is commonly used in U.S. West Coast groundfish stock assessments. However, the steepness parameter (h) within the SR function is often fixed in assessment models, due in part to difficulties in estimating the parameter in the face of the high recruitment variability observed in most U.S. West Coast populations. Additional complicating factors include the effects of catch history and subsequent level of contrast in stock abundance, which also influences whether the SR function can be adequately estimated. We conducted a simulation study of "data-rich" populations and age-structured assessments to evaluate the effects of recruitment variability and fishing history on estimation of the SR relationship. In the study, we used two simulated stock assessment models (Models 1 and 2) that represented two different life histories, one a moderate-lived species (age-plus group = 20 years, Model 1) and the other a long-lived species (age-plus group = 50 years, Model 2). In each model, two fishing histories were also simulated, with one representing heavy fishing (F1) and another representing moderate fishing (F2). We found that recruitment variability alone can lead to high uncertainty in estimation of h, as estimates often hit the bound of 1.0 in the simulation even when the true value is considerably lower. Inclusion of informative priors, either correctly or incorrectly specified, had a greater influence on estimated h values at higher levels of recruitment variability, further implying that the models do not have sufficient information for estimating h parameters when recruitment variability is high. Estimates of other assessment parameters, including growth, natural mortality, and stock depletion, were generally well estimated in both models and in both fishing scenarios, regardless of whether steepness was estimated without a prior, with the correct prior, or with an incorrect prior.

Presentation 7

Steepness for U.S. West Coast Rockfishes: Results from a Twelve-Year Experiment in Iterative Regional Meta-Analysis

J. T. Thorson, M. W. Dorn, and O. S. Hamel

Abstract

Theoretical and applied research suggest that survival during early life stages will increase when spawning biomass is reduced in marine fishes (termed "recruitment compensation"). However, the magnitude of recruitment compensation is generally difficult to estimate for individual fish stocks, and its average value for marine fishes remains highly contested. Scientists and managers for Pacific rockfishes (*Sebastes* spp.) on the U.S. West Coast have used a regional meta-analysis to estimate the likelihood distribution of the steepness parameter of the Beverton–Holt stock–recruit relationship using stock assessment models since 2007, and the method has been updated every assessment cycle since then (i.e., five biennial updates). Here, we provide a short history of this approach, its methodological assumptions, changes in results over time, and ongoing efforts to validate its assumptions. While the regional meta-analysis has been successful in ensuring a consistent approach to the treatment of steepness across assessments, the estimates of mean steepness have been unexpectedly variable as the meta-analysis has been updated. Specifically, we show that the estimated average value of steepness for west coast rockfish increased markedly from 2007 (average: <0.6) to 2011 (average: >0.75), before decreasing somewhat again in the 2017 analysis. We also show that this value has a strong impact on rockfish rebuilding plans, and showcase the example of canary and widow (*Sebastes entomelas*) rockfishes, where the estimated rates of rebuilding are strongly influenced by the assumed value of steepness. We conclude by discussing the bias-variance tradeoff between using global and regional meta-analysis, as well as the likely implications of difficult-to-validate assumptions including: 1) no recruitment autocorrelation within each stock, 2) no correlations among stocks, and 3) no bias from individual stocks resulting from misspecification of the stock assessment models used in the meta-analysis.

Presentation 8

Parameterizing the Low-Fecundity Stock–Recruitment Relationship for Pelagic Sharks in Stock Synthesis: Challenges and Results

F. Carvalho, K. Mikihiko, D. Courtney, J. Brodziak, K. Piner, and M. Maunder

Abstract

In the past fifteen years, society's concern about the status and fate of the world's pelagic shark populations has awakened and intensified. As sharks have become the focus of greater research attention and heightened conservation concerns, attention has focused on conducting formal stock assessments to determine population status. Recent advances have been made in length-based age-structured stock assessment modeling conducted with Stock Synthesis for U.S. pelagic shark stocks in the Pacific and Atlantic Oceans, as well as for the Indian Ocean. Although the use

of Stock Synthesis models for pelagic shark assessments is on the rise, one difficulty commonly encountered in these assessments is that the resulting stock status conclusions are extremely sensitive to the shape of the stock–recruitment function. This study examines alternative parameterizations of the Low-Fecundity Stock Recruitment Relationship (LFSR) available in Stock Synthesis involved in developing recent stock assessments for North Pacific blue shark (*Prionace glauca*) and North Atlantic shortfin mako shark (*Isurus oxyrinchus*).

Presentation 9

Forecasting Recruitment Using Model Ensembles

J. Brodziak and L. Brooks

Abstract

Our goal is to describe a general approach to forecasting recruitment and associated quantities of interest (QOI) like future spawning biomass or total allowable catch, using model ensembles. Our approach is based on using predictive accuracy as the measure of forecast quality, and assumes that two conditions hold: 1) there exists uncertainty about the stock assessment model structure, and 2) there exists uncertainty about the forecast model structure to predict future recruitment conditioned on the stock assessment model. The two conditions almost surely are true for any stock assessment. The approach uses multimodel inference to choose a set of credible stock assessment models from a set of plausible models. The set of plausible models comprises all combinations of selected input datasets and selected model features. For each credible model, the model is run for the full time horizon and the QOI are recorded. Assessment model weights are calculated using the model results run on a subset of the time horizon. Here the weights are an objective measure of the discrepancy between the full and subset model results, such as the mean squared error of the model fit to a relative abundance index or size composition. The same approach is used to calculate forecast model weights conditioned on each assessment model. This produces a model ensemble comprising a set of credible assessment models, each of which has an associated set of forecast models along with assessment and forecast model weights. The set of model ensembles, along with the model weights, provides a direct algorithm to characterize both assessment model-based uncertainties, including selection of input data, and forecast-based uncertainty in predictions of QOI for risk analysis, such as setting a total allowable catch that has a certain probability of not overfishing the stock. The capability to characterize these uncertainties is very important because fisheries are actively managed for the present and the future, not the past. We illustrate the general forecasting approach using recent assessment information from the Georges Bank haddock (*Melanogrammus aeglefinus*) stock, including uncertainty in the magnitude and scaling of natural mortality rate with body mass. We discuss some open questions for forecasting with ensembles, such as: How different should assessment or forecasting models be? or, What is an appropriate loss function when different model types are being compared?

