BOCACCIONOMICS: THE EFFECTIVENESS OF PRE-RECRUIT INDICES FOR ASSESSMENT AND MANAGEMENT OF BOCACCIO

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ABSTRACT

Bocaccio (*Sebastes paucispinis*) has been one of the most important species of rockfish to both commercial and recreational fisheries in California Current waters over the last century. Actions taken to rebuild the stock of bocaccio residing off of California have been responsible for dramatic changes on both commercial and recreational groundfish management and total allowable yields of most groundfish species in California waters over the last decade, including a virtual cessation of commercial and recreational fishing in 2003. In retrospect, it was determined that a strong 1999 year class was moving through the fishery at that time, resulting in high catch rates during a period in which management sought to drastically reduce catch. This results in a paradox, in which rebuilding requires strong year classes, which requires further constraints on fishing during periods in which the condition of the stock seems to be improving. Although this paradox exists for all stocks undergoing rebuilding, it is particularly pronounced for bocaccio as they have among the greatest variability in recruitment observed in any species of West Coast rockfish, as well as very rapid growth and very young age at recruitment to the recreational fishery. Consequently, accurate indices of the strength of incoming year classes both improve stock assessment estimates of future (near term) abundance trends, as well as aid regulators in making management decisions during those infrequent periods of high abundance of young fish. We discuss several indices of recruitment strength based on data on young bocaccio, evaluate their relative performance in the early detection of strong year classes, and consider both the oceanographic factors that may drive recruitment variability, as well as the spatial patterns of recruitment events which may aid in interpreting these indices.

INTRODUCTION

Bocaccio (*Sebastes paucispinis*) have long been one of the most important targets of both commercial and recreational fisheries in California waters, accounting for between 25 and 30% of the commercial and recreational rockfish (*Sebastes* spp.) catch over the past century. However, this percentage has declined in recent years as a result of stock declines, restrictive management actions and the development of alternative fisheries. Catches and abundance began to fall during the 1980s and declined rapidly in the 1990s, due to a combination of high harvest rates and poor ocean conditions (MacCall 2003; Field et al. 2009). More recently, since the southern sub-stock of bocaccio (currently representing the population of bocaccio south of Cape Blanco, OR)[1] was declared overfished by the Pacific Fishery Management Council (PFMC) in 1999,[2] management measures have been responsible for even more significant reductions of both commercial and recreational catches. Management measures included a virtual cessation of most commercial and recreational fishing in 2003, following a very pessimistic assessment of stock status in 2002 (MacCall et al. 2002).

The landings limitations and area closures that followed the 2002 assessment led to considerable economic hardships during a period in which many fishermen complained bitterly that bocaccio were "more abundant than ever before." Management constraints implemented to rebuild bocaccio, as well as six other species of rockfishes that were declared overfished, have substantially reduced rockfish landings coastwide since then (Berkeley et al. 2004, Punt and Ralston 2007). Although the stock is still estimated to have been in an overfished condition throughout the 1990s, the most recent assessment indicates that the population was not as depleted as estimated in the 2002 assessment (MacCall 2003, Field et al. 2009). Additionally, it is now clear that a relatively strong (relative to parental biomass) 1999 year class had indeed been moving through the fishery at that time, following a decade of record-low recruitment

[1]This paper investigates the recruitment and abundance trends of the southern sub-stock of bocaccio only, currently defined as waters south of Cape Blanco, Oregon to the U.S./Mexico border (Field et al. 2009). Bocaccio in U.S. waters north of Cape Blanco are likely to be more connected from a population perspective to bocaccio off of British Columbia, Canada, for which abundance has also been estimated to be at very low levels (Stanley et al. 2009).

[2]The PFMC is the management body charged with implementing the requirements of federal law for west coast groundfish fisheries, and defines a stock or population as being "overfished" if the stock is at or below the minimum stock size threshold (MSST). The MSST for West Coast rockfish is currently defined as 25% of the estimated spawning biomass or spawning potential that would occur in an unfished condition.

levels that began in 1990. Thus, the fishermen's complaints had validity, in that the bocaccio population was undergoing a significant increase in abundance during a period in which management sought to drastically reduce catch.

Consequently, management of bocaccio in recent years has been complicated by both changes in management regimes and objectives, and variable population trajectories driven (to a large extent) by highly variable recruitment. Despite the significant socio-economic hardships, management actions have been effective at reducing mortality. This combined with several recent strong year classes (1999, 2003, 2005), have resulted in an increase in abundance and spawning output over the past decade. Although the current estimate of abundance is substantially higher than those of the 1990s, the population will remain in "rebuilding" status until it has recovered to the target level of abundance, currently set to 40% of the unfished abundance for West Coast groundfish (Punt and Ralston 2007; Field and He 2009). In an analysis of the likely time to rebuild to this target level, recruitment variability remains among the most significant factors contributing to rebuilding success or failure by the currently adopted management target of 2026 (Field and He 2009). Rebuilding plans and targets are developed by simulating forward projections of the population under a variety of harvest rates to determine the probability of recovering to target abundance levels (40% of the unfished spawning potential) by target years that are defined by law (Punt 2003; Punt and Ralston 2007). For bocaccio, the current target is the year 2026, and while the most recent assessment projects that this rebuilding target has a greater than 75% probability of being met (at current harvest rates), this leaves an approximately 25% probability of not achieving this target. Most of the uncertainty regarding the probability of rebuilding is a consequence of recruitment stochasticity and the inability to accurately forecast future recruitment events.

Information regarding the magnitude and the determinants of impending year class strength can be of utility for tactical management actions, such as short-term catch projections and consideration of seasonal and area closures, particularly with respect to avoiding the mismatch between stock trends and management actions that took place following the 1999 year class and the overfishing declaration. In this manuscript, we will first briefly describe the early life history of bocaccio and introduce four fishery-independent sources of information regarding recruitment success as indexed by the abundance of young-of-the-year (YOY) bocaccio, and describe the methods typically used to develop recruitment indices from these data. Next we will provide a short overview of the structure and results of the most recent bocaccio assessment, including biomass trends and exploitation rates, but with a focus on the estimation of recruitment in either the most recent or in past stock assessments. Then we will evaluate the relative performance of the recruitment indices in predicting impending strong year classes (assuming that the stock assessment estimates of recruitment based on length composition data represent "true" recruitment). Finally, we will consider the performance of recruitment indices, including the spatial patterns of recruitment events and how these indices may relate to climate variables, and discuss how these indices could or should be used in future assessments and management.

DATA AND METHODS

Life history

Like all rockfish, bocaccio are primitively viviparous and bear live young at parturition. Copulation typically takes place during September–October, although fertilization is often delayed, and parturition occurs during the winter months (Moser 1967; Wyllie Echeverria, 1987). Figure 1 provides a conceptual overview of early life history stages of bocaccio following parturition. Early stage larvae (pre-flexion, approximately 0 to 20 days) are weak swimmers, however post-flexion late-stage larvae do have some swimming capabilities. Bocaccio are one of a very few number of *Sebastes* species for which data on larval abundance and distribution are available from 1951 to the present from California Cooperative Oceanic Fisheries Investigation research collections, as the larvae of most *Sebastes* species cannot be distinguished using morphological characteristics (Moser et al. 1977). These data have long been used as an indicator of population abundance in stock assessments (MacCall 2003; Field et al. 2009), under the assumption that larval abundance is a reflection of the female reproductive effort and thus spawning biomass. More recently, Ralston and MacFarlane 2010 have used these data to estimate total (rather than relative) spawning biomass. However, as year class strength for most California Current fish populations is thought to be set following parturition (Lasker 1977, Hollowed 1992), larval abundance data are not considered a reliable indicator of recruitment.

