Abstract–Cowcod (*Sebastes levis*) is a large (100-cm-FL), long-lived (maximum observed age 55 yr) demersal rockfish taken in multispecies commercial and recreational fisheries off southern and central California. It lives at 20–500 m depth: adults (>44 cm TL) inhabit rocky areas at 90–300 m and juveniles inhabit fine sand and clay at 40–100 m. Both sexes have similar growth and maturity. Both sexes recruit to the fishery before reaching full maturity. Based on age and growth data, the natural mortality rate is about M =0.055/yr, but the estimate is uncertain. Biomass, recruitment, and mortality during 1951–98 were estimated in a delay-difference model with catch data and abundance indices. The same model gave less precise estimates for 1916–50 based on catch data and assumptions about virgin biomass and recruitment such as used in stock reduction analysis. Abundance indices, based on rare event data, included a habitat-area–weighted index of recreational catch per unit of fishing effort (CPUE index values were 0.003–0.07 fish per angler hour), a standardized index of proportion of positive tows in CalCOFI ichthyoplankton survey data (binomial errors, 0–13% positive tows/yr), and proportion of positive tows for juveniles in bottom trawl surveys (binomial errors, 0–30% positive tows/yr). Cowcod are overfished in the southern California Bight; biomass during the 1998 season was about 7% of the virgin level and recent catches have been near 20 metric tons (t)/yr. Projections based on recent recruitment levels indicate that biomass will decline at catch levels > 5 t/yr. Trend data indicate that recruitment will be poor in the near future. Recreational fishing effort in deep water has increased and has become more effective for catching cowcod. Areas with relatively high catch rates for cowcod are fewer and are farther offshore. Cowcod die after capture and cannot be released alive. Two areas recently closed to bottom fishing will help rebuild the cowcod stock.

Biology and population dynamics of cowcod (*Sebastes levis*) in the southern California Bight

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Cowcod (*Sebastes levis*) are a large (up to 100 cm fork length, FL) laterally compressed rockfish with large head and large jaws that equip it for life as an ambush predator in the deep continental shelf and upper slope waters off the west coast of North America (Miller and Lea, 1972; Eschmeyer et al., 1983). Cowcod are found from central Oregon to central Baja California and Guadalupe Island, Mexico (Eschmeyer et al., 1983). Like many rockfishes (genus *Sebastes*), cowcod have been the object of commercial and recreational fisheries since at least the beginning of the 20th century (Lenarz, 1987).

The southern California Bight (SCB, Fig. 1) is located off southern California between Point Conception in the north and the Mexico-U.S. border in the south. It is the center of the cowcod's geographical distribution and they were "abundant" there during the 1890s (Eigenmann and Beeson, 1894). They are rare off Oregon and northern California

and were taken in only 13 of 3245 tows north of Cape Mendocino, California (40°28′N. lat.), during National Marine Fisheries Service (NMFS) triennial bottom trawl surveys on the continental shelf during 1976–98 (Wilkins[1] and see "Discussion" section). The NMFS survey tends to avoid rocky ground, however, where cowcod are most common.

As with other rockfishes, fertilization is internal and female cowcod give birth to first-feeding stage planktonic larvae (Moser, 1967; Boehlert and Yoklavich, 1984). Gonadosomatic indices of females are highest during November–April when embryos are maturing. Peak abundance of cowcod larvae in California Cooperative Oceanic Fisheries Investigation (CalCOFI)

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[1] Wilkins, M. 1999. Personal commun. Alaska Fisheries Science Center, National Marine Fisheries Service, 7600 Sand Point Way, BIN C15700, Seattle, WA 98115-0070.
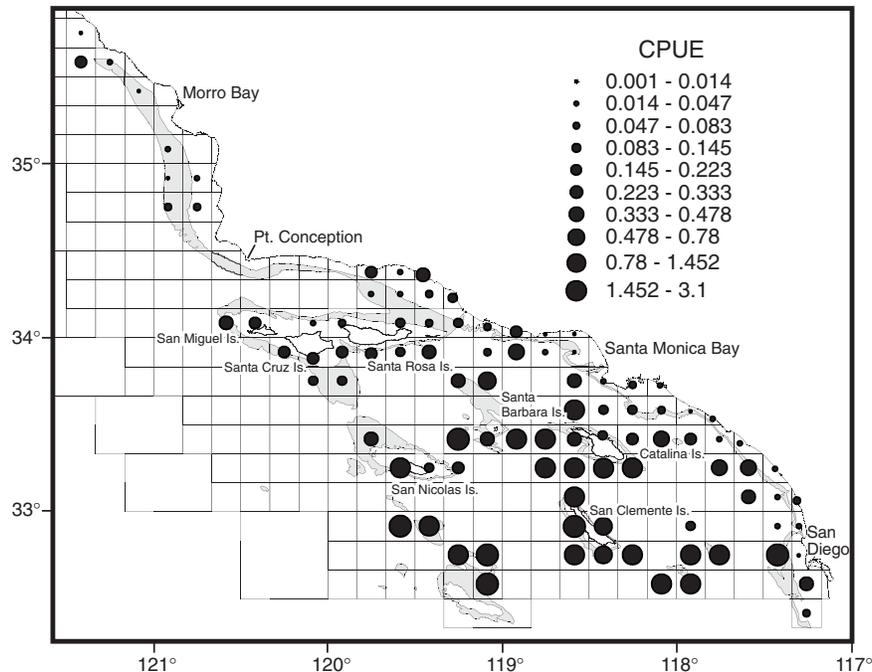
Figure 1

Cowcod habitat in central and southern California. The southern California Bight (SCB) between Pt. Conception and the Mexico–U.S. border is the center of the cowcod population's distribution. Assumed habitat areas for adult cowcod at 100–300 m are shaded light gray. Square outlines identify California Department of Fish and Game fishing blocks (generally 10′×10′) used to analyze commercial passenger fishing vessel (CPFV) logbook data. Dots show CPFV mean catch rates (cowcod per angler day) for each fishing block during the 1964–74 seasons (no dot means zero CPUE).

ichthyoplankton surveys is during January–April, and some larvae are present during November–August (Moser et al., 1994). Cowcod larvae spend about 100 days in the plankton and settle to the bottom as juveniles at about 50–60 mm FL (Johnson, 1997).
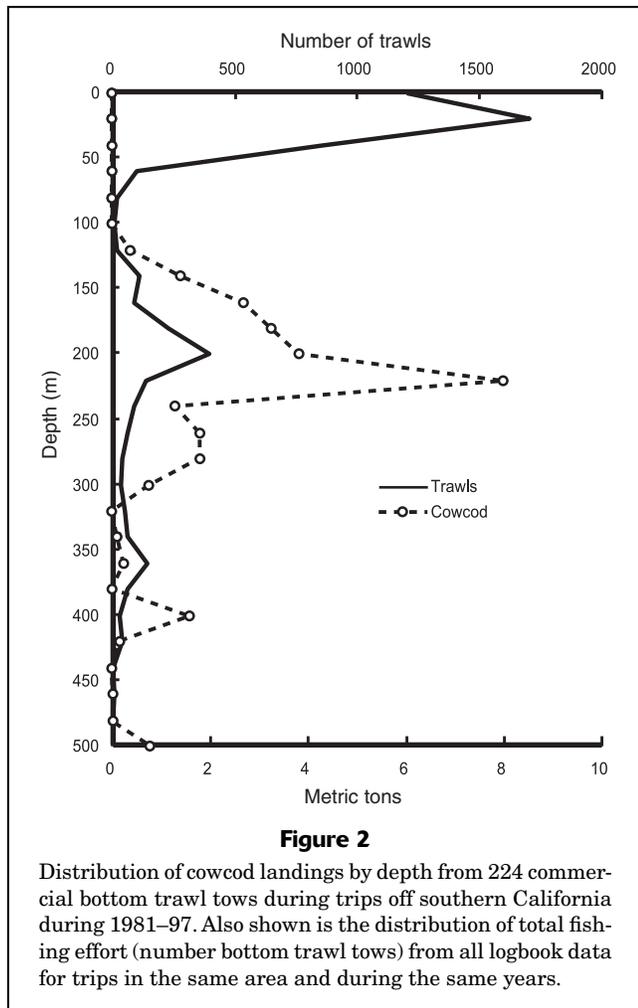
Cowcod are found at depths of 20–500 m. Juveniles (50% maturity at about 44 cm FL [Love et al., 1990]) generally inhabit relatively shallow water (<100 m) on relatively sandy bottom and adults generally inhabit deeper water (>100 m) on rocky bottom (Miller and Lea, 1972; Eschmeyer et al., 1983; Butler et al., 1999). Average length of cowcod increases with depth (Love et al. 1990) as is the case with many other species along the west coast of North America (Jacobson et al., 2001). Adult cowcod habitat off Southern California comprises a series of basins and ridges that form islands and offshore banks (Emery, 1960). Juveniles in Monterey Bay recruit to fine sand and clay sediments at depths of 40–100 m during the months of March–September (Johnson, 1997). In submersible surveys at the northern end of the SCB, juvenile cowcod (<40 cm TL) were most common at 90–149 m and adults were most common at depths of 120–209 m (Butler et al., 1999). California commercial bottom trawl fishermen take cowcod at depths of 120–500 m, but mainly at 120–300 m (Fig. 2). We used total bottom area at 100–300 m (measured

using a geographic information system and depth data) as a crude estimate of habitat area for cowcod (Fig. 1, see "Discussion" section).

Cowcod are an important part of multispecies commercial and recreational fisheries off central and southern California. Fishermen target cowcod, particularly in the recreational fishery, because of their large body size. Close association with rocky bottom features makes adult cowcod relatively easy to catch with stationary gear (e.g. hook-and-line and set nets) in both the recreational and commercial fisheries. Prior to 1983, the recreational fishery accounted for most of the annual catch, but the commercial fishery was usually dominant during subsequent years.

Commercial fishery

Cowcod have been landed in fifteen different California Department of Fish and Game market categories. Likewise, fourteen species of *Sebastes* have been landed in the cowcod market category. Of these, the bronzespotted rockfish, *S. gilli*, is most common. Exvessel (wholesale) prices (adjusted for inflation to 1998) paid by processors for landings in the cowcod market category rose from $1.02/lb in 1981 to $1.56/lb in 1998 and peaked at $1.85/lb in 1990 (Butler et al.,1999).

Figure 2

Distribution of cowcod landings by depth from 224 commercial bottom trawl tows during trips off southern California during 1981–97. Also shown is the distribution of total fishing effort (number bottom trawl tows) from all logbook data for trips in the same area and during the same years.