Presentation 10

See Keynote Address 3.

Presentation 11

Evaluation of Model Selection Tools for Recruitment–Environment Linkages in Stock Assessments

A. E. Weston, G. Fay, and C. R. McGilliard

Abstract

Recruitment success of groundfish in the Gulf of Alaska has been linked to large-scale environmental drivers in the North Pacific. Stock assessment models are capable of including these linkages to understand the effects on population dynamics and fishery management. However, it is not clear how to best select among assessment models that differ in the way they include recruitment–environment linkages. We simulation test the robustness of the Akaike information criterion (AIC), Mohn's retrospective statistic, and holdout vs. cross-validation as model selection tools for choosing among a set of five stock assessment models for Gulf of Alaska groundfish. Using Stock Synthesis to define operating models that contain alternatives for the effect of an environmental index on recruitment, we simulate pseudo-datasets. Estimation models correctly specify and misspecify the recruitment–environment linkages. Estimation model performance is evaluated using percent relative error estimates of current spawning stock biomass, current spawning stock status ($SSB_{current}$ / SSB_0), fishing mortality, recruitment over time, and catch at maximum sustainable yield. We quantify the frequency at which each model selection tool is able to identify the correctly specified model (the model from which the pseudo-data were generated). Initial results suggest that misspecified models led to biased estimates of derived quantities when the data were generated from a model with a recruitment–environment linkage on unfished recruitment. In addition, AIC and Mohn's retrospective statistic were not able to choose the correctly specified model consistently. Our study will inform best practices for including recruitment–environment linkages in a suite of stock assessments by discerning the robustness of tools for model selection.

Presentation 12

Improving Estimates of Abundance Using Regional Recruitment Signals Derived from Meta-Analysis of Stock Assessments

C. V. Minte-Vera, M. N. Maunder, P. Crone, J. Thorson, K. Piner, and A. Aires-da-Silva

Abstract

When using integrated models, recent research indicates that recruitment deviations are required to interpret abundance information from indices of relative abundance, at least for moderate- to short-lived stocks that have moderate to high recruitment variability. This is because increases in the indices of relative abundance during periods of large catches can only be explained by temporary changes in productivity, e.g., by large recruitments. To estimate recruitment within integrated models with enough precision to be useful for management, information about recruitment contained in the composition data is needed. The use of size-composition data in integrated models presents several challenges. For example, in face of model misspecification in key life history processes, composition data may inadvertently bias the results. Changing the weighting of the composition data, a common "solution" used to address the misspecification problem, can erroneously determine the outcome of the stock assessment. Alternative methods for estimating recruitment variability should be explored. Recruitment variation has long been thought to be related to environmental factors, in addition to the spawning stock biomass. If environmental factors are central to determining the variation in recruitment, then including environmental information may contribute to better estimates of recruitment. However, there is a debate as to which variables would best represent the drivers. Instead of focusing on input environmental variables, one can approach the problem from the other side—i.e., by looking at the outcome of the environmental driver. Species that occupy the same ecosystem might share signals of the influence of environmental drivers, after discounting for the stock–recruitment relationship of each species, as shown though correlations in their recruitment signals. In fact, it has been demonstrated that recruitment estimates based on multistock models of co-occurring species are more precise that those based on single-stock models, indicating that the effects of underlying environmental drivers on the dynamics of multiple populations can be estimated and serve as a proxy for those drivers. This method seems to be a promising alternative to using composition data to estimate recruitment variability in integrated assessments, for ecosystems where several species are assessed. In this study, we explore the accuracy of population trend and management quantities estimates when using a model forced by catches and fit only to indices of relative abundance and to regional recruitment signals derived from a meta-analysis of co-occurring stocks. We use the California Current Ecosystem as our case study, as more than 20 stocks are assessed routinely with integrated models created with the Stock Synthesis platform.

Presentation 13

Use of a Biophysical Model to Estimate Recruitment Strength of Red Snapper in the Gulf of Mexico

M. Karnauskas

Abstract
Recent advances in hydrodynamic ocean models and in biophysical modeling approaches—and in the computational power to link the two—now allow us to mechanistically understand the environmental processes driving recruitment. I will discuss how one biophysical modeling approach, the Connectivity Modeling System (Paris et al. 2013), has been used to predict larval recruitment strength for the Gulf of Mexico red snapper stock. The model uses output from the hydrodynamic model and tracks the three-dimensional movements of advected particles through time, given a specified set of release points and particle behaviors and traits that may change with ontogeny and environmental variables. The relative number of successful recruits, summed by year, represents the expected recruitment strength due solely to oceanographic forces. In the absence of fisheries surveys or other information with which to measure the abundance of newly recruited larvae, model predictions of recruitment are valuable in forecasting the short-term fluctuations in stock size, and thus informing management. I will also discuss other applications of the biophysical modeling approach to spatial fisheries management issues.