Both larval and juvenile stages are typically found in the mixed layer from 10 to 100 meters depth, (Ahlstrom 1959; Ross and Larson 2003). Pelagic juveniles are capable swimmers, and there is some evidence that both larval and juvenile stages of bocaccio tend to occur in the shallower sections of the water column (Ross and Larson 2003), which would imply greater dispersal relative to more deeply oriented larval and juvenile rockfish based on the propagule dispersal models

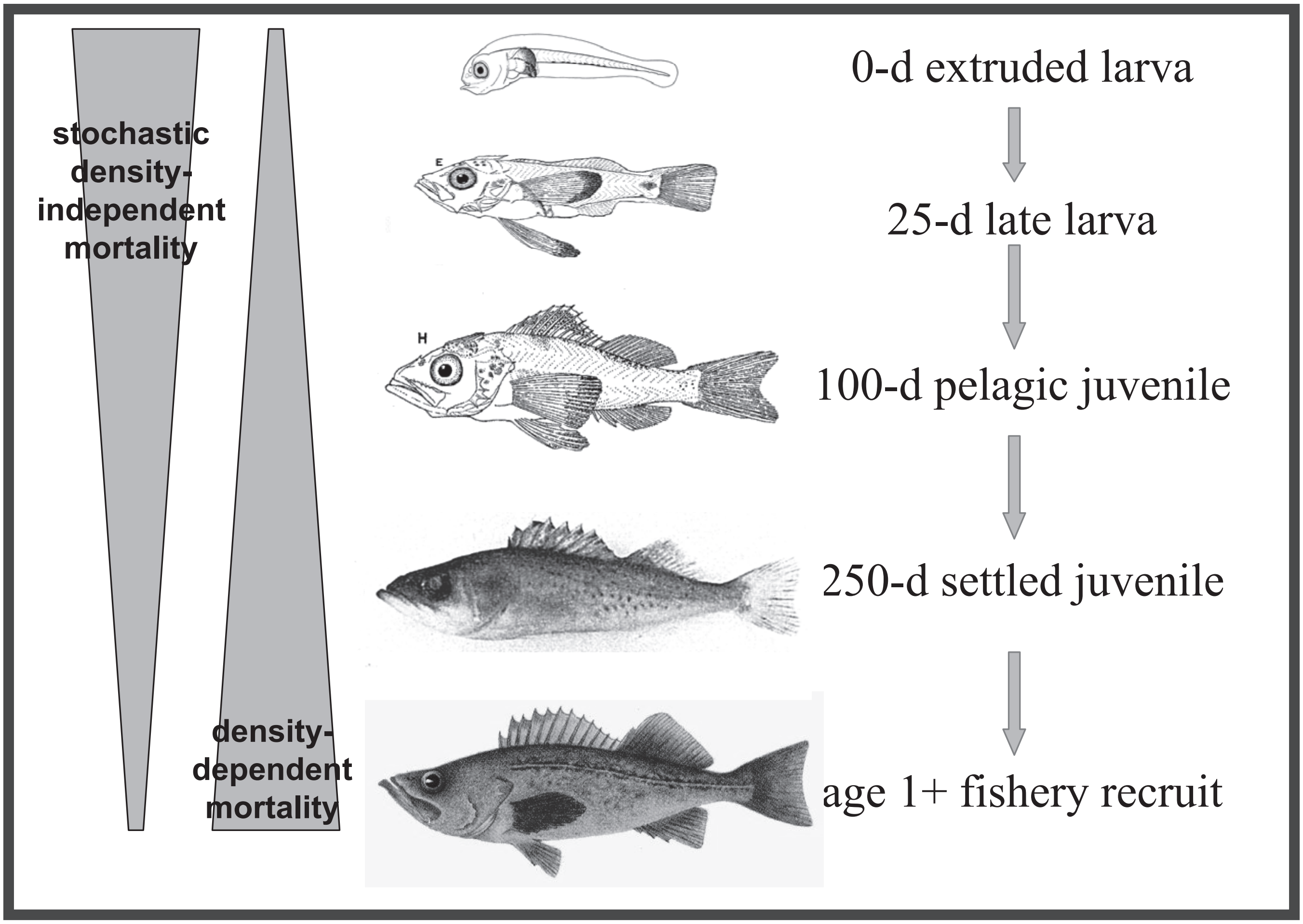

Figure 1. Ontogenetic sequence of bocaccio life history stages, as related to a conceptual model of the nature of density dependent and density independent mortality sources for each stage.

of Peterson et al. (2010). This may also lead to relatively greater dispersal to nearshore habitats immediately prior to settlement to benthic habitats, as bocaccio are entrained in surface waters that are pushed closer to the coastline than waters at depth. Settlement to nearshore and demersal habitats begins in late spring and extends throughout the summer months. Pelagic YOY typically recruit to shallow habitats, and subadult bocaccio are more common in shallower water than adults, with an apparent ontogenetic movement of adults to deeper water with size and/or age. Adult bocaccio occur in a broad range of habitats and depths, including midwater, although high densities tend to be more associated with more complex (e.g., rocky, high relief) substrates.

The rapid growth of bocaccio is also initiated at the juvenile stage; Woodbury and Ralston (1991) describe linear species-specific growth rates (and interannual variability in the same) for juvenile rockfish in approximately the first 50 to 150 days of life. Bocaccio growth rates ranged from 0.56 to 0.97 mm/day, the highest rate amongst the *Sebastes* species. This rapid growth continues into the settled juvenile and young adult stages, with fish growing to a mean size of 27 and 36 cm (fork length) by ages 1.5 and 2.5 respectively, the most rapid growth of any West Coast *Sebastes*. As bocaccio have been proven to be very difficult to age (Andrews et al. 2005; Piner et al. 2006), and age data are consequently not routinely developed or used in assessments, this rapid growth provides the primary means of estimating recruitment variability and year-class (cohort) strength from length frequency data (Ralston and Ianelli 1998). Such rapid growth is fueled by almost exclusive piscivory; Phillips (1964) reported that recently settled YOY typically preyed on other YOY rockfishes, surfperches (Embiotocidae), jack mackerel (*Trachurus symetricus*) and other small inshore species, and that such patterns of piscivory are retained throughout their life.[3]

[3]Juvenile rockfish appear to dominate the prey spectrum of juvenile bocaccio, as the original food habits notes of Phillips report that *Sebastes jordani, S. goodei, S. mystinus* and other species represented more than 60% of all prey, while the *Sebastes* genus, primarily *S. jordani*, represented 40% of the prey of adult *S. paucispinis*. Access to Phillip's original notes was graciously provided by Tim Thomas of the Monterey Maritime Museum.

Stock assessment results

The most recent bocaccio assessment was adopted as the scientific basis for management actions by the PFMC in September 2009 (Field et al. 2009). The resulting abundance trends and recruitment estimates were highly consistent with previous assessments (MacCall 2003; MacCall 2007), although changes in the estimated catch history resulted in a generally more optimistic perception of the stock status and productivity. The modeling framework used in this assessment (and most other West Coast groundfish assessments) is the age structured model Stock Synthesis III (Methot 2009a, 2009b). The model treats a cohort, or year class, as a collection of fish whose size-at-age is characterized by a mean and a variance, such that the numbers at age are distributed across defined length bins. Several sources of both fishery-dependent (catch per unit effort data) and fishery independent (surveys of larval abundance, trawl surveys, and juvenile abundance indices) information are available for this species, and there are hundreds of thousands of length observations across various fisheries and surveys which inform population structure and estimates of recruitment. In order to evaluate the performance of the recruitment indices independently from their effect in the assessment model, the adopted stock assessment model was re-run with the recruitment indices removed. This is done to avoid contaminating the estimated "true" recruitment time series,[4] based exclusively on fishery and survey abundance and length frequency data, to recruitment indices derived solely from the suite of juvenile (age-0) abundance data explored in this manuscript.