Commercial fishermen use hook-and-line, set nets, and trawl gear to catch cowcod, typically while targeting a group of species. Set nets accounted for 48%, trawls 27%, and hook-and-line 25% of cowcod landings in California during 1980–96 (Butler et al., 1999). Trawling accounted for 80% of landings north of 36°N, whereas hook-and-line and set nets accounted for 92% of landings south of 36°N (Butler et al., 1999). Differences in principal fishing gear north and south of 36°N are due to bottom topography in southern areas that makes bottom trawling impractical.

Recreational fishery

Due to their large size, and despite low catch rates (about 0.1 fish per angler day in recent years), cowcod are a highly prized trophy fish in the recreational fishery. Recreational fishing effort is undertaken from the commercial passenger fishing vessel (CPFV) fleet (Young, 1969; Golden, 1992) and private fishing boats. CPFV vessels include charter boats (contracted by a group of anglers), and party boats (open to the general public without reservations). Anglers take cowcod with hook-and-line gear using multiple baited hooks per rod, or single treble hooks. The official California

record for cowcod in the recreational fishery is about 10 kg, but specimens as large as about 15 kg have been confirmed in recent years (Wertz[2]).

CPFV fishing effort targeting multiple rockfish species was probably the most important recreational fishery component for cowcod prior to new restrictions on rockfish during 2000, although anglers on private vessels were also important. Marine Recreational Fisheries Statistical Survey (MRFSS, http://www.psmfc.org/recfin) results in the RecFIN (PSMFC[3]) database indicate that CPFV vessels accounted for approximately 60% of recreational fishing effort in southern California during 1980–89 and 1993–97. Young's (1969) list of preferred species in the southern California CPFV fleet during 1963 did not include rockfish, but they were listed as an important part of the catch. By 1974 attitudes had apparently changed, probably in response to declining catch rates for traditional sportfish, and fishing effort for rockfish increased (MacCall et al.[4]).

Although actively sought by anglers during recent decades, cowcod comprised less than 1% of the CPFV total rockfish catch in number during 1961 (Miller and Gotshall, 1965), 0.4% of the total during the 1970s, (Collins[5]), and 0.3% of the total during 1985–87 (Young, 1969; Golden, 1992). Limited data for 211 cowcod (Fig. 3) sampled during MRFSS creel surveys (PSFMC[3]) indicate that the southern California CPFV fishery takes cowcod that are mostly 30–80 cm FL.

Less is known about cowcod catch taken by private fishing vessels, but MRFSS survey data indicate that trends in catch and effort are similar to those in the CPFV fishery. Cowcod catch rates were low in the private boat fishery during 1975–76 when cowcod accounted for only 179 out of 140,296 fish sampled by the California Department of Fish and Game in a survey of private boats in the southern California sport fishery (Wine and Hoban[6]).

Fishery management

The Pacific Fishery Management Council manages cowcod and other rockfish under its fishery management plan (FMP) for groundfish (PFMC, 1982). The California
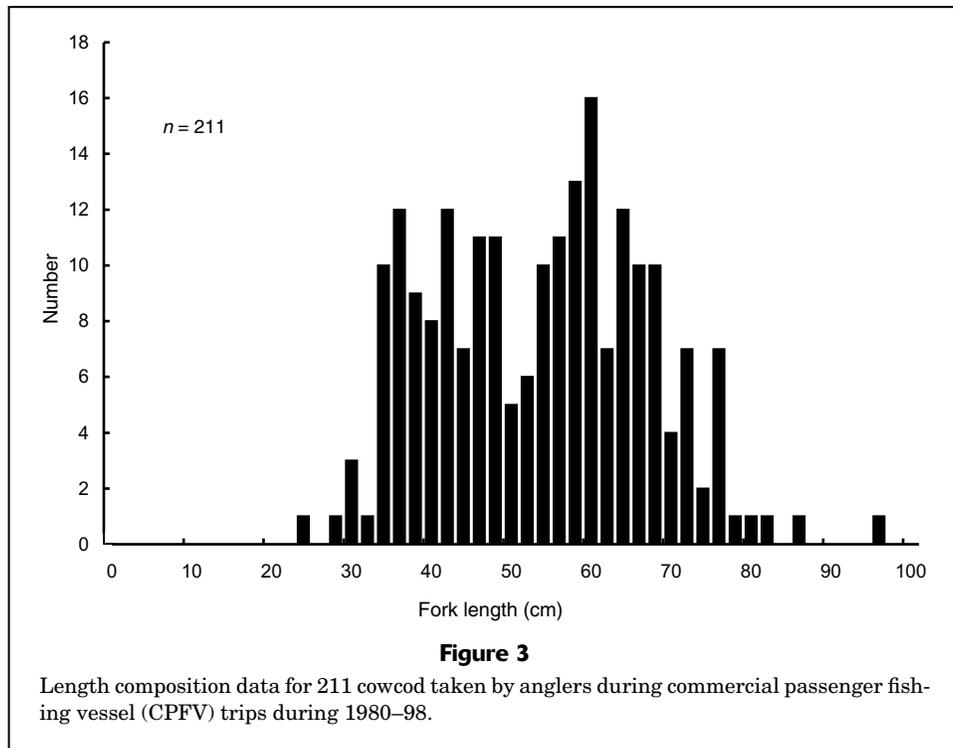

Figure 3

Length composition data for 211 cowcod taken by anglers during commercial passenger fishing vessel (CPFV) trips during 1980–98.

Department of Fish and Game plays a key role because cowcod are caught primarily off southern California. Cowcod received relatively little attention from managers until Butler et al.'s (1999) stock assessment indicated that the SCB stock was "overfished" and that "overfishing" was occurring. The Magnuson-Stevens Fishery Conservation and Management Act and National Standard Guidelines (DOC, 1998) require each FMP to specify a minimum stock size threshold ($B_{Threshold}$), and a maximum fishing mortality rate threshold ($F_{Threshold}$). According to Council guidelines (PFMC, 1999), $B_{Threshold}$ for cowcod is 25% of virgin biomass. $F_{Threshold}=F_{40\%}$ (the fishing mortality rate that reduces spawning biomass per recruit to 40% of the unfished level; Clark, 1991) when stock biomass is at or above 40% virgin biomass. $F_{Threshold}$ is reduced at lower biomass levels. According to the National Standard Guidelines, a stock is overfished when stock size falls below $B_{Threshold}$ and overfishing occurs when fishing mortality rates exceed $F_{Threshold}$ for a period of one year or more. The goal for most rebuilding plans is to achieve the target biomass level (usually B_{MSY}, the stock biomass for maximum sustained yield) in ten years or less. However, even with zero fishing mortality, ten years may not be sufficient to rebuild some overfished stocks, and this is the case for cowcod. In such situations, the National Standard Guidelines allow for a rebuilding time no longer than one mean generation time plus the expected time to recovery in the absence of fishing mortality.

In this paper, we summarize existing and new information (Butler et al., 1999) about cowcod; develop an extended time series of catch and abundance index data; estimate biomass, fishing mortality, and recruitment since 1951

(with crude but plausible estimates for 1916–50); describe current status of the stock and effects due to fishing and environmental changes; and discuss problems and opportunities in rebuilding the stock to higher abundance levels. In addition, we show how standardized abundance indices can be derived from rare event and presence-absence data. Finally, we demonstrate techniques for tuning stock assessment models to presence-absence indices with binomial distributions, low expected values, and zero values.

Materials and methods

We estimated annual commercial landings for cowcod during 1951–97 from two different types of information. Commercial landings estimates during 1980–97 were from the PacFIN (PSMFC[3]) database based on exvessel sales receipts (total landings by market category) and port samples (used to estimate proportions of each species by market category). During the period of 1980–97, cowcod comprised 0.5% of total commercial rockfish landings in California. The time series of annual ratios for cowcod and total rockfish landings was variable and showed no clear trend over time.

Direct estimates of cowcod landings were not available for years prior to 1980 because no port sampling was conducted to partition the catch for rockfish market categories into species-specific components. Consequently, we used the ratio estimate (0.00479, CV=26%) to reconstruct historic annual cowcod landings from 1916 to 1981 based on total reported rockfish landings in California in CMASTER records (California Commercial Fisheries Data Base,

Eres[7]). Total landings estimates for 1980–81 from PacFIN were imprecise because of inadequate port sampling, so we used the ratio estimates of cowcod landings for 1980–81 in further analysis.

Recreational landings

We developed a time series of annual recreational cowcod catch from three sources including MRFSS surveys (PSMFC[3]) for 1980–89 and 1993–97, California CPFV logbooks for 1964–98 (Hill and Barnes[8]) and *Los Angeles Times* newspaper reports for 1959–97 (Butler et al., 1999). The *Los Angeles Times* reports daily CPFV catches in California by species (including cowcod since 1959 and rockfish since 1939) and port. Small cowcod (<2 kg) in catches may not be identified to species and were likely counted as "rockfish" in logbooks and *Los Angeles Times* reports.

From 1964 through 1979, we estimated recreational catch of cowcod by expanding annual catch from CPFV logbooks and annual catch in *Los Angeles Times* reports. Expansions used ratio estimators based on MRFSS estimates of total recreational cowcod catch during years (1980–89 and 1993–97) when the MRFSS survey was conducted in California. Expanded estimates based on CPFV logbook and *Los Angeles Times* records were similar. Therefore, expanded CPFV and *Los Angeles Times* estimates were averaged to obtain a single time series of recreational cowcod catch estimates for 1965–97. For 1951–64, recreational cowcod catches were estimated by using the ratio of cowcod and total rockfish catch from CPFV logbooks during 1965–97, and CPFV logbook estimates of total rockfish catch in earlier years.

Age, growth, and reproductive biology

We used otoliths to estimate age and growth for 129 cowcod sampled from the recreational fishery during April 1975–June 1981 and 131 cowcod sampled from the commercial fishery during February 1982–January 1986. Four juveniles sampled from bycatch in the spot prawn pot fishery during 1996 were used as well. Otoliths were sectioned and read independently by three readers (four readers for some specimens). Individual age estimates for each fish were averaged and rounded to the nearest integer to obtain a single age estimate for each specimen. Von Bertalanffy growth curves were fitted to size-at-age data for male and female cowcod. The hypothesis of sexual dimorphism in growth was evaluated with a likelihood ratio test (Kimura, 1980).

Maturity at age was estimated by converting maturity-at-length estimates in Love et al. (1990) to maturity at age

based on a von Bertalanffy curve. Body weights (in grams) were calculated from fork lengths by using $W=0.0101\,L^{3.09}$, where L was fork length in cm (Love et al., 1990). The relationship between body size and fecundity for 27 female cowcod (46–80 cm FL) was $E=0.170\,L^{3.15}$, where E was fecundity in millions of eggs (Love et al., 1990).