Presentation 14

Applying the Separability Assumption for Recruitment Estimation into a Length-Based Stock Assessment Model

C. M. Canale, M. J. Cuevas, L. Cubillos, N. Adame, and N. Sánchez

Abstract
The extent of the parameters set to be solved in a stock assessment model is strongly determined by the extent of the recruitment time series and the fishing mortality vector. Often, recruitments are modeled as random deviations around an expected value, either an overall average or dependent on a stock–recruitment relationship. There are multiple factors that can determine the behavior of these random deviations, and few are the cases where seasonal patterns are modeled explicitly.

In order to explicitly model the intra-annual seasonal effect in a large-scale stock assessment model, we developed a recruitment model expressed as the sum of fixed or systematic effects dependent on temporal strata (quarter and year) and another nonsystematic effect that depends on the individual size. We applied this length-based stock assessment model to trimester data of anchoveta (*Engraulis ringens*) from southern Peru and northern Chile for the period 1984–2015.

The results show that the separability hypothesis allows the length of the solved parameter vector to be reduced by 25% (from 394 to 302) without greater loss in the fit quality of the model, nor significant differences in the main population variables. In this way, the annual and seasonal effects can be examined independently and with greater ease. Recruitment is estimated to be distributed in a range of smaller lengths through a normal distribution, while the seasonal effect indicates that it is in the third quarter of each year where the largest recruitment to the fishery should be observed.

Presentation 15

Recruitment Signals Commensurate to Ocean Circulation and Climatology

M. Fitchett

Abstract

Recruitment variability of highly migratory tunas and billfishes is often considered to be a result of ocean circulation and other ecosystem-forcing processes affecting early life history stages. The Indo-Pacific sailfish in the eastern Pacific Ocean recruits to the fisheries off Central America by age-5. The magnitude of fully recruited sailfish entering recreational and commercial fisheries off Central America corresponds statistically with seasonal intensities of five-year delayed Northern Equatorial Current (NEC) and the Equatorial Counter-Current (ECC) indices. Likewise, catch-per-unit-effort of black marlin caught in the eastern Pacific corresponds with delayed EEC indices. Thus both NEC and ECC indices may be indicative of large-scale ocean circulation effects that are conducive to eddy formations which are propitious to larval fish retention, food sources, and survivorship. In the Atlantic Ocean, catches of blue marlin in high-seas fleets correspond with delayed Atlantic Multidecadal Oscillation (AMO) climatology indices. These findings underscore the importance of incorporating trends in oceanographic and climatologic statistical signals in surplus production assessments. Most current stock assessment methodologies do not account for such environmental drivers, which may lead to misspecification of recruitment trends in models used to assess the status of exploitation.

Presentation 16

Reviewing Assumptions Surrounding Year Class Strengths in the Recruitment Dynamic

C. Marsh, N. Sibanda, and A. Dunn

Abstract

There have been several different approaches to the parameterization and estimation of recruitment in stock assessment models. New Zealand assessments have typically parameterised recruitment as relative year class strengths (YCS), which scale an average recruitment (R_0) for each year. In the United States, recruitment has often been parameterized using a multiplier on the log scale (rec_devs), which also scales average recruitment for each year. Other approaches

that have been applied include not using a constraint of mean rec_dev = 0 or mean YCS = 1, and use of different priors for YCS, including choice of σ_r for lognormal/normal priors.

In this study, we evaluate whether and when these assumptions matter. We use New Zealand's new generalized stock assessment model, CASAL2, to investigate alternative methods of estimating and parameterizing recruitment. We compare the results using different model estimation approaches and different assumptions of the priors and constraints on annual recruitment estimates, including maximum posterior density (MPD) and Markov chain Monte Carlo (MCMC) performance.

We apply this to two species stock assessments that had contrasting quantity and quality of biomass and age composition data. The first was for orange roughy (*Hoplostethus atlanticus*), where data were limited. The second was southern blue whiting (*Micromesistius australis*), which had a rich time series of abundance and age compositional data.

We will present the model parameter estimates from the different assumptions of recruitment parameterization and priors and constraints, and show if and when different assumptions may lead to different parameter estimates and model conclusions, and how these differ between MPD and MCMC estimation techniques.

Presentation 17

Modeling Episodic Recruitment Events: Methods and Implications for Stock Assessment in the Presence of Occasional Very Large Year Classes

V. Trijoulet, A. R. Hart, A. E. Weston, R. P. Wildermuth, M. V. Winton, and G. Fay

Abstract

Recruitment, or the estimation of the magnitude of year class strength, is a primary goal of stock assessments. While recruitments are frequently variable, some populations exhibit occasional large cohorts that dominate stock biomass over their lifespan. These episodic recruitment events can then form the economic focus of fisheries while available for exploitation, with catches largely from these single year classes. When developing reference points or target levels of fisheries yield, the inclusion of these large year classes has the potential to modify estimates of productivity of the stock, because these are often derived based on an average level of recruitment over some period of time. When accounted for during stock assessments, modeling decisions to account for episodic recruitment events are somewhat ad hoc and also affect estimates of reference levels of recruitment, important for stock projections and determination of catch advice. Here we discuss the implications of fitting stock assessment models that differ in their treatment (or not) of large year classes when estimating recruitment and when calculating reference points. We use a state-space, age-structured statistical catch-at-age model to test alternatives, characterizing episodic recruitment dynamics based on observations from Atlantic haddock (*Melanogrammus*

aeglefinus) stocks in both the United States and Europe. We fit stock assessment models that ignore differences in year class strength in the estimation and calculation of catch advice, along with models that attempt to account for large year classes, and compare outcomes. We use short-term projections to demonstrate the consequences of these modeling choices for catch advice, and evaluate estimation performance of assessment model alternatives with simulation tests.