Juvenile abundance data

We evaluate four sources of juvenile abundance data for consideration as indices of impending recruitment for bocaccio assessment and management. The first is an index of pelagic juvenile abundance based on data from a standardized midwater trawl survey specifically designed to estimate the abundance of pelagic juvenile rockfishes, and to develop indices of year-class strength for use in groundfish stock assessments (Ralston and Howard 1995). The remaining three indices reflect a slightly later life history stage for YOY rockfish, as settling or recently settled juveniles from power plant impingement studies, recreational pier fisheries, and submersible (*in situ*) surveys of fish abundance at both oil platforms and natural reef habitats in the Southern California Bight. We develop these data sources into

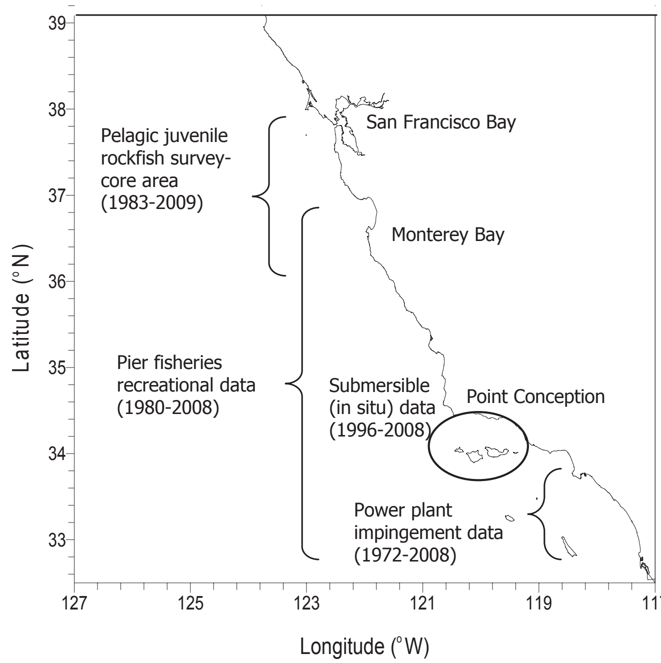

Figure 2. Spatial distribution of the four sources of data on juvenile abundance used to develop recruitment indices.

relative recruitment indices, and subsequently contrast them with the recruitment estimates from the statistical catch-at-age model in order evaluate their performance in early detection of recruitment events. Each of these four datasets represents a different region of the range of the population of bocaccio subpopulation (fig. 2), although most of the data overlap spatially. Although the southern subpopulation is currently considered to range from the U.S./Mexico border to Cape Blanco, Oregon, recruitment of YOY bocaccio is rarely observed north of 38°N, the approximate northern boundary of the midwater trawl survey. Recruits are rarely observed between this region and the apparent center of the northern subpopulation off of Vancouver Island, Canada.

The midwater trawl survey samples YOY rockfish when they are ~100 days old, an ontogenetic stage that occurs after year-class strength is established from the larval stage, but well before cohorts recruit to commercial and recreational fisheries. This survey has encountered strong interannual variability in the abundance of the rockfishes that are routinely indexed, as well as high apparent synchrony in abundance among the ten most frequently encountered species. This synchronicity appears to be related to physical climate indicators (S. Ralston and J. Field, unpublished data). Several past assessments have used this survey as an index of year-class strength, including assessments for widow rockfish (*Sebastes entomelas*, He et al. 2005), Pacific hake (*Mer-*

[4]In most age structured stock assessment models, annual recruitment estimates are estimated with parameters that represent lognormally distributed deviations around the "expected" recruitment based on the spawner recruit relationship (Maunder and Deriso 2003, Methot 2009). The standard deviation of these parameters, σ_R, defines the magnitude of recruitment variability. For bocaccio this value is fixed at 1 and estimated to be (effectively) slightly greater (1.1).

luccius productus, Helser et al. 2006[5]), shortbelly rockfish (*S. jordani*, Field et al. 2007) and chilipepper rockfish (*S. goodei*, Field 2008). The midwater trawl survey has taken place during May–June every year since 1983, with a historical range (1983–2003) between 36°30' to 38°20' N latitude (approximately Carmel to just north of Point Reyes, CA). Beginning in 2004, the spatial coverage expanded to effectively cover a broader range of the California Current, from Cape Mendocino in the north to the U.S./Mexico border in the south (Sakuma et al. 2006). Although the expanded survey frame is considered to be a more appropriate index for use in stock assessments[6], the time series of the expanded survey is thus far insufficient to accurately assess performance relative to the time series from the core area. Consequently, we focus on the long-term data for this evaluation, in order to address the long-term performance of the index. The survey index is calculated after the raw catch data are adjusted to a common age of 100 days to account for interannual differences in age structure (Ralston and Howard 1995).

The power plant impingement index represents data collected from coastal cooling water intakes at five Southern California electrical generating stations from 1972 to 2008 (and ongoing). These data have been previously described and published by Love et al. (1998) and Miller et al. (2009) with respect to trends in abundance of *Sebastes* species and queenfish (*Seriphus politus*), respectively (See either of these manuscripts for additional information, and the precise location of the facilities). The dataset includes observations on over 13 million fish encountered in three basic types of power plant impingement surveys (E. Miller unpublished data). The three principle "types" of survey data include fish sampled off of intake screens during normal operations (typically over a 24 hour period, however we aggregated normal operations data by month for any given plant), fish abundances estimated during heat treatments (a periodic event in which a given volume of water is treated at high temperatures to kill off biofouling organisms [mussels, barnacles, etc.; Graham et al. 1977], and all fishes are subsequently enumerated), and a third set of impingement survey data that are unique to the San Onofre power plant but were not used in this analysis due to the low frequency of occurrence of bocaccio in those data (Miller et al. 2009). Fish are identified to the lowest possible taxon, and standardized length measurements are obtained for all species. The frequency of all of these sampling methods is irregular, as a result of changes in operating schedules, regulatory requirements and changes in ownership over time, however the time series is uninterrupted at the annual scale from 1972–2008.

Recreational fisheries catch, and often target, bocaccio of all sizes throughout their range, including high catches of YOY bocaccio in pier fisheries in central and southern California during good recruitment years. Since 1980 (but excluding 1990–1992), these pier fisheries have been sampled, first by the Marine Recreational Fisheries Statistics Survey (MRFSS) and then by the California Recreational Fisheries Survey (CRFS), with data analyzed and made available on the RecFIN internet site. The stock assessment also incorporated data from studies in the 1950s and 1960s that were insightful with respect to several large historical recruitment events.[7] Catches of bocaccio typically take place during infrequent strong recruitment years from San Mateo county (south of the entrance to San Francisco Bay) through Ventura county (somewhat north of Palos Verdes peninsula in the Southern California Bight), with the highest catch rates being observed in San Luis Obispo county. Juveniles were rarely observed at piers south of Los Angeles County, and in analyzing spatial patterns of recruitment, MacCall (2003) concluded that there was no evidence of separate recruitment events north and south of Point Conception in these data. For this analysis, RecFIN records of bocaccio catch per angler hour were summarized by years, 2-month sampling periods ("waves," using only waves 3, 4 and 5, corresponding to data from May through October, as bocaccio catches in other waves were very infrequent), and counties, such that each combination constitutes a single record.