Natural mortality

Four methods based on age data (i.e. catch curves, Heincke, 1913; Robson and Chapman, 1961; Ricker, 1975; and Hoenig, 1983) were used to estimate average total annual mortality rates (Z) for cowcod during 1975–86. The purpose in estimating Z from age composition data was primarily to find bounds for estimates of the annual natural mortality rate (M) in cowcod. In addition, we used Jensen's (1997) method based on von Bertalanffy growth parameters to estimate M. Age data for cowcod used in our study were for an exploited stock; so total mortality estimates included natural mortality (M) and fishing mortality (F).

Biological reference points

We calculated biological reference points (Thompson and Bell, 1934; Clark, 1991) for cowcod based on yield-per-recruit (F_{MAX} and $F_{0.1}$) and spawning biomass-per-recruit ($F_{40\%}$). Managers use $F_{40\%}$ as a proxy for $F_{Threshold}$ and F_{MSY} (the fishing mortality rate for maximum sustained yield) in managing rockfish (PFMC, 1982). Fishery selectivity assumptions in reference point calculations were based on catch curve results and fishery length composition data (Butler et al., 1999). Female body mass was used to measure reproductive output in reference point calculations.

CalCOFI ichthyoplankton data

We used CalCOFI ichthyoplankton survey data to construct an index of larval presence-absence for cowcod (Mangel and Smith, 1990; Smith, 1990). The CalCOFI index gives the probability of a positive tow (i.e. catching one or more cowcod larvae) under standard conditions. CalCOFI ichthyoplankton data are used routinely to track spawning biomass of pelagic fish (Jacobson et al., 1994; Deriso et al., 1996; Hill et al.[9]) but are seldom used for rockfish because of difficulties in identifying the species of rockfish larvae and lack of overlap between the area surveyed and distribution of many groundfish stocks. However, cowcod are one of several rockfish species readily identifiable as larvae (MacGregor, 1986; Moser, 1996; Jacobson et al.[10]).

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[7] Eres, J. 1999. Personal commun. California Department of Fish and Game, 4665 Lampson Ave., Suite C, Los Alamitos, CA 90720.

[8] Hill, K. T., and J. T. Barnes. 1998. Historical catch data from California's commercial passenger fishing vessel fleet: status and comparisons of two sources. Calif. Dept. Fish and Game, Marine Region Tech. Rep. 60, 44 p. [Available from California Department of Fish and Game, Marine Region Library, 4665 Lampson Ave., Suite C, Los Alamitos, CA 90720.]

[9] Hill, K. T., M. Yaremko, and L. D. Jacobson. 1999. Status of the Pacific mackerel resource and fishery in 1998. Calif. Dep. Fish Game, Marine Region Admin. Rep. 99-3, 57 p. [Available from: California Department of Fish and Game, Marine Region Library, 4665 Lampson Ave., Suite C, Los Alamitos, CA 90720.]

[10] Jacobson, L.D., S. Ralston, and A.D. MacCall. 1996. Historical larval abundance indices for bocaccio rockfish (*Sebastes paucispinis*) from CalCOFI data. Southwest Fisheries Science Center, Admin. Report LJ-96-06, 30 p. [Available from: Southwest Fisheries Science Center, P.O. Box 271, La Jolla, CA 92038.]

Moreover, the geographic area of the CalCOFI survey and cowcod stock are both centered in the SCB.

Sampling gear, sampling procedures, and standardization of numbers of larvae caught in CalCOFI tows are described by Moser et al. (1993) and Ohman and Smith (1995). Our analysis used data from all tows within the "current" sampling area in the SCB during calendar years 1951–98 because it was the largest region sampled consistently since 1951 (Hewitt, 1988; Moser et al., 1993; 1994), and because cowcod larvae are most common there (Moser et al., 1994). CalCOFI data from the current sampling pattern included a total of 46 "seasons" used in modeling (e.g. the 1951 season was July 1951–June 1952) and 12,274 bongo or ring net tows of which 120 (0.98%) contained at least one cowcod larva. Almost all positive tows (116 or 97%) were inshore of CalCOFI station 67.5 (Moser et al., 1994). Almost all positive tows (117 or 98%) were made during January–June (Moser et al., 1994). Numbers of positive tows ranged from 5 to 32 per month between January and June and only 1 to 2 per month otherwise. Based on these preliminary results, we used data for all tows (n=5003) collected inshore of CalCOFI station 67.5 during January–June for the remainder of our analysis.

We used a logistic model to derive a standardized index of larval presence for cowcod from CalCOFI data. The logistic model was a generalized linear approach (McCullagh and Nelder, 1989) that accommodates zeroes (tows catching no cowcod larvae). It was fitted to tow-by-tow CalCOFI data by logistic regression (assuming a binomial distribution for statistical errors). The dependent variable was 0 (if no cowcod larvae were observed in a tow) or 1 (if larvae were observed). Independent variables included years, months, and a dummy variable that was 1 if the tow was in the "inshore" area (Butler et al., 1999) and 0 otherwise. The best model for cowcod CalCOFI data was identified by using a step-wise procedure and Mallow's C_p statistic. The index of abundance was the expected probability that a CalCOFI tow is positive for cowcod larvae in each year for an arbitrary reference month and arbitrary reference location.

Trawl surveys

Two sets of trawl survey data were available for cowcod. Trawl survey data collected by the Los Angeles City Sanitation District and Orange County Sanitation District (LAOCSD) off southern California were used as an index of presence for juvenile cowcod. Beginning in 1973, the Los Angeles City Sanitation District sampled twelve stations along four cross-shelf transects and at three depths (23 m, 61 m, and 137 m) twice each year (Stull, 1995; Stull and Tang, 1996). Beginning in November 1970, the Orange County Sanitation District sampled a fixed grid of 8 stations at 20–170 m quarterly (Mearns, 1979). Juvenile cowcod in these trawls ranged from 3 to 38 cm in length. Catch rates were highly variable; therefore we used a simple average of the proportion of positive tows in both surveys as a single index (LAOCSD) of juvenile cowcod presence-absence in the SCB during the 1972–94 seasons (Mangel and Smith, 1990).

CPFV catch per unit of effort (CPUE)

We calculated a habitat-area–weighted (Hilborn and Walters, 1992) average recreational catch per unit of fishing effort (CPUE) index for cowcod from CPFV logbook data for trips in the SCB during 1963–97. As described in the discussion section, the index measured catch rates while accounting for important changes in the spatial distribution of fishing effort over time and spatial differences in abundance trends. Data for trips before 1964 were not available because cowcod catches were combined with rockfish in early years. Each record contained total number of rockfish caught, number of cowcod caught, and total angler hours from logbooks for one month and one "block" (10'×10' area, Fig. 1).

We assumed total angler hours reported on CPFV logs for sampling blocks with rockfish catches during November–April was a measure of relative fishing effort for cowcod. CPUE was in units of numbers of fish per angler hour (fish/h).

We used CPFV logbook records for November–April to model trends because the CPFV fishery tends to target rockfish during the winter when migratory game fish are seldom caught. Data from blocks in U.S. waters south of Point Conception (blocks 651–897, Butler et al., 1999) were used in the analysis so that CPUE was measured for the entire SCB. Logbooks for 1979 were not summarized by month in logbook records and were therefore excluded. We excluded records for blocks 600, 699, 700, 799, 800, and 899 because these codes are used for data of uncertain origin. We excluded a few records that reported cowcod catches larger than total rockfish catches, and records with high catches from blocks with no cowcod habitat as likely database errors. We also excluded data for the 1979 and 1998 seasons because data for some months were missing and the number of blocks with logbook reports was low (<150).

It was necessary to have at least one logbook record for each spatial stratum during each season, but many blocks had missing data for some seasons. We therefore stratified CPFV logbook data based on "pseudo-blocks." In some cases, pseudo-blocks were the same as fishing blocks. In other cases, pseudo-blocks were composed of many fishing blocks with similar average catch rates.

The first step in stratifying the data was to delete data for blocks with mean CPUE (over the entire time series) that was zero or in the first quartile (<0.05 cowcod per angler day). Blocks with zero CPUE values were from areas where cowcod had never been reported and where there was probably no habitat. Blocks with very low mean CPUE provided little information about trends in cowcod abundance. Of 190 blocks (covering 19,000 nmi^2), there were 102 blocks with mean cowcod CPUE greater than the first quartile.

In the second step, we calculated the number of seasons with rockfish catch and effort data for each block. Twenty-seven blocks had complete time series and were assigned to a pseudo-block that was the same as the original fishing block.

The third step was to assign blocks with incomplete time series to pseudo-blocks based on mean CPUE. Specifically,

blocks with incomplete time series and mean CPUE in the second quartile were assigned to pseudo-block 2. Blocks with mean CPUE in the third quartile were assigned to pseudo-block 3. Blocks with mean CPUE in the fourth quartile were assigned to pseudo-block 4.

We fitted a "Poisson" generalized linear model to CPFV logbook data and used it to compute CPUE indices for cowcod in each pseudo-block and year. The model was fitted by quasilikelihood assuming the Poisson distribution for statistical errors (McCullagh and Nelder, 1989). This approach accommodated zeroes in the data (no cowcod in some blocks during some months) and the generally rare and random nature of cowcod catches. Quasilikelihood estimation (McCullagh and Nelder, 1989) assumes that the variance of CPUE data increases in proportion to the mean (i.e. $\sigma^2 = \phi\mu$, ϕ not necessarily equal to one) and is appropriate for CPUE data that typically show this pattern (Hilborn and Walters, 1992). CPUE was the dependent variable. Independent variables were pseudo-blocks, years, and months, and interactions occurred between pseudo-blocks and years. The interaction between psuedo-blocks and years allowed the model to estimate different trends in each psuedo-block. Other interactions were not included because of data and computer limitations. The best Poisson model for cowcod CPUE data was identified by using a step-wise procedure with Mallow's C_p statistic.

The CPUE index for the whole stock in each season was computed as the habitat-area–weighted average of CPUE in each pseudo-block. Variance estimates for the Poisson CPUE index were from standard formulas for weighted means and Poisson model estimates of variances. Variance estimates were biased low because the poststratification scheme (pseudo-blocks) was based on block means.

Population dynamics modeling

The assessment model for cowcod in the SCB (Butler et al., 1999) was a biomass dynamic approach based on Schnute's (1985) delay difference equation implemented in C++ using AD-Model Builder (Otter Software, Ltd.[11]). It estimated "fishable" biomass of cowcod about 40+ cm FL (roughly age 10+), fishing mortality, and recruitment to the fishable biomass. Fishable biomass is less than total biomass because it includes only the portion of the stock available to the fishery. The assumed natural mortality rate $M = 0.055$/yr was the same for all ages and years.