Presentation 18

Modeling Gradual Recruitment to Legal Size by Dynamically Accounting for Both Age and Length: Slice Partition

R. McGarvey and J. E. Feenstra

Abstract

Recruitment to legal size of each cohort is a gradual process. It involves the growth of fish as increasing mean length, the (increasing) spread of lengths-at-age of the cohort, and length selectivity or a minimum legal length. To make explicit the proportion that is susceptible to exploitation as a function of body length, partial recruitment is therefore ideally modeled by representing the length distribution of each cohort dynamically based on a growth description. Several ways to approach this problem in discrete-time fishery models have been proposed, but none have been widely adopted, and fully dynamic length- and age-based models are rare in practice. Given that lengths are the most common and inexpensive sample measurement, that nearly all fish that are aged are also measured for length, and that exploitation is nearly always strongly dependent on length, there are abundant data and a clear need to represent lengths-at-age of each cohort, especially as they recruit into legal size. We present one such model formalism, applied to South Australian fish stocks. The lengths of each cohort are assumed to be normally distributed prior to reaching a designated legal minimum length (LML), or some chosen length below which exploitation is negligible. In each model time step, a new portion of the length-at-age distribution grows across LML. These length bins, denoted “slices” (as in slices from a loaf of bread), partition each cohort’s harvestable size range by length. Under this approach, to model the growth of fish in each time step rather than fish transitioned between fixed length bins, fish remain in their respective slices experiencing only mortality, and the slices themselves grow with the overall cohort. Standard length-at-age growth models are applied, specifically, the mean (often von Bertalanffy) and standard deviation (allometric) of the normal cohort lengths-at-age are estimated parametrically, usually integrated with the assessment. This slice-partition approach allows a clean separation of harvestable-size fish from prerecruits based on their length, and is computationally efficient. It can eliminate bias in growth by dynamically accounting for the earlier removals of faster-growing fish in each cohort. It provides an accurate prediction for fitting to the proportions by age and length in fishery samples when the cohort is partially recruited. And we would argue that it has advantages over an empirical age-length key—notably, that it is dynamic and can account for changing levels of fishing mortality in simulation, informs partial recruitment by the growth submodel as well as by the sampled numbers with age and length, and is not subject to sometimes high multinomial sampling error in the lengths-at-age (or ages-at-length), especially with older ages for which sampled numbers are typically low. This assessment model formalism is described in McGarvey et al. (2007).

Presentation 19

Recruitment in the Integrated Assessment for Antarctic Krill

D. Kinzey, G. M. Watters, and C. S. Reiss

Abstract

Recruitment of Antarctic krill around the Antarctic Peninsula (CCAMLR Subarea 48.1) is highly episodic. Research trawl samples in most years from 1982 to 2016 contain very few juvenile krill (<36 mm in length), but about every fifth or sixth year the majority of krill in the samples can be <36 mm. Some studies suggest a typical cycle of two years of high recruitment, followed by three or four years of low recruitment. The integrated assessment for Antarctic krill models recruitment as annual deviations from a mean value. Departures from a deterministic spawner–recruit relationship, either Beverton–Holt or Ricker, are allowed, but penalized. Different values of the "sigmar" parameter for recruitment variability may be estimated or prespecified to allow for differing ranges of recruitment variability. This method was derived from the approach used to model recruitment by the Alaska Fisheries Science Center's `amak.tpl` in 2003.[1] There is little evidence in the model for correlations between spawning stock size and recruitment success the following year. The climate around Antarctica is changing rapidly, with unknown effects on future recruitment and survival of krill. The magnitude of movement of krill into Subarea 48.1 from surrounding regions is unknown, but potentially substantial. In making forward projections to estimate the effects of potential future harvests, the recruitment series estimated for the most recent 20-year period with summer research surveys is projected forward, and proposed catches are removed from the simulated population.

Presentation 20

Addressing Cohort Strength Correlated Ageing Error in Fishery Stock Assessment

O. S. Hamel and I. J. Stewart

Abstract

Age data are important in stock assessment for estimating parameters such as growth rate, age of maturity, fecundity at age, and the natural mortality rate. However, even modern otolith annulus counting techniques are subject to uncertainty and error, as seen in double- and cross-reads and through the use of various validation techniques. Ageing uncertainty (and bias) is accounted for in stock assessments via lab-, era-, and/or reader-specific ageing error matrices, which generally result in improved parameter estimation and statistical fit to age data. In the Pacific hake assessment, however, ageing error matrices did not resolve poor fits to age data for strong year classes. The Pacific hake stock is characterized by infrequent strong year classes, typically

[1] The Assessment Method for Alaska (AMAK) was developed at NOAA Fisheries' Alaska Fisheries Science Center by Dr. James Ianelli using AD Model Builder. This is an age-based estimation model that supports multiple fisheries and sparse data availability.

surrounded by average and below-average cohorts. Ageing is conducted on a yearly basis, such that readers know the year of collection. We hypothesized that readers are more likely to assign uncertain reads to predominant ages. In order to test the hypothesis that strong year classes effectively experience less ageing error, we conducted a double-blind study wherein previously read otoliths across years were reread without the age readers having knowledge of the collection year. Results confirmed that strong year classes experienced less effective ageing error in the regular course of ageing otoliths. Fits to age data and estimation of year class strength improved greatly when cohort-specific ageing error was accounted for in the assessment. The "strong cohort effect" is a potential problem for any species with appreciable ageing imprecision and a high degree of recruitment variability.