In southern California, settling juvenile bocaccio recruit to a variety of habitats, including both natural reefs and oil platforms, often in large numbers during strong recruitment years. Observational data collected from submersible (*in situ*) surveys have been used to assess the abundance of rockfish and other species on both natural reefs and oil platforms to develop absolute abundance indices for other species of rockfishes (e.g., Love et al. 2005; Yoklavich et al. 2007) and to characterize assemblages of rockfish communities (Love et al. 2009); details of the survey methods and results can be found in those publications. Over the course of these

[5]The index evolved to a coastwide index following the 2006 assessment, but has not been used on the most recent assessment (Hamel and Stewart 2009), although it continues to be reported in the assessment documentation.

[6]See discussion in J. Hastie and S. Ralston, 2006, "Summary Report of Pre-Recruit Survey Workshop, September 13-15, 2006, Southwest Fisheries Science Center Santa Cruz, California," prepared for the PFMC (reported in April 2007 in the NWFSC Supplemental Science Report, Agenda Item E.1.b) and available online at http://www.pcouncil.org/bb/2007/0407/E1b_NWFSC3_sup.pdf.

[7]URL for recfin: http://www.recfin.org/data.htm. Historical data are from Miller and Gotschall (1965), who reported large numbers of YOY bocaccio in piers throughout central California in 1956 and 1957; an event also observed by one of the coauthors (M. Love). Large numbers of bocaccio were also observed in pier fisheries in the Central California region during the fall of 1966, for which bocaccio accounted for 26% of the 1.3 million fish estimated to have been caught in pier fisheries in that year (Miller and Odemar 1968).

surveys, bocaccio catches have been shown to be very patchily distributed, with the highest catch (observation) rates at oil platforms relative to natural reef habitats (Love et al. 2006). For all of the submersible data, we obtained dive-specific "catch" (observation) rates, which were standardized to reflect observations per 100 square meters. Only bocaccio smaller than 30 cm were included in developing the catch rate index.

All of the recruitment indices were developed using a Delta-GLM (generalized linear model) approach, consistent with the approach used in past assessments (MacCall 2003; Field et al. 2009). The Delta-GLM approach combines a binomial model for presence/absence information with a model of catch per unit effort for positive observations (Stefansson 1996, Maunder and Punt 2004). Akaike's Information Criterion (AIC) was used to determine the appropriate error distributions and to assess the most parsimonious model with respect to the number of covariates (Dick 2004). Year effects are independently estimated covariates which reflect a relative index of abundance for each year, error estimates for these parameters are developed with a jackknife routine. Seasonal (or temporal) effects are estimated using month, two-month periods, or season as covariates depending upon the resolution of the original data. For the midwater trawl survey, which takes place over an approximate 50 day period in May and June, bins of 10 Julian day periods are used, while two month periods ("waves") were used for the recreational pier fisheries data, one month periods were used for the impingement data, and no temporal effects were used for the submersible data (which only takes place during weather windows in late fall). Similarly, spatial effects are described by spatial covariates, represented by individual trawl stations for the midwater trawl survey data, counties for the recreational pier fishery data, individual power plants for the impingement data, and habitat types (oil rig base, oil rig midwater, and natural reef) as well as depth for the submersible data. For the impingement data, "survey type" was also included as a factor, with only two types estimated, these being the "normal operations" and "heat treatment" types described previously.

The resulting recruitment indices were compared to the estimated recruitments from the stock assessment. The natural logarithm of both the predictor (indices) and response (assessment recruits) values were used for the regression, to best mimic the behavior of stock assessment models which perform maximum likelihood parameter estimations (Maunder and Punt 2004, Methot 2009). In addition to comparing the results of the recruitment indices to the results of the assessment, we evaluate the extent to which the recruitment indices improve the predictive ability of the stock assessment model. This is done by retrospectively estimating the magnitude and confidence in estimates of one of the strongest recruitment events in recent years, the 1999 year class, when data are sequentially removed from the model going backwards in time. By sequentially removing entire years of data for two models with and without the recruitment indices we can compare both the absolute recruitment estimates and the confidence in those estimates. The estimated precision of the absolute values of annual recruitment are provided by the asymptotic approximation used in the stock synthesis model (Methot 2009a, b). This allows us to better evaluate how well the recruitment indices may, or may not, perform with respect to predicting strong incoming year classes of bocaccio.

RESULTS

The bocaccio stock assessment model that was re-run without the recruitment indices suggested a biomass trend and recruitment estimates nearly identical to those from the adopted assessment model (fig. 3). As with bocaccio assessments done over the past 10 years, the results indicate that the spawning output (a reflection of the spawning biomass, accounting for the greater fecundity of larger fish) fluctuated significantly through the 1960s and 1970s, peaking near 1970 and declined rapidly through the rest of the 1980s and 1990s. These declines were primarily a result of high exploitation rates, although a period of anomalously poor recruitment appears to have taken place throughout most of the 1990s. The estimated recruitment time series illustrates that recruitment has a high degree of interannual variability, but that the relative size of the strong recruitment events have declined in concert with the decline of spawning output through the year 2000. Since that time, fishing mortality has declined markedly due to severe management restrictions, and the stock has been increasing at a fairly rapid rate coincident with a series of several relatively strong year classes (1999, 2003, 2005). Note that the differences in the magnitude of recruitment events in the late 1950s and early 1960s, shown in Figure 3, results from exclusion of the recreational pier fishery time series in the model used for evaluating the performance of recruitment indices, as there were a mix of qualitative and quantitative data used in the full assessment.

For all of the models, several alternative model structures were explored and evaluated using AIC, and the most parsimonious model (explaining the greatest amount of relative variance with the lowest number of parameters) was used. Similarly, for each of the recruitment data sources, the year effects from the delta-GLM models led to an improvement in the AIC, indicating that the year effects provided information potentially usable as a recruitment index. We provide a summary