The assessment model for cowcod included "virgin" (prior to any fishing), "historical" (1917–50) and "recent" (1951–98) seasons, as well as deterministic projections for the 1999–2009 seasons (Butler et al., 1999). Virgin and historical periods were linked in the model by stock biomass calculations, an assumed level of constant mean recruitment during the historical period, and an assumed low level of fishing mortality ($F = 0.001$/yr) prior to the 1917 season. The historical and recent periods were linked by stock biomass calculations and assumptions about mean recruitment during the historical period. Similar to stock

reduction analysis (Kimura and Tagart, 1982; Kimura et al., 1984; Kimura, 1985), virgin and historical calculations were used to estimate the maximum size of the cowcod stock, and recent data and calculations were used to estimate trends as the cowcod stock was fished down from maximum size. Only catch data were available for the historical period. Both abundance index and catch data were available for the recent period.

Abundance index data for the recent period used to tune the cowcod assessment model included the Poisson CPUE index from CPFV logbooks, the logistic index from CalCOFI survey data, and proportion of positive tows from LAOCSD bottom trawl tows. Probability of a positive tow in CalCOFI and LAOCSD indices is almost proportional to abundance when positive tows are rare (Mangel and Smith, 1990). At higher levels, the probability of a positive tow is a nonlinear function of larval abundance. Goodness of fit for proportions (CalCOFI and LAOCSD data) assumed binomial measurement errors with adjustments for effective sample size (Appendix).

LAOCSD bottom trawl data for cowcod were used to track recruitment because the LAOCSD survey takes cowcod about three years old. In tuning the model, we compared recruitment of three-year-old cowcod in 1980 as measured by LAOCSD data, for example, with model estimates of recruitment at about age 10 during 1987.

In modeling, CalCOFI presence-absence data were used as an index of fishable stock abundance (Appendix). CalCOFI data were not used as an index of recruitment because the link between spawning adults and the presence of larvae is shorter and more direct than the link between presence of larvae and numbers of recruits to the fishable stock at about age 10 yr. The latter would be more variable due to variability in larval, juvenile, and adult survival and growth rates.

CPFV index data were assumed proportional to abundance in the fishable stock and goodness-of-fit was computed by assuming lognormal measurement errors. The original logbook data were assumed to follow a Poisson-like distribution in calculation of the index (see "Material and methods" section). However, the index, like a log normally distributed random variable, had no zero values (Butler et al., 1999).

Yearly catch data were assumed accurate in modeling although cowcod catch data, particularly for early years, were imprecise. Recruitments were assumed to follow a random walk process with relatively small changes from year to year.

Results

Estimated commercial landings (Table 1 and Fig. 4) were less than 20 t/yr during 1916–44, and ranged from 18 to 39 t/yr during 1951–72. Commercial landings increased during the 1970s and early 1980s, peaked during 1984 at about 108 t and then declined rapidly to 8 t in 1991. During 1993–97 commercial landings averaged 20 t/yr. Estimated recreational catch peaked in 1973–74 at about 228 t (Table 1 and Fig. 4) and declined steadily to only 6 t

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[11] Otter Reseach Ltd., Box 2040, Sidney, British Columbia, V8L 3S3, Canada.

Table 1

Catch, fishable biomass, recruitment (in metric tons [t]), and fishing mortality estimates for cowcod during the 1951–97 seasons. Seasons start in July and end in June. The 1951 season, for example, started 1 June 1951.

Season	Recreational landings (t)	Commercial landings (t)	Total landings (t)	Biomass (t)	CV	Recruitment (t)	CV	Fishing mortality (/yr)	CV
1951	7	18	24	3198	0.09	31	0.36	0.008	0.09
1952	9	24	33	3181	0.09	34	0.45	0.011	0.09
1953	10	23	34	3156	0.09	38	0.50	0.011	0.09
1954	24	27	50	3133	0.10	42	0.53	0.017	0.10
1955	42	27	69	3096	0.10	46	0.55	0.023	0.10
1956	49	28	76	3044	0.11	50	0.55	0.026	0.11
1957	37	32	69	2989	0.12	54	0.55	0.024	0.12
1958	33	35	68	2946	0.13	57	0.55	0.024	0.13
1959	22	39	61	2907	0.14	58	0.54	0.022	0.14
1960	36	30	66	2878	0.15	59	0.53	0.024	0.15
1961	33	24	57	2846	0.16	59	0.53	0.021	0.16
1962	35	21	56	2824	0.17	58	0.53	0.021	0.17
1963	51	26	76	2802	0.18	56	0.53	0.021	0.18
1964	70	18	88	2778	0.18	53	0.53	0.019	0.18
1965	95	20	115	2756	0.19	50	0.54	0.024	0.19
1966	218	22	240	2719	0.19	47	0.54	0.041	0.20
1967	199	21	220	2633	0.20	43	0.54	0.052	0.21
1968	190	21	210	2519	0.22	39	0.53	0.041	0.22
1969	130	20	150	2436	0.22	36	0.52	0.031	0.23
1970	190	23	213	2377	0.23	34	0.51	0.045	0.23
1971	143	24	167	2285	0.24	33	0.50	0.039	0.24
1972	221	36	257	2210	0.24	33	0.49	0.060	0.25
1973	228	48	276	2096	0.25	33	0.49	0.074	0.26
1974	228	47	275	1963	0.27	35	0.48	0.097	0.28
1975	206	51	258	1803	0.28	37	0.47	0.096	0.30
1976	223	53	277	1665	0.30	41	0.46	0.127	0.32
1977	172	45	218	1501	0.32	46	0.46	0.104	0.33
1978	136	45	181	1399	0.32	54	0.47	0.090	0.33
1979	193	62	255	1341	0.30	66	0.52	0.120	0.32
1980	133	31	165	1255	0.28	65	0.56	0.092	0.30
1981	135	49	184	1192	0.27	42	0.58	0.107	0.28
1982	143	41	184	1123	0.25	47	0.59	0.108	0.26
1983	64	71	135	1040	0.24	25	0.62	0.104	0.25
1984	65	108	173	963	0.23	20	0.64	0.170	0.25
1985	61	81	142	830	0.24	15	0.66	0.142	0.26
1986	55	100	155	735	0.25	13	0.67	0.181	0.27
1987	47	75	122	626	0.27	12	0.68	0.161	0.29
1988	42	62	104	543	0.29	10	0.69	0.172	0.31
1989	39	22	61	465	0.31	8	0.70	0.087	0.32
1990	27	16	43	433	0.31	8	0.70	0.070	0.32
1991	32	8	40	412	0.30	8	0.70	0.061	0.31
1992	35	35	70	395	0.29	9	0.71	0.144	0.31
1993	24	19	43	350	0.30	9	0.69	0.088	0.32
1994	37	24	61	328	0.30	8	0.69	0.143	0.32
1995	6	27	32	292	0.31	8	0.72	0.114	0.33
1996	23	16	39	268	0.32	8	0.77	0.099	0.34
1997	10	13	23	250	0.33	7	0.80	0.080	0.34

in 1995. During 1993–97 recreational landings averaged 20 t. Total landings were relatively high during 1986–88, peaked at 277 t in 1976, but fell to 23 t in 1997 (Table 1 and Fig. 4).

Figure 4

Estimated recreational, commercial, and total cowcod landings during 1951–97.
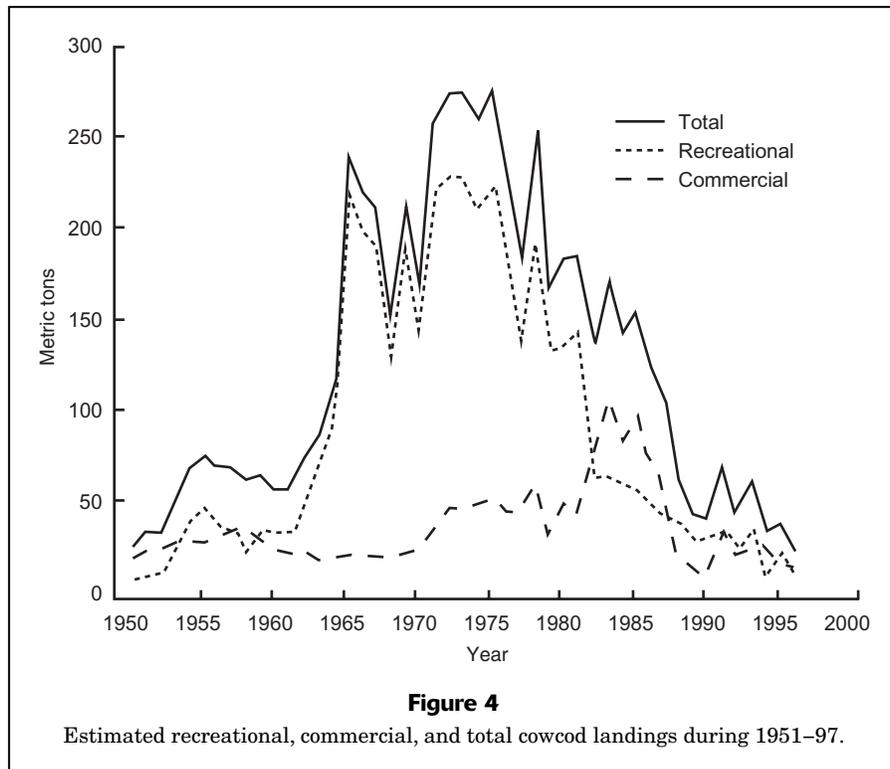
Age, growth, and maturity

The youngest fish in the 263 cowcod sampled for age determination was age 1, and the oldest was age 55. Average percent error (Beamish and Fournier, 1981) for readings by three (or four) readers was 0.09 and the index of precision (Chang, 1982) was 0.08.

Von Bertalanffy parameter estimates for male and female cowcod size at age were L_∞ = 91.5 and 91.8 cm FL, k = 0.0459 and 0.0447, and t_0 = –2.41 and –1.88/yr. Growth parameters were not significantly different; therefore we combined data from both sexes and included specimens for which sex was not determined. Von Bertalanffy parameter estimates for growth in length with sexes combined were L_∞ = 86.9 cm FL, k = 0.0524, and t_0 = –1.94/yr (Fig. 5). The corresponding von Bertalanffy parameter estimates for growth in weight were W_∞ = 35.1 kg, K = 0.00605, t_0 = 4.78 (Fig. 6). The estimate $\overline{W}_\infty$ = 35.1 kg appears to be an imprecise estimate of maximum body mass because the largest cowcod reported in the recreational fishery are about 10–15 kg (Wertz[2]). Male and female cowcod appear to reach sexual maturity at about the same ages and lengths (Table 2).