Presentation 21

Exploring Predictions of Recruitments Using Individual Mean Weight

I. Payá

Abstract

Chilean hoki, Chilean hake, and jack mackerel inhabit the Humboldt current system, where there are huge environmental changes related with El Niño events and decadal oscillations. Their recruitments have large fluctuations, autocorrelations, and some strong annual classes. Their stock–recruitment models cannot fit these fluctuations unless process errors are included in the stock assessment models. These process errors have been related to environmental variables, but the models have not been able to fit the strong annual classes. These stocks are overexploited, their age structures are truncated, and their mean weight at age have changed through the years. The effects of age truncation on the spawning biomass, and therefore on recruitments, are predicted by the classical stock–recruitment model. However, the impact of age truncation—not only on spawning stock, but also on the whole stock—seems not to have been investigated. This work in progress tries to understand the impact of change of mean individual weight of the whole stock on recruitments of mentioned stocks. State variables used were the results of age-structure stock assessment models with process errors in the stock–recruitment models that were conducted in AD Model Builder (ADMB).[2] Different generalized additive models (GAM) were analyzed and compared using AIC. The best models included the numbers of individuals and individual mean weight of the previous year. Against expectations, the El Niño index did not improve the GAM. The three species form schools and have been fished by purse seiners, and therefore the positive contributions to recruitment of small weights could be related to more fish of similar sizes producing more protection.

[2] http://www.admb-project.org/

Presentation 22

See Keynote Address 4.

Presentation 23

The Importance of Accurately Accounting for Geographic Stock Structure in Recruitment Estimation

S. Cadrin, D. Goethel, L. Kerr, G. Fay, and M. Morse

Abstract

Accurate estimation of recruitment relies on the identification of a self-sustaining stock, but many fishery management units do not reflect the underlying geographic structure of the population. Stock identification, alternative stock assessments, and simulation testing for several Atlantic fisheries demonstrate how assumed stock structure influences estimates of recruitment. Incorporating stock structure and stock mixing into estimation models changed the perception of recruitment events for yellowtail flounder (*Pleuronectes ferruginea*), Atlantic bluefin tuna (*Thunnus thynnus*), and the northern stock of black sea bass (*Centropristis striata*). The influence of stock structure on recruitment estimates depended on movement rates and relative stock sizes. Simulation testing conditioned on these case studies suggests that correct identification of stock structure improves model performance, but accounting for movement does not always improve general model performance. These case studies demonstrate that misspecifying stock structure and mixing can produce misleading estimates of spawning stock biomass, recruitment, and the stock–recruitment relationship, as well as inaccurate estimates of reference points for overfishing or rebuilding.

Presentation 24

Estimating Recruitment in Spatially Explicit Stock Assessment Models: The Impact of Population Structure Assumptions on Recruitment Bias

K. Bosley, D. Goethel, A. Berger, D. Hanselman, B. Langseth, A. Schueller, and J. Deroba

Abstract

Recruitment estimation within stock assessment models can be difficult when limited data on year class strength exist, and estimation difficulties may be exacerbated as demographic data become more sparse (i.e., when data are disaggregated to perform a spatially explicit stock assessment). However, spatially explicit modeling techniques may improve estimates of population productivity by simultaneously assessing individual spawning components (along with the connectivity among them) instead of aggregating data and parameter estimates across multiple reproductive units (which commonly occurs with closed population models). Although spatial models can more accurately represent the underlying population dynamics, there has been little research into the potential risks associated with incorrect assumptions regarding population structure and how this might impact the resulting productivity estimates. We develop a spatially explicit tag-integrated assessment model that directly estimates movement and is able to account for a variety of population structure assumptions (e.g., panmictic, single-population with spatial heterogeneity, metapopulation, and natal homing). A simulation framework is applied to compare bias in recruitment estimates when population structure is correctly or incorrectly specified for both spatially explicit and spatially aggregated assessment methods. We also investigate how recruitment and movement assumptions interact within spatially explicit models to determine whether certain parameterizations may act to reduce parameter correlation. When the underlying population structure is correctly specified, recruitment and movement are often well estimated. However, misspecification of spatial structure can lead to biases equivalent to or worse than assuming a panmictic population. Even when incorrectly specified, spatial models may be more useful than aggregated models, because outputs are provided on scales more likely to represent real-world biology and may better inform fine-scale spatial management.

Presentation 25

Spatial Considerations for Assessment

F. Contreras and J. C. Quiroz

Abstract

The pink cusk-eel (Australian rockling or kingklip, *Genypterus blacodes*) is managed in Chile in two zones, separating the stocks by administrative causes. Each zone has indices of abundance (catch per unit effort), catch-at-age matrices, landings, and parameters of growth and maturity differentiated by zones. At present, the stock assessment considers stock analysis separately, without interaction; however, similar levels of recruitment are obtained in terms of trends. Therefore, a spatial model will be developed to analyze the combined information and analyze the implications on management.

Presentation 26

Recruitment Dynamics in a Changing Environment: Integrating Spatial and Temporal Variability into Stock Assessment and Management Strategies

K. F. Johnson, E. Councill, J. T. Thorson, E. Brooks, R. D. Methot, and A. E. Punt

Abstract

Estimates of the recruitment of juveniles to marine populations are often large or small for several years in a row (i.e., autocorrelated recruitment). Autocorrelated recruitment can be due to numerous factors, but typically is attributed to multiyear environmental drivers affecting early-life survival rates. We used a simulation experiment to evaluate the estimability of

autocorrelation within a stock assessment model over a range of levels of autocorrelation in recruitment deviations, given that it is often unfeasible to model recruitment variability using environmental linkages. The precision and accuracy of estimated autocorrelation, and the ability of an integrated age-structured stock assessment framework to forecast the dynamics of the system, were compared for scenarios where the autocorrelation parameter within the assessment was fixed at zero, fixed at its true value, internally estimated within the integrated model, or input as a fixed value determined using an external estimation procedure that computed the sample autocorrelation of estimated recruitment deviations. Internal estimates of autocorrelation were biased toward extreme values, while estimates of autocorrelation obtained from the external estimation procedure were nearly unbiased. Forecast performance was poor (i.e., true biomass outside the predictive interval for the forecasted biomass) when autocorrelation was ignored, but was nonzero in the simulation. Applying the external estimation procedure generally improved forecast performance by decreasing forecast error and improving forecast interval coverage. However, estimates of autocorrelation were shown to degrade when fewer than 40 years of recruitment estimates were available.