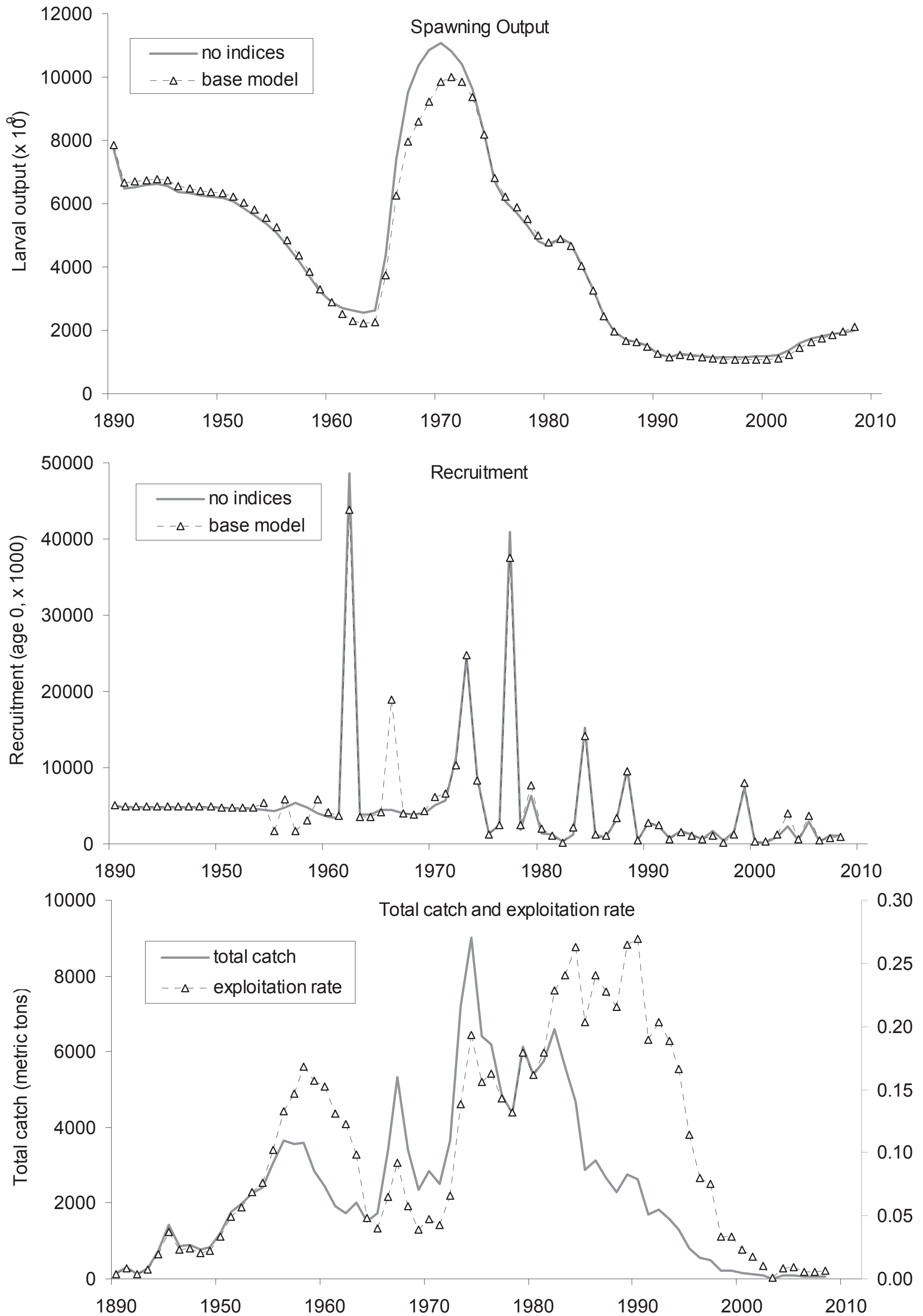

Figure 3. Estimated reproductive potential (spawning output) and recruitment of bocaccio from the base 2009 model (dashed lines) relative to the same model in which all juvenile indices are removed (solid lines), to avoid confounding the performance of the various indices.

TABLE 1
Summary of data availability, the number of parameter estimated, and GLM model performance for the four recruitment indices.

	Pelagic trawl	Recreational Pier	Power Plant Impingement	Delta Submersible
Time period	1983–2008	1980–2008	1972–2008	1995–2008
Number of years*	17	19	31	13
Temporal parameters	6	0	12	0
Spatial parameters	34	6	6	7
Data points	2225	312	2628	914
Coefficients of variation				
average	0.56	0.73	0.60	0.41
maximum	0.87	1.11	0.83	0.63
minimum	0.34	0.40	0.37	0.30
Change to AIC				
Remove year				
binomial	123.3	0.2	36.7	6.4
positive	75.4	3.9	78.2	5.0
Remove spatial				
binomial	18.9	45.6	25.5	41.3
positive	–9.0	66.2	–5.7	87.6
Remove temporal				
binomial	0.5	n/a	5.8	n/a
positive	7.6	n/a	14.3	n/a
Null model				
binomial	142.7	66.2	71.6	51.3
positive	93.1	49.6	167.4	92.8

of available data for each index, listing the time period for which data are available, the number of observations, the number of covariates used in the GLM, and both the null and final model AIC (tab. 1). The mean, and range, of the estimated coefficients of variation that result from the jackknife routine are also reported in this table. We focus subsequent discussion on the year effects (covariates) for each model, although the intra-annual (seasonal) and spatial covariates are also relevant.

All four of the resulting indices tracked most of the strong recruitment events estimated from the assessment model (fig. 4a-d). All of the indices were significantly correlated to the assessment estimates of recruitment (at the $p<0.05$ level), with coefficients of determination (R^2) values ranging from 0.28 for the pier fishery index to 0.58 for the power plant impingement data, with the juvenile trawl survey and submersible survey having coefficients of 0.35 and 0.41 respectively. One particular challenge with this type of model is how to deal with missing data. Many indices have years with insufficient numbers of positive observations to estimate a year effect (generally speaking, two positive observations in a given year are necessary), despite having fairly comprehensive sampling coverage (and data) overall. For the correlations shown here, those years have been dropped, although one approach to including that information is to use some fraction of the minimum estimated value for years with insufficient numbers of positive observations (for example, half). This is consistent with the practice frequently used in stock assessments. Although admittedly ad-hoc, this approach recognizes that there is information in the data regarding the relative strength of a given year class when data are collected and no juveniles are observed (the year class is presumably weak in such circumstances, although differences in sampling intensity are also relevant). The juvenile trawl survey index, the pier fishery index and the impingement survey index have eight, ten, and five years that meet this criteria respectively (there are no years of submersible data with this problem); if half of the minimum estimated values are used for these years and added to the regressions, the resulting R^2 values are 0.21, 0.45 and 0.46 respectively. Thus, the information content of the juvenile survey and the impingement survey are slightly degraded, that of the pier fishery is slightly improved, if this approach is adopted.

Another challenge is how to address the problem of errors in variables (EIV). In ordinary regression models, the independent variables are assumed to be measured without error, such that all error is a function of the dependent variable. This issue has a deep history in fisheries science and in the fisheries literature (Ricker 1975, Hilborn and Walters 1992), a comprehensive review of which is beyond the scope of this manuscript, but it is worth noting that the issue remains generally unresolved (Kimura 2000). We explored several approaches to addressing the issue, ultimately settling upon reporting both the "standard" linear regression relationship and the geometric mean estimate of the functional regression (GM regression; Ricker 1975), both of which are presented in Figure 4. Note that the coefficients of variation are unchanged among the two models, it is