Natural mortality

Slopes of catch curve regressions were similar for male and female cowcod and for samples from the commercial and recreational fisheries (Butler et al., 1999). We therefore combined data for males, females, and unsexed samples to increase sample size and reduce variance. The best choice for age at full recruitment in catch curve analysis was not

clear, but the age at full recruitment appeared to fall somewhere between age 10 and age 20. Age 17 was used in the catch curve analysis because it gave the highest coefficient of determination (r^2) in catch curve regressions. The mean of four estimates of mortality based on age data (Table 3) was Z=0.071/yr.
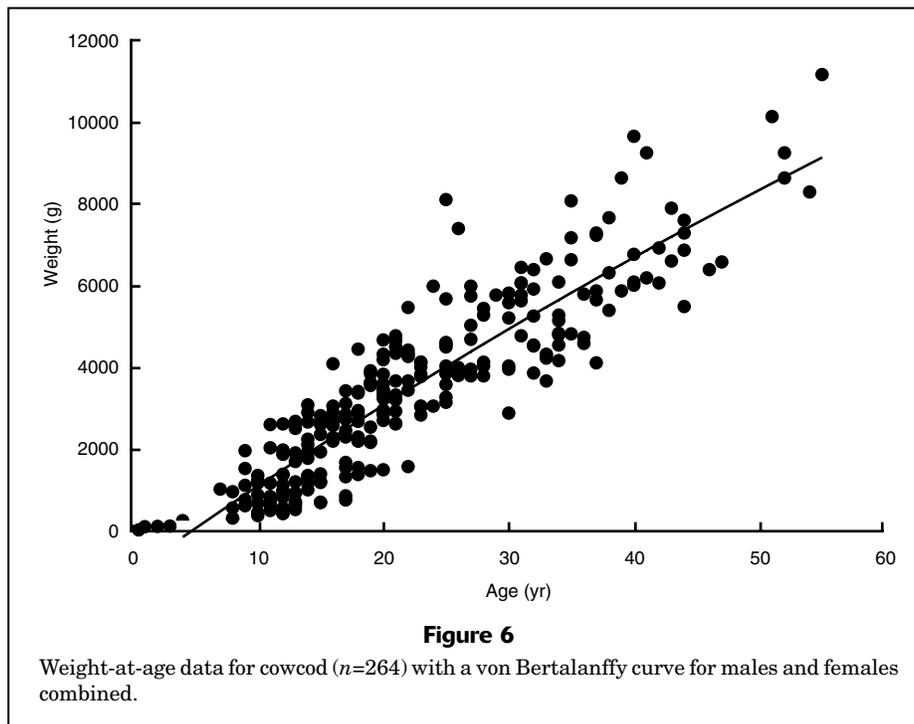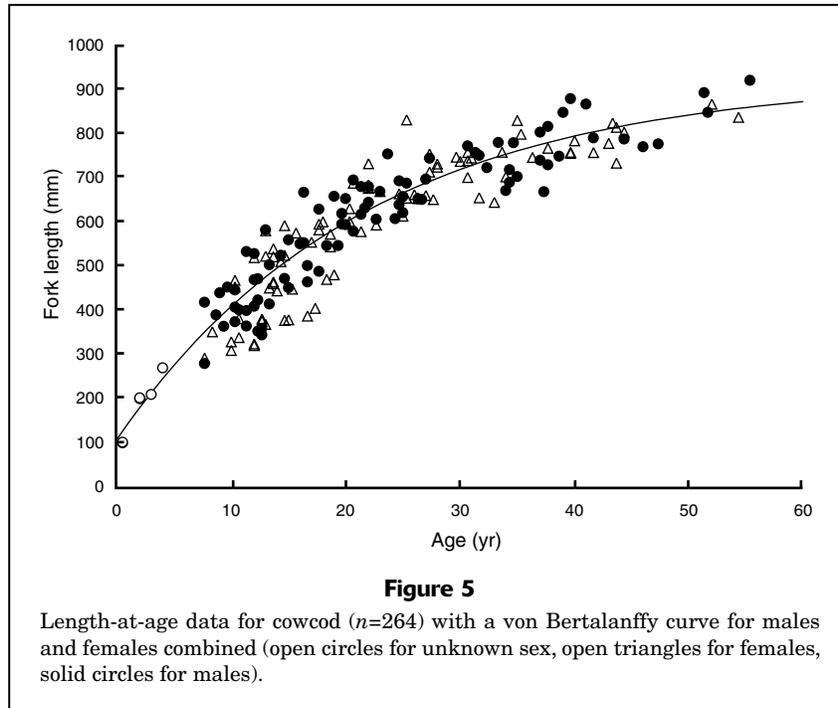
The natural mortality rate (M) for cowcod by Jensen's (1997) method was 0.069/yr. In modeling and reference point calculations for cowcod, we used the lowest estimate (Z=0.055/y) to approximate M. This estimate is crude, imprecise, and may be biased high because total mortality Z includes both natural mortality (M) and fishing mortality (F).

Yield per recuit and spawning biomass per recruit

Biological reference points for cowcod rockfish from yield-per-recruit and spawning-biomass-per-recruit calculations were relatively low because of low natural mortality, prolonged growth, and recruitment to the fishery prior to full maturity. In particular, with M=0.055/yr, F_{MAX}=0.11, $F_{0.1}$=0.048, and $F_{40\%}$=0.039/yr.

Abundance index data

The best logistic model for CalCOFI data included terms for season, month, line, and station effects and all 2- and 3-way interactions. Residual plots showed no evidence of lack of fit. Larval presence for cowcod in the SCB (Table 4 and Fig. 7) varied without trend during 1950–67, was elevated during 1968–74, and was then low beginning in

Figure 5

Length-at-age data for cowcod (*n*=264) with a von Bertalanffy curve for males and females combined (open circles for unknown sex, open triangles for females, solid circles for males).

Figure 6

Weight-at-age data for cowcod (*n*=264) with a von Bertalanffy curve for males and females combined.

1977, with the exception of the period 1989–91. The proportion of LAOCSD survey bottom trawls with juvenile cowcod declined from about 30% in 1974 to near zero levels in the late 1990s (Table 4 and Fig. 8).

The "best" Poisson model for CPFV logbook data included pseudo-block, year, and months as main effects and interac-

tions between pseudo-blocks and years. CPFV results suggest declining trends in catch rates in most pseudo-blocks (Fig. 9) and for the SCB as a whole (Table 4 and Fig. 10). Love et al. (1998) found similar trends in CPUE for cowcod and five other species of rockfish during 1980–96 based on MRFSS data.
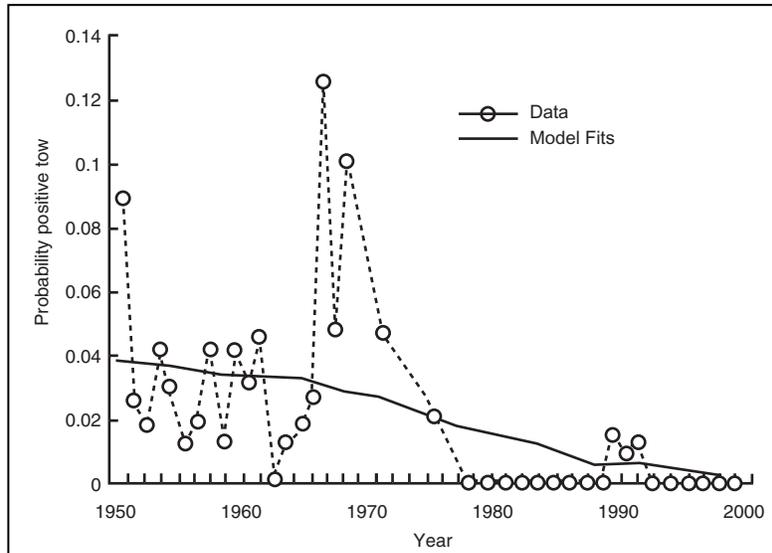
Figure 7

Probability of positive tows (at least one cowcod larvae, an index of larval presence used to track spawning biomass) in California Cooperative Oceanic Fishery Investigation (CalCOFI) ichthyoplankton surveys. "Data" are from the logistic model for larval presence. "Model fits" are predicted values from the stock assessment model fitted to the data.

Table 2

Length and age at first, 50%, and 100% sexual maturity for cowcod (first and 100% maturity as defined by Love et al., 1990).

	Males		Females	
Maturity	Fork length (cm)	Age (yr)	Fork length (cm)	Age (yr)
First	34	8	42	11
50%	44	12	43	11
100%	48	14	52	16

Table 3

Estimates of total mortality (Z) using age composition data for cowcod sampled in commercial and recreational fisheries during 1975–86.

Method	Z (/yr)	Method	Z (/yr)
Catch curve (Ricker, 1975)	0.055	Heincke (1913)	0.065
Robson-Chapman (1961)	0.087	Hoenig (1983)	0.075

Effective sample sizes (Appendix) based on goodness of fit in preliminary assessment model runs were less than actual sample sizes. This discrepancy often occurs when binomial or multinomial proportions are used to track biological characteristics of fish stocks (e.g. age composition of catches) and sample size is large (Fournier and Archibald, 1982). Geometric mean effective sample sizes for cowcod were about 75 bongo net tows per year for CalCOFI index data and about 50 bottom trawl tows per year for LAOCSD index data. The number of actual CalCOFI tows during 1987–98 was about one-third of the number during 1951–86 because sampling intensity was reduced beginning in 1987 (Hewitt, 1988). For simplicity and to avoid placing too much emphasis in fitting our assessment model to LAOCSD and noisy CalCOFI indices, goodness-of-fit

calculations in subsequent assessment model runs assumed sample sizes of 75 tows per year for CalCOFI data during 1951–86, 25 tows per year for CalCOFI data during the 1987–98 seasons, and 50 tows per year for LAOCSD index data. Use of smaller effective sample size values in model calculations helped us avoid placing too much weight on the noisy CalCOFI data when fitting our model.