Presentation 27

Modeling the Impacts of Two Age-Related Portfolio Effects on Recruitment Variability with and without a Marine Reserve

C. R. McGilliard, A. E. Punt, R. Hilborn, and T. Essington

Abstract

Many rockfish species are long-lived and thought to be susceptible to being overfished. Hypotheses about the importance of older female rockfish to population persistence have led to arguments that marine reserves are needed to ensure the sustainability of rockfish populations. However, the implications of these hypotheses for rockfish population dynamics are still unclear. We modeled two mechanisms by which reducing the proportion of older fish in a population has been hypothesized to influence sustainability, and explored whether these mechanisms influenced mean population dynamics and recruitment variability. We explored whether populations with these mechanisms could be managed more sustainably with a marine reserve in addition to a constant fishing mortality rate (*F*) than with a constant *F* alone. Both hypotheses can be seen as portfolio effects, whereby risk of recruitment failure is spread over a "portfolio" of maternal ages. First, we modeled a spawning window effect whereby mothers of different ages spawned in different times or locations (windows) with local environmental conditions. Second, we modeled an offspring size effect whereby older mothers produced larger offspring than younger mothers, where length of a starvation period over which offspring could survive increased with maternal age. Recruitment variability resulting from both models was 55–65% lower than for models without maternal age-related portfolio effects in the absence of fishing, and increased with increases in *F*s for both models. An offspring size effect caused lower output reproductive rates such that the specified reproductive rate input as a model parameter was no longer the realized rate measured as the reproductive rate observed in model results; this quirk is not addressed in previous analyses of offspring size effects. We conducted a standardization such that offspring size effect and control models had the same observed reproductive rates.

A comparison of long-term catch, the probability of falling below a biomass threshold, and recruitment variability over a range of exploitation rates for models with an age-related portfolio effect showed no benefit of a marine reserve implemented in addition to a constant *F* (as compared to a constant *F* alone) for populations with sedentary adults and sedentary or mobile larvae.

Presentation 28

See Keynote Address 5.

Presentation 29

Letting the "Data" Speak for Themselves: The Use of Stock–Recruitment Relationships to Determine a Biomass Threshold above which Management Should Aim to Keep a Resource

C. L. de Moor and D. S. Butterworth

Abstract

Recruitment in fisheries is well known to be highly variable, and in most cases this variability swamps visible indications of dependence of recruitment on (spawner) biomass. As a result, many short-term predictions informing quantitative management advice for particularly low trophic level fisheries rely on, say, the recent median recruitment and associated variability. However, there must nevertheless be some biomass below which recruitment success will be impaired. The difficulty is how to estimate this threshold, sometimes called a biomass limit reference point (B_{lim}). This value is relevant not only to short-term predictions at low biomass, but even more so in a Management Strategy Evaluation framework where future biomass may be simulated to be near this B_{lim}. A Beverton–Holt stock–recruitment relationship is sometimes used but may not be robust, as steepness is frequently not well determined. Alternatively, the hockey stick form can provide a more robust estimate of average unexploited biomass and expected recruitment at higher biomasses, but the biomass below which expected recruitment decreases can also be difficult to estimate, particularly where data are sparse at low biomass. We investigate parametric and nonparametric forms (such as kernel smoothing techniques) for stock–recruitment relationships which avoid prejudicing estimates of such a B_{lim} (with their associated implications for acceptable levels of risk) by preconceptions about functional forms. Rather, we try to let the stock and recruitment estimates ("data") speak more for themselves. The implications of the alternative choices of stock–recruitment relationships for future resource risk are of particular importance for South African sardine, given current low levels of abundance.

Presentation 30

Shifts in Stock Productivity: Recruitment Potential and Static/Dynamic Reference Points

A. M. Berger

Abstract

Reference points guide rational fishery management systems worldwide, and often form the basis for defining sustainable fishing levels and population sizes, population states that result in preferred fishery performance, and population states that trigger management action. Many reference points used for determining stock status are presupposed by equilibrium population assumptions, which may be inappropriate when stock productivity differs in space or through time as a result of persistent environmental change, variable management and fishing practices, predator–prey dynamics, and many other factors. Static reference points may not be robust to new equilibrium states (e.g., due to regime shifts), leading to a mismatch between the productive capacity of the population and the benchmarks used to guide management. Dynamic reference points, e.g., dynamic B_0, could be used to take into account shifts in the underlying productivity of the population, but careful consideration of the recruitment dynamics is warranted to ensure that management benchmarks are informed by current productivity potential, not cyclical, white-noise, or other process-based errors in recruitment estimation. Static and dynamic reference points were calculated for 18 recent U.S. West Coast groundfish stock assessments to first evaluate if differences in depletion-based stock status indicators were apparent between the two approaches. Second, a set of simulations was conducted to further compare differences between static and dynamic reference points under alternative states of nature driven by recruitment dynamics (productivity regime), fishing dynamics (mortality regime), and species biology and longevity. The use of dynamic B_0 often implies a different state of the stock under directional productivity regime shifts, but is more similar to static (equilibrium) B_0 under cyclic or white-noise productivity scenarios. Despite the approach used to define reference points for current stock status and management, it remains unclear how best to forecast recruitment when developing stock rebuilding plans, and is an area of future research.