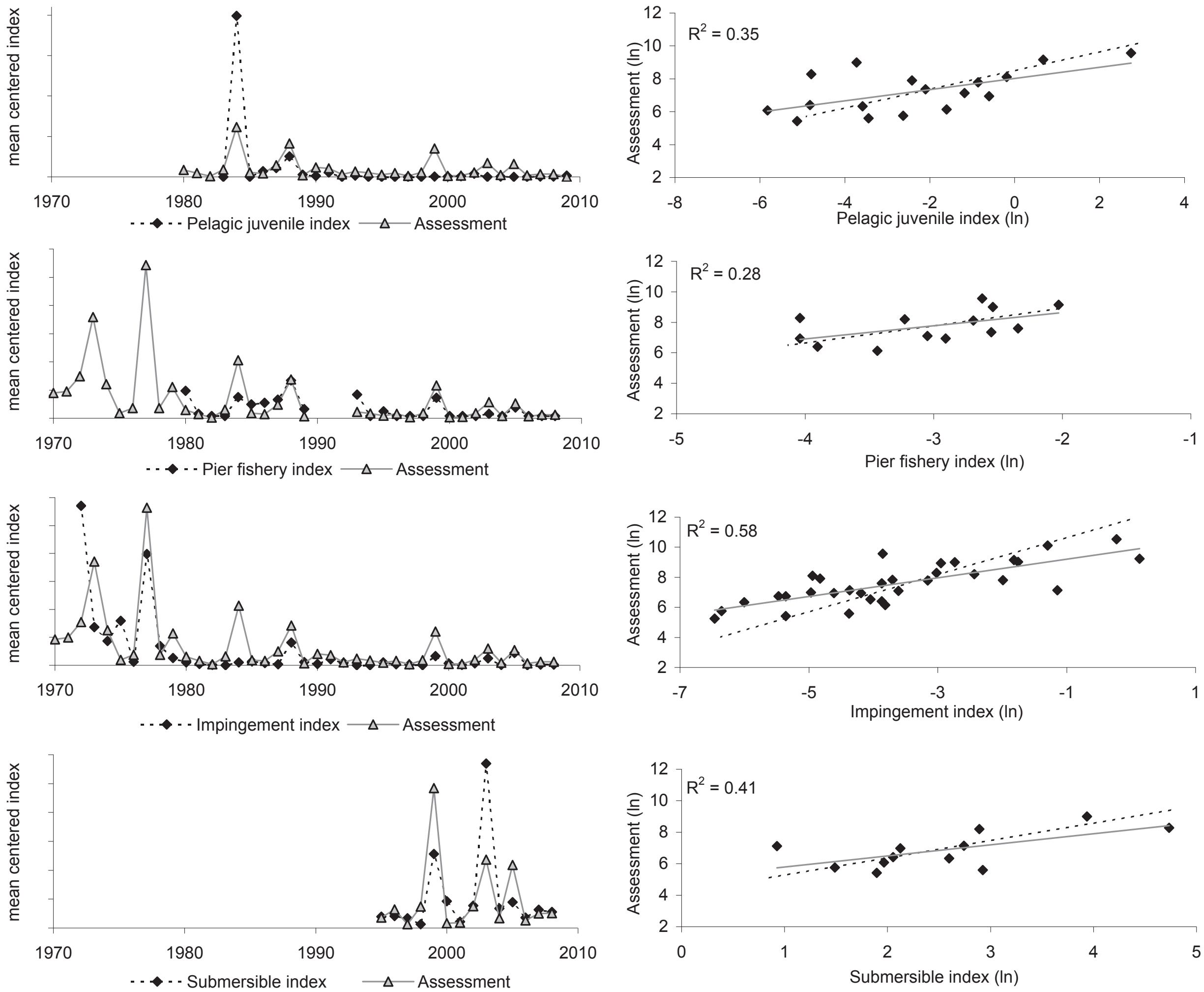

Figure 4. Mean-centered estimates of recruitment from the base stock assessment model (absent recruitment index data) relative to mean-centered indices of juvenile abundance from the data sources reported here (left panels). Corresponding regression results for each index (right panels), with both ordinary least squares regression (solid grey line) and geometric mean regression (dotted black line).

only the slope and intercept parameters that differ, and neither of these parameters are utilized further for the purposes of this manuscript.

While the recreational pier fishery index has a relatively modest correlation to assessment estimates of recruitment, this index does capture the magnitude of the 1984, 1988 and importantly the 1999 year class. The midwater trawl survey was among the noisier of indices ($R^2 = 0.35$), although this index captured the magnitude of the 1984 and (perhaps to a lesser extent) the 1988 year classes, there have been very few bocaccio juveniles observed in the catches since that time. Consequently, this index did not detect the strong year classes observed in 1999, 2003 and 2005, which may be an artifact of changes in the relative distribution of spawning biomass (and subsequent recruitment) over recent years. In fact, the failure of the juvenile survey to capture the magnitude of the 1999 year class for bocaccio or any other species contributed to the decision to expand the geographic range of the juvenile rockfish survey, under the assumption that expanding the survey accross space would lead to more effective predictions of coastwide recruitment events (Sakuma et al. 2006). The power plant impingement index also compares favorably with the stock assessment estimates of recruitment ($R^2 = 0.58$), and as the only index that precedes the 1980s it is reassuring to observe that the index does particularly well with respect to capturing the magnitude of the 1973, 1977 and 1988 year classes. This index also captures apparently strong recruitment in 2005 and 2007, which are now showing up in fishery data. Interestingly, this index appears to miss the magnitude of the 1984 and 1999 year classes, although it does recognize some recruitment in both of those years. Finally, although it is the shortest of the time series evaluated here, the submersible index also performs fairly

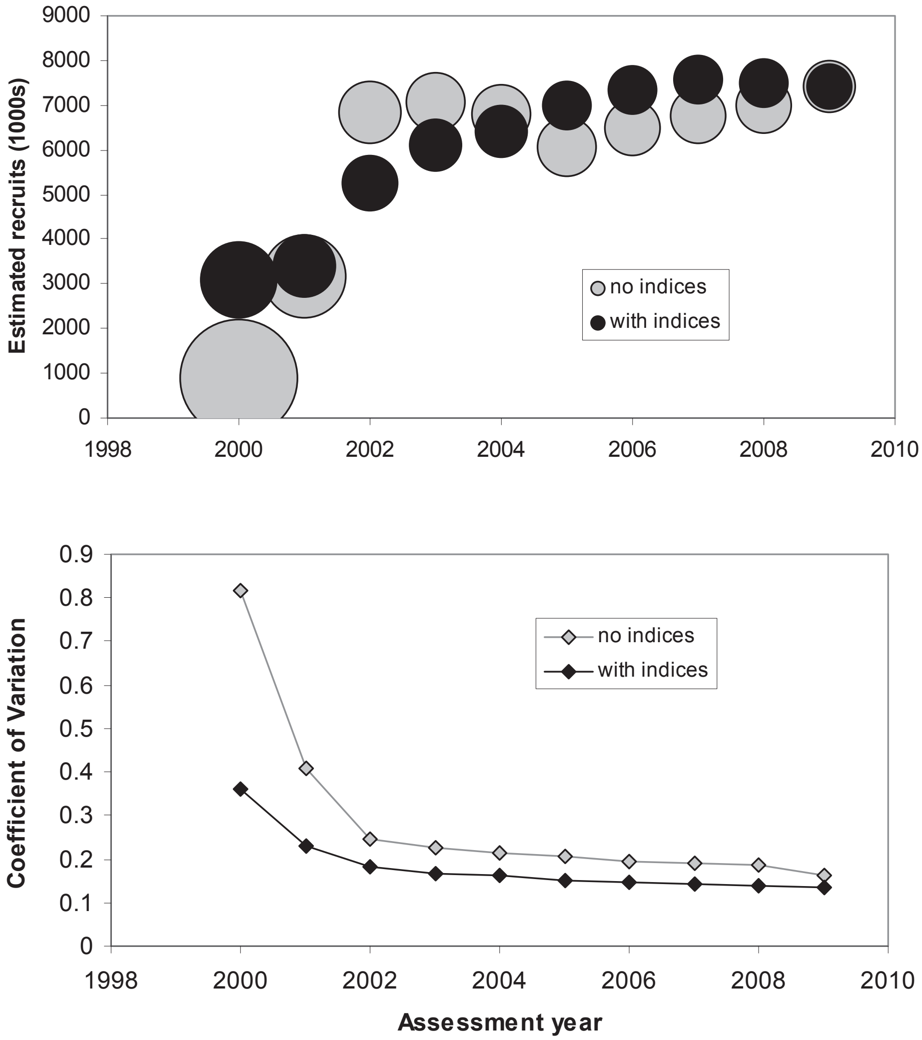

Figure 5a (top). Relative information content of the 1999 recruitment from retrospective bocaccio assessment models with (black) and without (grey) the juvenile indices developed in this manuscruipt. Size of bubbles corresponds to the CV of the estimates, which are also shown in Figure 5b (bottom).

well in capturing the magnitude of large year classes (R^2 = 0.41), although it overestimates the 2003 and underestimates the 1999 year class.