Population dynamics modeling

Like the abundance data, preliminary model runs indicated that cowcod biomass declined during the 1951–98 seasons and that recruitment declined after the 1980 season. Catches were relatively low during the historical period prior to 1951, particularly during earlier years. Therefore, biomass was likely high prior to the 1951 season due to good recruitment and low catches. Based on these consid-

Table 4

Abundance data for cowcod in the southern California Bight including catch per unit of effort for anglers on commercial passenger fishing vessels (CPFV), probability of a positive tow for cowcod larvae in CalCOFI ichthyoplankton survey tows, and probability of a positive tow for juvenile cowcod in Los Angeles and Orange County Sanitation District (LAOCSD) bottom trawl survey tows. Seasons start in July and end in June. The 1951 season, for example, started 1 June 1951.

| Season	CalCOFI (probability of positive tow)	CV (%)	LAOCSD (probability of positive tow)	CV (%)	CPFV (fish/h)	CV (%)
1951	0.0238	0.58				
1952	0.0165	0.53				
1953	0.0403	0.47				
1954	0.0271	0.55				
1955	0.0121	0.65				
1956	0.0184	0.59				
1957	0.0425	0.49				
1958	0.0143	0.59				
1959	0.0403	0.48				
1960	0.0309	0.60				
1961	0.0441	0.56				
1962	0.0000	7.02				
1963	0.0122	0.60			0.051	0.18
1964	0.0152	0.67			0.056	0.15
1965	0.0247	0.53			0.046	0.15
1966	0.1255	0.83			0.066	0.11
1967	0.0474	0.60			0.055	0.11
1968	0.1014	0.42			0.036	0.14
1969					0.057	0.12
1970					0.042	0.16
1971	0.0466	0.50			0.041	0.12
1972			0.281	0.28	0.023	0.14
1973			0.300	0.20	0.035	0.11
1974	0.0266	0.48	0.088	0.43	0.034	0.14
1975			0.271	0.21	0.052	0.09
1976			0.036	0.69	0.025	0.13
1977	0.0000	4.37	0.091	0.39	0.026	0.12
1978	0.0000	5.19	0.018	0.99	0.027	0.21
1979	0.0000	6.67	0.051	0.49	0.018	0.15
1980	0.0000	5.73	0.049	0.49	0.014	0.15
1981	0.0000	9.01	0.025	0.70	0.028	0.11
1982	0.0000	8.98	0.012	0.99	0.009	0.2
1983	0.0000	6.10	0.013	0.99	0.015	0.15
1984	0.0000	6.03	0.024	0.70	0.012	0.16
1985	<0.0001	4.99	0.000		0.006	0.27
1986	<0.0001	8.15	0.061	0.43	0.010	0.22
1987	<0.0001	7.71	0.013	0.99	0.006	0.31
1988	<0.0001	8.65	0.038	0.57	0.010	0.18
1989	0.0149	0.83	0.000		0.011	0.19
1990	0.0095	0.83	0.013	0.99	0.011	0.19
1991	0.0124	0.83	0.000		0.008	0.2
1992	<0.0001	8.73	0.000		0.008	0.25
1993	<0.0001	7.23	0.009	1.00	0.008	0.23
1994	<0.0001	9.01	0.020	0.70	0.005	0.3
1995	<0.0001	9.13			0.003	0.38
1996	<0.0001	9.04			0.003	0.33
1997	<0.0001	8.85			0.012	0.43
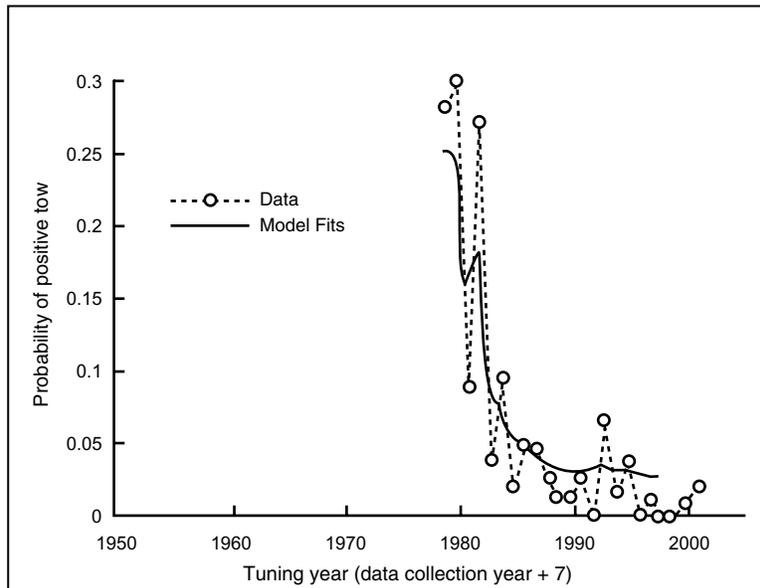
Figure 8

Observed and predicted probability of positive tows (at least one juvenile cowcod, an index of juvenile presence used to track recruitment) for Los Angeles City and Orange County Sanitation Districts (LAOCSD) bottom trawl surveys. "Data" are trawl survey data. "Model fits" are predicted values from the stock assessment model fitted to the data.
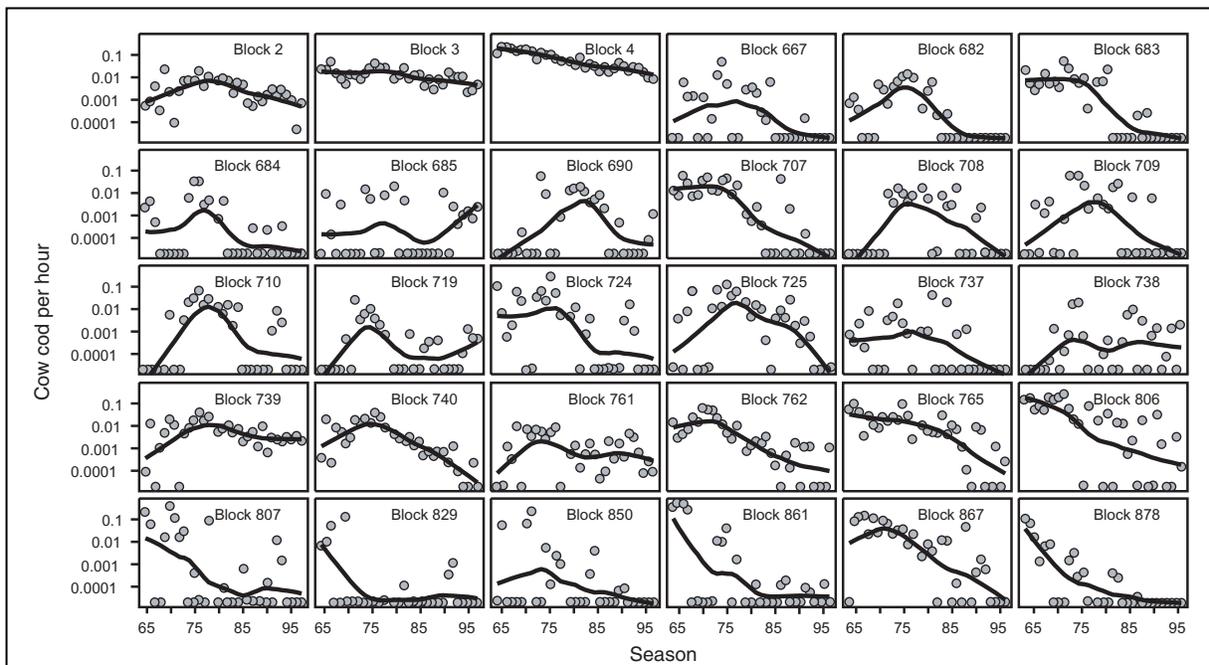

Figure 9

Log scale mean catch per unit of effort (CPUE) for cowcod from the Poisson model for commercial passenger fishing vessel logbook data. Smooth lines were fitted by LOESS (locally weighted regression smoothing) (Cleveland et al., 1988) to show trends.

Figure 10

Area-weighted catch per unit of effort (CPUE) for cowcod in the commercial passenger fishing vessel fleet during 1964–96. "Observed" values are habitat-area–weighted means. "Model fits" are predicted values from the stock assessment model fitted to the data.
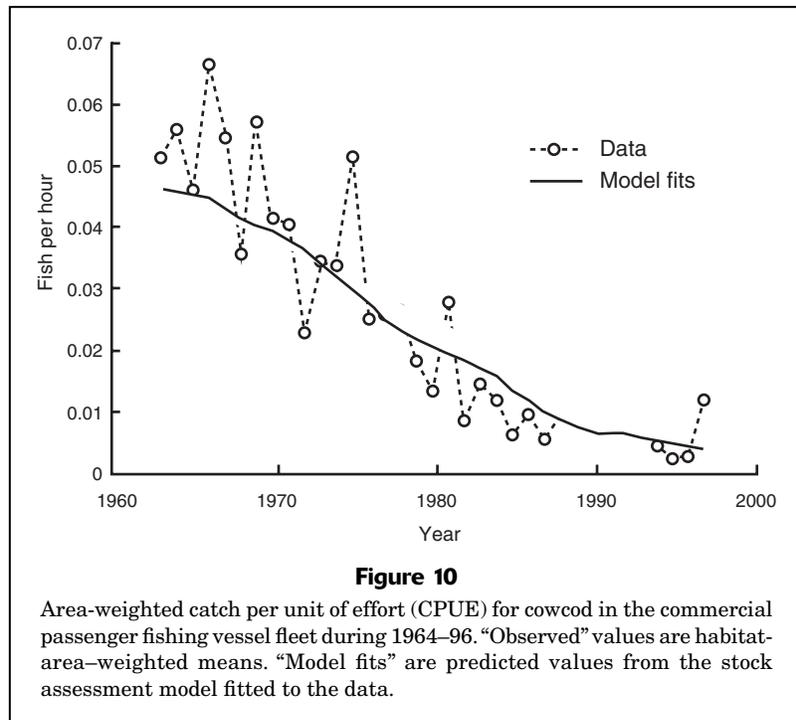
erations, we used average estimated recruitment during the 1951–80 seasons as the assumed level of constant recruitment during the virgin and historical periods in the final model run used to estimate biomass, recruitment, and fishing mortality for management purposes.

Trends in historical estimates indicate that cowcod biomass was near the virgin level in 1916 and remained relatively stable throughout the historical period (prior to 1951), whereas catches were low and recruitment was assumed relatively high (Table 1 and Fig. 11). Biomass began to decline slowly in the 1950s, and the decline accelerated through the 1970s because catch increased while recruitment remained relatively constant. Recruitment, biomass, and catches all declined dramatically after the early 1980s. Reduced catches from the mid-1980s to 1990s were not enough to offset continuous reductions in biomass and recruitment; fishing mortality rates increased and usually exceeded 0.1/yr. SCB cowcod biomass during the 1998 season (about 238 t, CV 33%) was 7.4% (CV 28%) of the level in the 1951 season (3198 t) and 6.5% of the virgin level (3472 t). During the most recent decade (1989–98 seasons), recruitment biomass averaged 8 t/yr and catches averaged 52 t/ yr.

Discussion

We used the best available information to estimate total cowcod catch but the data and our estimates were imprecise. It is possible, for example, that CPFV captains over-report cowcod catches as a means of attracting business, although cowcod are a small part of the catch on most CPFV vessels, but we are not aware of such a practice. Un-

certainty about catch affects the magnitude of F and biomass estimates, but had little effect on estimated biomass trends after 1951 or the ratio of current and virgin biomass (Butler et al., 1999).