Presentation 31

A Simulation Approach Developed to Assess Resilience, Rebuilding Time as a Function of Steepness, and Perceived Risk to Reference Points on Indian and Atlantic Ocean Tuna and Tuna-Like Populations

R. Sharma

Abstract

A simulation approach was developed using the life history characteristics of albacore (*Thunnus alalunga*), skipjack (*Katsuwonus pelamis*), bigeye (*Thunnus obesus*), and yellowfin tuna (*Thunnus albacares*), and tested the interim target and limit reference points recommended by the Indian Ocean Tuna Commission and the International Commission for the Conservation of Atlantic Tunas. The effect of fishing at optimal rates and the risk of going below these reference points are evaluated, and the trade-offs between the harvest rates, the limit reference points, the autocorrelation of the process error, and the time to recovery to the target and limit abundance levels are evaluated. Managers eventually have to evaluate a trade-off on the risk to the resource and the optimal catch levels on the long term for the stock being managed. The approach presented here displays the probability of adverse events occurring and evaluates different outcomes based on the specified thresholds and rates at which the stocks are fished. The concept of Type I and Type II errors is introduced, primarily defining the probability of taking a management action when it was not needed (a false positive, the risk from taking a management action on a fishery) versus failing to take a management action when it is needed (a false negative, the risk of failing to protect the resource when needed). For illustrative uses, we demonstrate how well it would work for theoretical albacore (ALB), skipjack (SKP), bigeye (BET), and yellowfin (YFT) tuna stocks similar to the ones used in models in the Indian Ocean based on life history parameters, and North Atlantic Ocean ALB and swordfish (*Xiphias gladius*).

The risks of falling below 40% of S_{MSY} are below 7% and 10% for ALB and SKP respectively, if fished at optimal levels. For BET and YFT, these risks are less than 1% each to fall below 50% of S_{MSY} and 40% of S_{MSY} respectively. Thus, based on these limit reference points, managers should be willing to take a management action every 15 years for ALB, every 10 years for SKP, and every 100 years for BET and YFT respectively, provided fishing is kept at optimal levels. The risk of failing to detect an issue with overfishing is less than 2% for ALB at levels exceeding optimal fishing levels, about 40% for SKP, and about 60% for BET and YFT at these reference points. If managers wish to minimize the risk of failing to detect overfishing for SKP, BET, and YFT, these stocks should be managed at levels higher than 40% of S_{MSY} for SKP and YFT, and >50% of S_{MSY} for BET. The other reference point, namely F_{MSY}, indicates that, when exceeded by a factor of 1.5, all tuna stocks will rarely recover to optimal levels of spawning stock size or yield unless severe harvest controls are applied on these stocks. Minor controls have insignificant effects on recovery times, indicating that when fishing exceeds F_{MSY} levels, a longer recovery time to both the threshold and limit recovery times can be expected. Based on the results of this study, a more robust approach for critical reference points for management would be in the realm of 0.6–0.8 S_{MSY} (and not to exceed 1.2 F_{MSY} for all tuna stocks). This would keep the Type II error (risk of overfishing) to 10–20% for all Indian Ocean tuna stocks, and ensure recovery to optimal yield levels within two or three generations for all stocks other than SKP and BET with simple harvest control rules.

For the Atlantic Ocean, similar trends were seen for swordfish (SWO) and ALB, where this approach was tested. In essence, Atlantic ALB and SWO would recover to optimal stock sizes quickly if their limits would be set at 0.6 $S_{MSY.}$ If stocks were fished at rates exceeding F_{MSY} by 50% or more, recovery to target reference points would never occur. Both SWO and ALB recover to limit reference points in relatively short amounts of time (less than five years for ALB and 10 years for SWO) if simple control rules reduce the operating fishing mortality by a third. As in the case of the Indian Ocean populations, the risk of failing to detect a drop in productivity if it actually occurs was high for ALB (0.9) and SWO (0.85). However, if both stocks are managed to optimal SSB, the chance that they would fall below that is low (<2% for both stocks). This is primarily driven by the high values of steepness used for both these stocks (0.9 for SWO and 0.8 for ALB).

The following conclusions were drawn from the simulations:

1. The risks of falling below 40% of SSB_{MSY} are low (<10% for most populations) if the limit is 40% SSB_{MSY} if operating at F_{MSY} and $f < 0.4$, and steepness is between 0.8 and 0.9.
2. However, the risk of failing to detect a risk to the resource is high (>0.9) in most cases.
3. The risk to the resource is lowest if $F_{target} < F_{MSY}$.
4. SSB_{LIM} >0.4 SSB_{MSY} if you are to minimize the risk of recruitment overfishing.
5. Steepness is positively correlated to recovery time and negatively correlated to probability of exceeding thresholds.