The comparison of estimates of the magnitude of the 1999 year class with retrospective model runs with and without all of the recruitment indices is shown (fig. 5a), along with the estimates of the CV of that recruitment point estimate in subsequent years. Here, we can see that the information content of informative indices is limited to the first 1–2 years before fish show up in fishery and survey data. For example, an assessment done in 2000 using data through 1999 would predict considerably greater recruitment with the recruitment indices than without them, due to the limited information available on that cohort available in length frequency data and the statistical "penalties" imposed on data with low information content in the model (thus the first two years represent primarily a recruitment estimation drawn from the spawner recruit curve), with considerably greater confidence (CV of 0.38 versus 0.85). However, by 2001 fishery-based length frequency data for bocaccio have already demonstrated the presence of the 1999 year class, and although the recruitment indices lead to a smaller variance estimate of that year class strength, the magnitude is generally well established based on simply the recreational fishery length composition data alone. As this example includes all of the recruitment indices in the model simultaneously, which would not necessarily be an optimal approach in a typical assessment, the difference among the estimated recruitments after the second year is negligible. That these recruitment events appear so strongly defined so early in the fishery reflects the unique life history of bocaccio, which grow very rapidly and are encountered by sport fisheries in particular at very young ages, whereas other *Sebastes* species are typically not vulner-

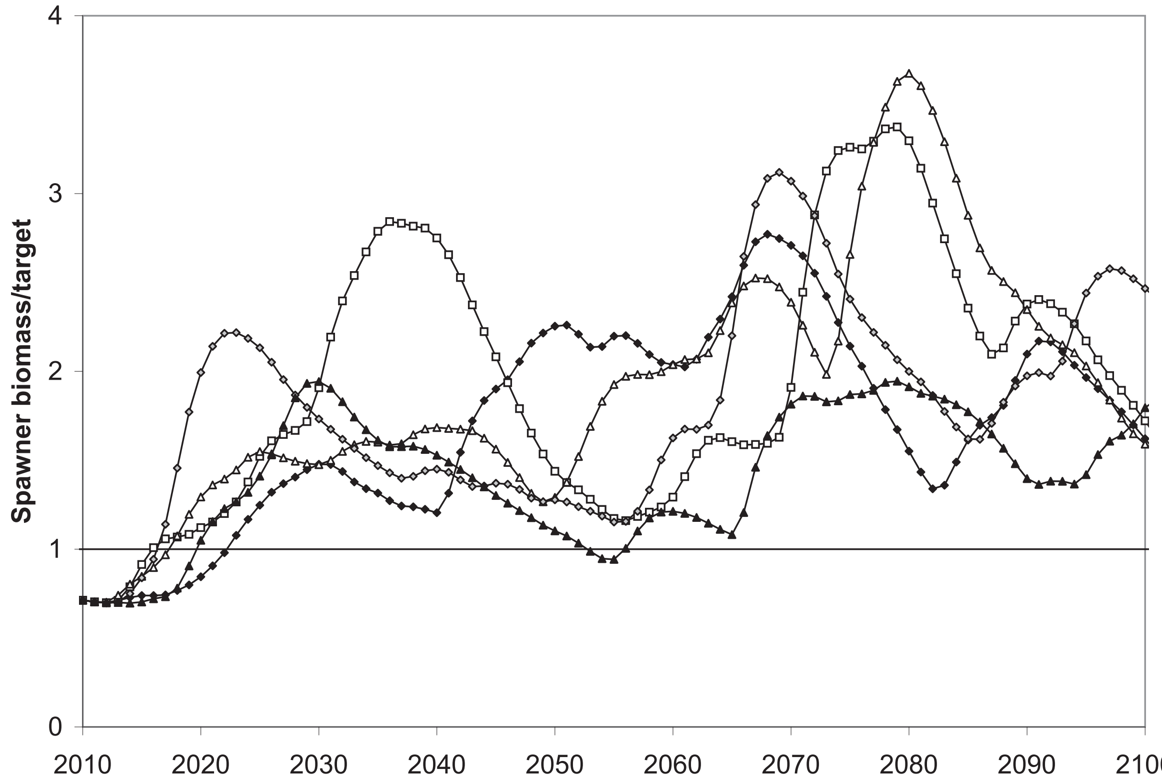

Figure 6. Five example trajectories, of the thousands simulated in the rebuilding analysis for bocaccio rockfish, illustrating the significance of highly variable recruitment events on population trends (harvest rates are constant set to current level in all scenarios). These individual trajectories are used to assess the probability of rebuilding by management targets.

able to fisheries until individuals reach ages of 3–10 years. For such slower-growing species, recruitment indices would be more useful in assessing abundance and productivity in the long term. For bocaccio, the period in which recruitment indices are useful in forecasting productivity is relatively brief (one to two years), although given the significance of changing bocaccio bycatch rates on other fisheries, improved forecasting of such recruitment events is still of great importance to resource management activities.

DISCUSSION

The southern bocaccio population is fortunate to have multiple sources of informative data that can provide estimates of the magnitude of recruitment events. As such, bocaccio are a good case study for evaluating the effectiveness of pre-recruit indices for West Coast groundfish, particularly as the correlation coefficients from this evaluation are comparable to or considerably greater than the correlations between the spawner recruit curve and subsequent recruitments. Currently, only two of these indices (the midwater trawl survey, albeit an index based on greater spatial resolution and shorter duration, and the recreational pier fishery index) are used are used in the stock assessment. Both of the other indices described here hold considerable potential for future assessments, and should be evaluated accordingly in the future. Moreover, the performance of most these indices is consistent with what DeOliveira and Butterworth (2005) describe as a reasonable threshold for the application of indicators (albeit, environmental indicators in their case) for improving stock assessment models, for which indicators should be able to explain approximately 50% or more of the total variation in recruitment.

Moreover, the data from these recruitment indices could provide insights into the physical and biological conditions that either enable or repress strong recruitment events. The high recruitment variability exhibited by this species leads to considerable uncertainty with respect to the estimated time to rebuild to target levels for this stock, as illustrated by five equally plausible trajectories of stock biomass developed as a part of a comprehensive rebuilding analysis (fig. 6, from Field and He 2009). Essentially, thousands of these individual trajectories are used to assess the probability of rebuilding by management targets, using the methods developed in Punt (2003). The rebuilding analysis also indicates that upon rebuilding to target biomass levels, the chance of returning to an overfished condition in the future remains significant if the default harvest policies are followed, simply due to the highly variable nature of recruitment for this stock. Comparable results have been described for Pacific hake (*Merluccius productus*), another species with highly variable recruitment and population trajectories (Haltuch et al. 2008). Consequently, for stocks with such high variability in recruitment, such that harvest policies based on constant harvest rates may not be optimal for either ecological or socio-economic stability.