Our estimates of habitat area for cowcod (Fig. 1) were crude because depth preferences are uncertain and because we were not able to distinguish rocky areas that are preferred by adult cowcod. Fortunately, our analysis of CPUE in the CPFV fishery was robust to errors in estimating total potential habitat because habitat areas were used as relative (rather than absolute) weights in computing average CPUE.

Biomass, recruitment, and fishing mortality estimates from the stock assessment model for cowcod were less precise for seasons prior to 1951 because historical estimates were based on catch data and no abundance data and because they involved assumptions about virgin biomass and an educated guess about average recruitment during 1916–51 (Kimura and Tagart, 1982; Kimura et al., 1984; Kimura, 1985). Despite these caveats, the estimates for seasons prior to 1951 were plausible and based on all available data.

Rare-event data

Our experience with cowcod suggests that rare-event data for fish stock assessment work is an important topic for future research. Rare events may be particularly important in understanding the population dynamics of naturally rare, severely overexploited or difficult to sample organisms, particularly if long-term data from intensive sampling programs are unavailable. The underlying theory is understood (Mangel and Smith, 1990), statistical tools are

available (McCullagh and Nelder, 1989), and applications have been described (e.g. Smith, 1990; Newman, 1997), but more research and experience are required.

Zero observations ("zeroes") can be expected to be common in rare-event data and frequently encountered in fishery survey data for many species (Lo et al., 1992; Syrjala, 2000). They are usually considered a problem in stock assessment work because conventional assessment models assume lognormal measurement errors for abundance indices and the lognormal distribution does not include the possibility of zero values. However, our experience with CalCOFI and LAOCSD data for cowcod demonstrates the tractability of maximum likelihood estimation using the binomial distribution for proportion positive data with zeroes. Effective sample size calculations can be used with binomial data (e.g. for cowcod) in the same way that Fournier and Archibald (1982) and Methot (1990) used effective sample size techniques to gauge the information content of multinomial age- and length-composition data.

CPFV data

CPFV logbook data present a bleak time series for cowcod. Because this series was critical to the analysis, it is important to consider factors other than abundance that may affect CPUE in the CPFV fishery. For example, changes over time in targeting and identification of cowcod in catches would affect reporting and CPUE, but we are not aware of any changes in catch reporting since 1964.

Trends in CPUE tend to be optimistic (biased towards high biomass in recent years) if fishing effort becomes more effective over time. Changes in angler's gear likely had little effect on catch rates for cowcod because gear used on CPFV vessels has changed little since the early 1960s. Ability of the CPFV fleet to identify, locate, and return to fishing grounds with high catch rates have improved over the last three decades as electronics, including depth finders and global positioning systems, became available and were improved. Effort in later years was likely more effective because CPFV operators were better able to locate and return to locations where rockfish and cowcod were abundant.

Logbook data indicate that recreational fishing effort for rockfish moved from inshore areas (where cowcod are less abundant) to offshore areas during the 1960s to 1980s. Thus, the proportion of total angler hours in the CPFV fishery that could potentially catch cowcod in relatively deep water increased over time as the proportion of anglers fishing offshore and in deep water increased.

Robustness of area-weighted CPUE index

The area-weighted CPUE index for cowcod is robust to interannual changes in the spatial distribution of fishing effort among blocks. This is an important point because CPUE computed as the sum of total catch divided by total fishing effort would be biased high, for example, if the amount of relative fishing effort in a stratum with high catch rates increased. Blocks and pseudo-blocks are strata, in statistical terms, that are sampled during each year. Our area-weighted CPUE index for cowcod is a weighted average of mean CPUE in each stratum during one year. The weights used in computing the index are proportional to the amount of potential cowcod habitat in each stratum.

Thus, the contribution of each stratum to the overall index is proportional to the amount of cowcod habitat in each stratum, not the amount of fishing effort. Increases or decreases in the amount of fishing effort in a stratum with high catch rates will change the precision of the stratum mean and the precision of the index as a whole but would not change the expected value of the area weighted index as a whole. In statistical terms, the expected value of the area-weighted CPUE index should be similar to the expected value of mean CPUE computed from anglers distributed randomly across the entire area of potential habitat. Of course, our area-weighted approach does not accommodate interannual changes in the distribution of fishing effort within strata, and movement of fishing effort within strata towards areas of high catch rate would tend to inflate the index as a whole.
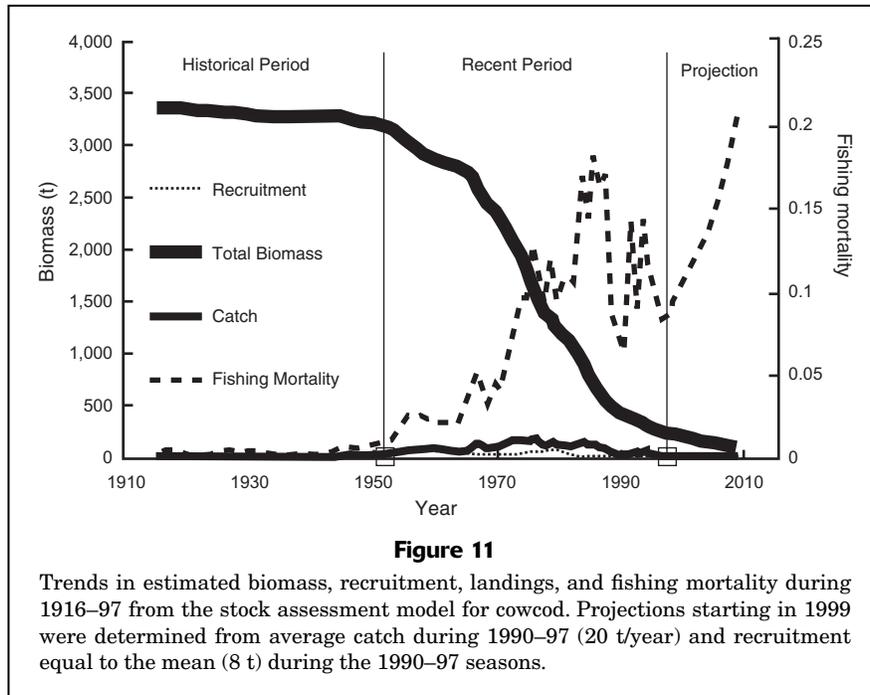
CalCOFI presence-absence data

CalCOFI data were not used in the assessment model as a recruitment index (see "Materials and methods" section). However, considering the time lag between cowcod larvae and juveniles at about age 3, the qualitative trend in CalCOFI ichthyoplankton data appears to match the trend in LAOCSD bottom trawl survey data. In particular, CalCOFI and LAOCSD data both suggest that cowcod recruitment is likely to be poor in the coming years.

Climate change

Declines in cowcod abundance over the last several decades may have been due to reductions in spawning biomass from fishing or to the environmental regime shift (Lluch-Belda et al., 1989) in the SCB and California current towards warmer water during the late-1970s (Barnes et al., 1992, Moser et al., 2000), or to both factors (Jacobson and MacCall, 1995). CalCOFI data show that the probability of occurrence for cowcod larvae in CalCOFI tows declined during the mid- to late-1970s (Fig. 7) and that estimated recruitment to the fishable stock, predictably, declined a decade later (Table 1 and Fig. 11). Catches, recruitment, and abundance for other stocks in the California current changed at about the same time (Beamish, 1995).

Environmental effects on recruitment estimates during 1917–50 are a source of uncertainty in calculating virgin biomass. Historical calculations for cowcod assumed recruitment at average levels during 1951–80, which was a relatively cold-water period in the SCB (as measured by sea surface temperatures at Scripps Pier in San Diego, California; Barnes et al., 1992). However, sea surface temperatures in the SCB were moderately warm during 1917–50 (Barnes et al. 1992). If warm sea surface temperatures are correlated with poor cowcod recruitment, then we may have overestimated historical recruitment and virgin biomass, so that the ratio of biomass in 1998 and virgin biomass (6.5%) was underestimated. However, this

Figure 11

Trends in estimated biomass, recruitment, landings, and fishing mortality during 1916–97 from the stock assessment model for cowcod. Projections starting in 1999 were determined from average catch during 1990–97 (20 t/year) and recruitment equal to the mean (8 t) during the 1990–97 seasons.

uncertainty has little affect on our estimate of the ratio of biomass in 1998 and biomass in 1951 (7.4%) or on the general conclusion that cowcod biomass was low in 1998.

Offshore fishing grounds

Over time, the total number of blocks with rockfish effort in the SCB increased (Fig. 12) as the fishery expanded offshore. Catch rates in blocks nearest to shore have decreased to levels that are low in relation to earlier years (Figs. 1 and 13). Thus fishing grounds in the SCB nearest to shore have been most heavily exploited. Areas of highest cowcod abundance and catch rates are now offshore (Figs. 1 and 13).