Presentation 32

Unraveling the Recruitment Problem: A Review of Environmentally Informed Forecasting

M. A. Haltuch, J. Brodziak, L. Brooks, J. A. Devine,K. F. Johnson, N. Klibansky, R. D. M. Nash, M. R. Payne, K. W. Shertzer, S. Subbey, and B. Wells

Abstract
Articles describing and hypothesizing the impact of climate change and environmental processes on vital rates of fish stocks are increasing in frequency, and concomitant with that is interest to incorporate these processes in fish stock assessments and forecasting models. Basson (1999) evaluated the value of including these effects in forecasting, concluding that the improvements were minimal while potential spurious relationships were sufficient to advise against inclusion at that time. In this review, we evaluate progress in implementing environmental factors in stock–recruitment projections and Management Strategy Evaluations since the publication of Basson (1999) by considering manuscripts that incorporate environmental processes into recruitment forecasting and others which also complete full-cycle MSEs or conduct simulations investigating harvest control rules. The only successes identified were for species with a short prerecruit survival window (e.g., opportunistic life history strategy), where the abbreviated life span made it easier to identify one or a limited set of key drivers that directly impact dynamics. Autoregressive methods appeared to perform as well, if not better, for species with a longer prerecruit survival window (e.g., seasonal, interannual) during which the environment could potentially exert influence. We argue that the inclusion of environmental drivers into assessment and forecasting

is most likely to be successful for species with short prerecruit survival windows (e.g., squid, sardine) and for those that have bottlenecks in their life histories during which the environment can exert a well defined pressure (e.g., anadromous fishes, those reliant on nursery areas). The effects of the environment may be more complicated and variable for species with a longer prerecruit survival window, reducing our ability to quantify the relationship between environment and recruitment. To accommodate this, we advise that future research should advance from correlative approaches and instead focus on relevant species-specific, spatiotemporal scale process studies to improve mechanical understanding of abiotic–biotic interactions.

Presentation 33

Strategy to Evaluate the Risks and Benefits of Including Environmental Predictors of Recruitment

L. Denson, J. Walter, E. Babcock, and R. Sharma

Abstract

Incorporating environmental covariates into a stock assessment has had a checkered performance history. There has been great progress in the availability of environmental data, the understanding of mechanistic drivers of fish recruitment, and the mechanics for incorporating these drivers into stock assessments. Conversely, simulation work has raised the concern that getting the fish–environment relationship wrong could do more harm than good. Given this history, there has rarely been explicit calculation of risk as to whether the benefit of including environmental covariates outweighs the cost of being wrong, nor has this information been used to inform decision-making in the face of uncertainty. We propose a strategy for evaluating whether to include or exclude the environment in a stock assessment. This can be done through conditional simulations (meaning they largely reflect each particular assessment) and constructing decision tables to calculate whether the benefits of including an environmental covariate outweigh the risk of getting it wrong, whether partially (environment has no effect) or entirely (environment has the opposite effect). We perform a crossed design where an operating model with and without an environmental covariate, coupled with an assessment model with and without the covariate, are used to determine the expected benefits of each scenario. Further, by creating best-, moderate-, and worst-case scenarios, it is possible to produce a decision table that informs on the expected value of each scenario, providing decision support advice under environmental uncertainty.

Presentation 34

Good Practices for Including Environmental Data to Model Spawner–Recruit Dynamics and Recruitment Variability in Integrated Stock Assessments: A Small Pelagic Species Case Study

P. R. Crone, H.-H. Lee, K. R. Piner, and M. N. Maunder

Abstract
The spawner–recruit relationship is a fundamental parameterization in fish stock assessment models that generally represents the underlying productivity exhibited by the stock and thus, a critical biological process to consider when assessing the status of a population for advising management. An important assumption when developing spawner–recruit relationships, particularly those applicable to short-lived and relatively productive fish stocks, is the extent to which the environment (oceanographic conditions) versus parental stock (spawner) size alone influences recruitment success. Although it is broadly recognized that oceanographic factors likely impact recruitment survival to some degree in any given year, very few assessment applications have actually used environmental data to inform recruitment estimation within the model. Two methods of incorporating environmental information in an assessment model are evaluated in this study, based on 1) including an environmental covariate as an additional parameter inside the stock–recruitment function, and 2) using an environmental covariate as an index (proxy for survey-based recruitment time series) outside the stock–recruitment function. The alternative methods for including an environmental factor were implemented in a popular integrated assessment model for a commercially important species (Pacific sardine) of a major small pelagic fish assemblage of the California Current Ecosystem. Simulation methods were used to compare results and examine how environment–recruit considerations in the assessment influence model performance. Model performance was examined statistically with respect to the quality (bias and precision) of critical estimated parameters of the spawner–recruit relationship (e.g., virgin recruitment) and derived quantities useful to management (e.g., terminal-year stock biomass). Finally, statistical and practical considerations associated with the choice of the method for including environmental data in the stock assessment model are also discussed.

Presentation 35

Environmental Dependence of Pacific Sardine Recruitment—Another Spurious Correlation?

J. Zwolinski

Abstract
A collapse of Pacific sardine in the northeastern Pacific during a cold period, 1945 to 1970, and its resurgence during a warm period, after 1980, inspired the hypothesis that recruitment to the northern stock is related to sea surface temperature (SST). Supporting this hypothesis, recruitment indices from a 2010 sardine stock assessment correlated with an index of coastal SST measured at the Scripps Institution of Oceanography (SIO) pier. This index (SST_{SIO}) was used from 2000 to 2011 in a novel management strategy to modulate the U.S. fishing exploitation rate

of sardine. However, after SST_{SIO} failed to track low sardine recruitments during 2006 to 2009, it was replaced by an index of oceanic SST measured quarterly off Southern California (SST_{annual}). Contemporaneously, we showed that another environmental index ($PDO_{combined}$), derived from a combination of summer and spring Pacific Decadal Oscillation values, also correlated well with logarithmic recruitment success estimated by the 2010 stock assessment model. We cautioned, however, that this stock assessment model included landings data from both the northern and southern stocks, and therefore, that its recruitment indices could be confounded. Here, we redo the analysis using recruitment indices from 2016 and 2017 stock assessments that include only landings data from the northern stock. We confirm that recruitment to the northern stock of Pacific sardine does correlate to the environment as described by $PDO_{combined}$, but, contrary to previous analyses, it does not correlate to SST_{annual}.

Presentation 36

See Keynote Address 6.

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