The potential for bocaccio recruitment indices to provide insights beyond just the bocaccio stock should also be explored. Several other commercially and ecologically important species have recruitment trends that covary with bocaccio rockfish, including chilipepper and Pacific hake. There is also some synchrony in recruitment variability of other species, for example nearly all of the assessed groundfish stocks on the U.S. west coast experienced good to excellent recruitment in 1999, and most also experienced strong recruitment in 1980 and 1984. Similarly, there tends to be poor recruitment during strong El Niño events, such as those 1982–83, 1986–87 and 1997–98 El Niño events (it is noteworthy to consider that many of the strongest recruitment events for West Coast groundfish have taken place in years that immediately followed these El Niño events). However, thus far the degree of synchrony in groundfish recruitment has been relatively modest; the leading principal components explain 25–45% of the variance for groundfish recruitment deviations for well-informed stocks (range reflects the subset of stocks evaluated), which is comparable to results for other regions (Mueter et al. 2007). While suggestive of some generalized response to ocean conditions, this fraction of the total variance is relatively modest in comparison to the high amount of synchrony observed in juvenile rockfish abundance in the pelagic stage, where the leading principle component explains 85% of the variance for the ten most abundant rockfish species (J. Field and S. Ralston, unpublished data). The spatial component of recruitment for shelf rockfish has also been shown to be strongly coherent over broad spatial scales (Field and Ralston 2005), although this reflects post-settlement and recruitment based primarily on fishery data and may not reflect the patchy nature of recruitment prior to dispersal. All of these observations suggest that many of the processes contributing to variable year class strength for rockfish, and perhaps other groundfish, occur at the post settlement stage, and vary considerably among species, again consistent with expectations for most marine species more generally (Ralston and Howard 1995, Houde 2008). For bocaccio, a closer evaluation of both the synchrony and the spatial structure of strong recruitment events using the different indices could lead to insights regarding the nature of the physical and biological ocean conditions that lead to strong year classes.

The geographic frame of the various indices also appears to be informative with respect to stock structure trends. The data used in the most recent assessment suggest that the stock biomass south of Point Conception appears to be rebuilding at a more rapid rate than to the north, based on the relative influence of data from these respective regions. The patterns observed in the recruitment index time series are consistent with this, in that the strong recruitment in 1984 seemed to be a "northern" recruitment event. This recruitment event was strongest in the central California data, including both the midwater trawl survey and the recreational pier fishery index (particularly Santa Cruz and San Luis Obispo counties). Since the 1990s however, the signal from the pier survey index has been dominated by San Luis Obispo and Santa Barbara Counties, and both the impingement index and the visual survey index suggest that recruitment south of Point Conception is strongly correlated with the model estimates of recruitment for the entire stock. This too is consistent with the abundance indices that suggest greater population increases in the southern part of the stock range relative to the central portion (Field et al. 2009), indicating that both recruitment and rebuilding may have a regional component.

With respect to further utility of these recruitment indicators, it may be that they are also useful for managers contemplating the duration of fishing seasons and seasonal depth restrictions. As one of several rebuilding species of rockfish on the West Coast, bocaccio is a constraining species for fisheries on healthy populations, and regulations focus on minimizing the catch of bocaccio while allowing opportunities to exploit more productive stocks. Thus, effective forecasting catches of this constraining species is key for maintaining fishing opportunities, while avoiding the chance of exceeding the allowable catch of bocaccio. Given the dramatic spikes in both catch rates and the percentage of the total southern California rockfish catch that is bocaccio following strong recruitment events (fig. 7)[8], improved predictions of future catch rates of constraining species could be of considerable value not only in assessments that include future year projections, but in year-to-year management activities as well. The latter point may be particularly true in a management regime in which the bocaccio stock assessment is performed every two years at most, and with a greater lag between the data and the time period in which the results are applied to management, making "fine tuning" of management measures

[8]There are statistically significant relationships among these variables, the R^2 between the assessment recruitment and a one-year lagged change in the percentage of all southern California rockfish (with an arcsine transform to account for proportionality) is 0.34, while the R^2 between recruits and one year lagged catch per angler hour is 0.35. However, a linear regression may be too simplistic, as both relationships show signs of non-linearity.

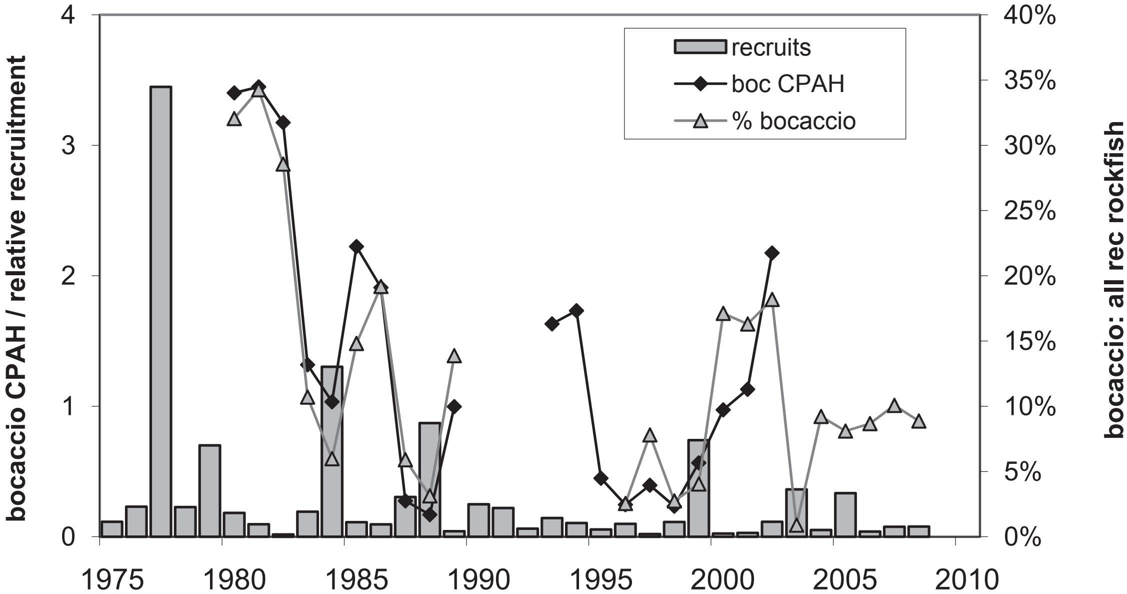

Figure 7. Estimated annual recruitment (grey bars) relative to Southern California recreational fishery catch rates (catch per angler hour, black line) and to the percentage of the total recreational catch represented by bocaccio (grey line).

in response to changing conditions even more important. In such a scenario, integrating all of the indices into a single indicator of impending recruitment, using principle components analysis or comparable means, might be more useful for management with respect to predicting spikes in bocaccio catches in recreational fisheries.

We have shown that there are several sources of information that could improve the prediction of strong year classes in stock assessment of bocaccio. Such information is useful to assessing stock status and productivity, to tracking rebuilding success, and likely to improving real time management of commercial and recreational fisheries that routinely encounter large numbers of young bocaccio during strong recruitment events. Additionally, these data could be informative with respect to recruitment trends for species of groundfish that tend to covary with bocaccio, and could ultimately lead to an improved understanding of the oceanographic processes that drive variable recruitment. In the long term, such information should aid both scientists and managers, by improving the ability to monitor and respond to the variable abundance and catch rates of bocaccio, as well as by leading to a greater appreciation for the connectivity between environmental changes in coastal ecosystems and fisheries productivity.

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