Northern areas

Our analysis focused on the SCB where cowcod abundance is highest. However, Butler et al. (1999) examined presence-absence data and CPUE for cowcod in triennial bottom trawl surveys on the continental shelf during 1977–98 (Wilkins[1]). Cowcod were rare in trawl catches north of the SCB and CPUE was generally zero off Oregon and Washington. However, changes in the spatial distribution of positive tows over time indicated that cowcod became more abundant north of the SCB or colonized northern areas after 1986.
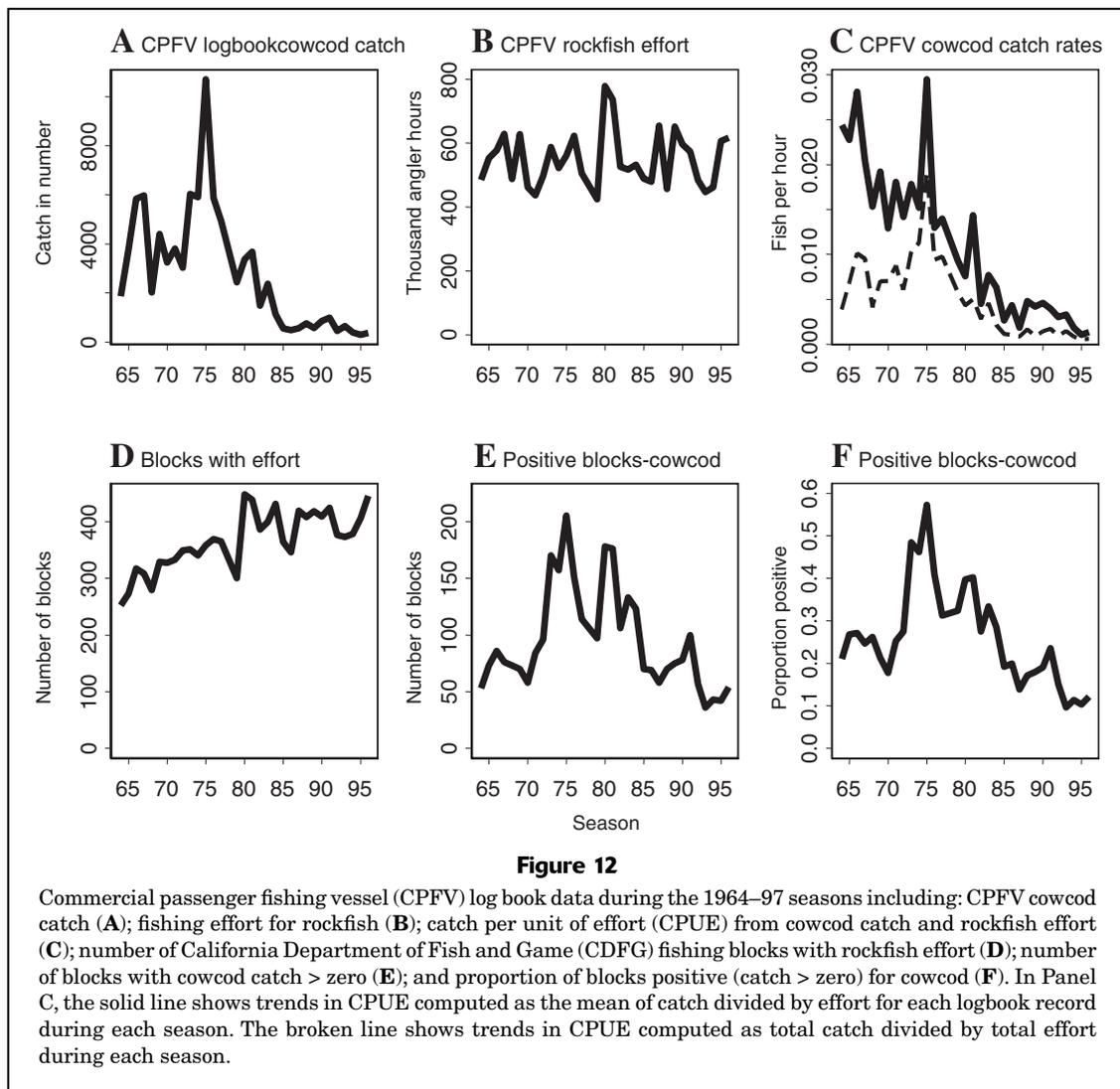
Rebuilding

Recent recruitment levels are probably not sufficient to sustain or rebuild the SCB cowcod stock at recent or substantially reduced catches levels. Short-term projections (Fig.11), assuming recruitment at the estimated average

for the 1990–98 seasons, indicate that cowcod biomass will continue to decline and that fishing mortality rates will continue to increase over the next ten years at constant catch levels > 5 t/yr (Butler et al., 1999).

Estimates of rebuilding time for cowcod are much longer than the ten-year default time frame used by managers (DOC, 1998). Jacobson and Cadrin (2002) used cowcod as an example in calculating rebuilding times of 30–50 yr for cowcod with F=0, based on a simple logistic surplus production model, but stressed that their "calculations are examples only and not for use by managers." Refined calculations with better models, additional information, and more realistic assumptions about incidental mortality and recruitment (DeVore[12]) give estimated rebuilding times that are generally longer than those of Jacobson and Cadrin (2002). Mean generation time (Restrepo et al., 1998) for cowcod is approximately 37 years. Thus, managers' estimates of the time frame for rebuilding SCB cowcod (one generation time plus expected time to rebuild with F=0) may be greater than 87 yr.

Recreational fishing effort in the SCB directed at rockfish, and likely to encounter cowcod, remains relatively high. Logbook records indicate that CPFV vessels alone generate 400–600 thousand angler hours of rockfish effort each year (Fig. 12). MRFSS data indicate that CPFV vessels constitute about half of the recreational fishing effort during each year off California. Thus, total recreational fishing effort likely to impact cowcod rockfish might be as high as 800–1200 thousand angler hours/yr.

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[12] DeVore, J. 2002. Personal commun. Pacific Fishery Management Council, 7700 Northeast Ambassador Place, Suite 200, Portland, OR 97220-1384.

Figure 12

Commercial passenger fishing vessel (CPFV) log book data during the 1964–97 seasons including: CPFV cowcod catch (**A**); fishing effort for rockfish (**B**); catch per unit of effort (CPUE) from cowcod catch and rockfish effort (**C**); number of California Department of Fish and Game (CDFG) fishing blocks with rockfish effort (**D**); number of blocks with cowcod catch > zero (**E**); and proportion of blocks positive (catch > zero) for cowcod (**F**). In Panel C, the solid line shows trends in CPUE computed as the mean of catch divided by effort for each logbook record during each season. The broken line shows trends in CPUE computed as total catch divided by total effort during each season.

Managers may develop harvest limits to discourage targeting and catch of cowcod but effectiveness will likely be undermined by discard mortality. Cowcod are part of a multispecies commercial and recreational fishery and are harvested along with a large number of other species. As shown above, an increasing fraction of recreational fishing effort occurs offshore where cowcod are most common. Adult cowcod are associated with rocky bottom features that attract other species of recreational and commercial fishing interest and are easy to find with modern navigational equipment. Adult cowcod are strictly demersal, are generally found in waters deeper than 90 m, and cannot be released alive because they have swimbladders that rupture when these fish are caught and brought to the surface during commercial and recreational fishing.

In response to the challenging problems in rebuilding cowcod, the Pacific Fishery Management Council and California Department of Fish and Game established new management measures, effective January 2001. New measures for cowcod include two cowcod conservation areas (CCAs)

in the SCB, which encompass about 14,750 km² of surface area and include prime offshore cowcod habitat (Fig. 13). Regulations prohibit most bottom-fishing activities in waters deeper than 37 m within the CCAs, no retention of cowcod taken anywhere along the coasts of California, Oregon, and Washington, and reductions in the number of hooks per rod in the California recreational fishery (from five to two per rod). In planning, a 1% harvest rate is used to account for unavoidable mortality due to contact with fishing gear directed at other species.

Cowcod is just one example of a long-lived, relatively sedentary apex predator closely associated with bottom structure that has been exploited by commercial and recreational fisheries. Data for cowcod, including long time series of catch estimates, recreational CPUE, and ichthyoplankton data, are sufficient to describe the stock's decline in the SCB. The cowcod conservation areas were the first large no-take marine protected areas on the West Coast and may be important in rebuilding rockfish populations off southern California. However, managers have
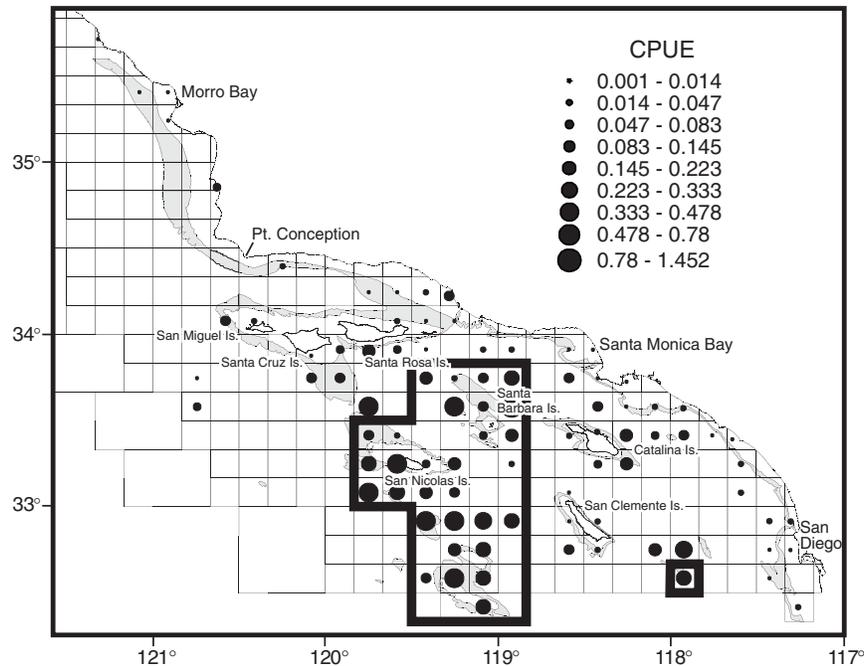
Figure 13

Commercial passenger fishing vessel (CPFV) mean catch rates (cowcod per angler day) for each fishing block during the 1990–98 seasons (no dot means zero CPUE). Heavy black lines surround two cowcod conservation areas.

little experience managing cowcod to increase abundance. Long time series do not exist for many species of groupers and snappers that have similar life histories and similar abundance declines in the Caribbean (Huntsman et al., 1997, Coleman et al., 2000). No-take marine protected areas in the Caribbean Sea have greater numbers and more biomass of large grouper species than adjacent areas where fishing takes place (Chiappone et al., 2000). Thus, comparative studies may be useful in understanding the population dynamics of similar species with little data and in rebuilding species with little management history.

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Appendix

Modeling abundance based on presence absence data and effective sample size

The negative log-likelihood used to measure goodness of fit for CalCOFI and LAOCSD data in the cowcod assessment model was

$$L = -\lambda \left\{ \sum_{i=1}^{N} \left[I_i \ln(\hat{I}_i) + (1 - I_i)\ln(1 - \hat{I}_i) \right] - A \right\},$$

where A is a constant;

N = the number of years with data; λ was the effective sample size (tows/yr); and observed I_i and predicted $\hat{I}_i$ index values are proportions.

The constant A has no effect on model estimates but makes the log-likelihood easier to interpret, plot, and understand. Following Methot (1990), it was calculated with the following equation:

$$A = \sum_{i=1}^{N} D_i \left[I_i \ln(I_i) + (1 - I_i)\ln(1 - I_i) \right],$$

where the dummy variable D_i was one if $0 < I_i < 1$ and zero otherwise.

The constant depends only on the data (not the fit) and is the minimum possible log likelihood (if observed and predicted values match exactly).

Effective sample size calculations were based on the variance of residuals in preliminary model runs (Methot, 1990). This manual "iterative re-weighting" approach was repeated several times until assumed and calculated variances were roughly equal. The expected variance of an index value based on standard formulas for proportions and n tows is

$$Var(\hat{p}) = \frac{\hat{p}(1 - \hat{p})}{n},$$

so that

$$\lambda = \frac{\hat{p}(1 - \hat{p})}{Var(p)},$$

with λ instead of n for the effective sample size. The variance $Var(p)$ of residuals in one year was calculated by using another standard formula:

$$Var(p) = \frac{\left\{ (p - \hat{p})^2 + \left[(1 - p) - (1 - \hat{p}) \right]^2 \right\}}{n - 1} = 2(p - \hat{p})^2.$$

To estimate an effective sample size for the time series as a whole, we calculated the geometric mean of the effective sample sizes for each year.