Age and growth of blue rockfish (*Sebastes mystinus*) from central and northern California

Thomas E. Laidig

Donald E. Pearson

Southwest Fisheries Science Center
National Marine Fisheries Service
110 Shaffer Rd.
Santa Cruz, California 95060
E-mail: tom.laidig@noaa.gov

Lorraine L. Sinclair

Pacific States Marine Fisheries Commission
411 Burgess Drive
Menlo Park, California 94025

Abstract—Otoliths from blue rockfish (*Sebastes mystinus*), were aged by using a combination of surface and break-and-burn methods. The samples were collected between 1978 and 1998 off central and northern California. Annual growth increments in the otoliths were validated by using edge analysis for females up to age 23 and for males to age 25. The first annual growth increment was identified by comparing the diameter of the otolith from fish known to be one year old collected in May (when translucent zone formation was completed) to the mean diameter of the first translucent zone in the otoliths from older fish. Our estimated maximum ages of 44 years for males and 41 years for females were much older than those reported in previous studies. Von Bertalanffy growth models were developed for each sex. Females grew faster and reached larger maximum length than males. The growth models were similar to those generated in other studies of this species in southern and central California. Fish from northern and central California had similar maximum sizes, maximum ages, and growth model parameters.

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Accurate information on age and growth is critical for reliable assessments and effective management of fish stocks. Most assessments of west coast groundfish stocks use age-based models (PFMC, 2001). It is important to obtain reliable ages for maturity schedules, age-specific fecundity, and age-specific selectivity, as well as estimates of aging accuracy, in order to correctly estimate biomass and acceptable biological catch numbers for these assessments. Inaccurate age estimates can lead to over-harvesting or denial of fishing opportunities.

In the present study, we examine age and growth of blue rockfish (*Sebastes mystinus*). The blue rockfish is a schooling species that occurs from Sitka Strait (southeast Alaska) to northern Baja California (Love et al., 2002). They reach a maximum size of 508 mm fork length (FL). Blue rockfish are frequent inhabitants of nearshore rocky reefs, and are commonly found from the surface to about 90 m water depth. Blue rockfish comprise a major fraction of the recreational fishery off California (Miller and Geibel, 1973; Karpov et al., 1995) but are less common in the commercial fishery. In 1994, blue rockfish landings off California totaled 172 metric tons (t) from recreational fisheries and only 68 t from commercial fisheries (Rogers et al., 1996).

Age structure of blue rockfish has been determined previously by using length-frequency analyses, tag-and-recapture studies, scales, and whole otoliths (Wales, 1952; Miller and Geibel, 1973; McClure, 1982; MacGregor, 1983; Karpov et al., 1995). We estimated age by examining the surface of whole otoliths and broken-and-burnt cross sections of otoliths. Aging the surface of whole otoliths is only effective for young rockfish (Six and Horton, 1977; Kimura et al., 1979; Chilton and Beamish, 1982). The break-and-burn technique (Chilton and Beamish, 1982) is used widely for age determinations of west coast groundfish (including Dover sole [*Microstomus pacificus*], sablefish [*Anoplopoma fimbria*], and numerous species of rockfishes).

We used edge analysis to verify the annual periodicity of growth increments in the otoliths of blue rockfish. Edge analysis and marginal increment analysis have been used to validate annual growth increments in numerous species. In recent studies, Crabtree and Bullock (1998) validated the first seven annual growth increments in black grouper, and Brown and Sumpton (1998) validated the ages of the redthroat emperor off Australia. The procedure has been used to validate annual growth increments in many rockfish species, including redfish, (Mayo et al., 1981), yellowtail (Kimura et al., 1979), shortbelly (Pearson et al., 1991), widow (Pearson, 1996), gopher, and kelp rockfish (Lea et al., 1999).

Methods

Rockfish sampling

Otoliths of blue rockfish were obtained from 1) the recreational catch of commercial passenger fishing vessels (CPFV); 2) the catches of midwater trawls deployed from a research vessel; and 3) specimens speared by researchers equipped with SCUBA (Table 1). CPFV landings were available from Monterey to Bodega Bay, California, from 1978 to 1998. All fish were caught at depths deeper than 20 m; total length (TL) and sex were recorded for each specimen, and otoliths were removed. Pelagic young-of-the-year blue rockfish were caught in a 13 × 13 m midwater trawl deployed periodically from the RV *David Starr Jordan* off the central California coast from Monterey to Marin counties during 1988–93 at depths of 5–30 m. In the laboratory, each specimen was measured (standard length [SL]) and otoliths were removed and attached to microscope slides for later examination. Specimens were taken with spears from 1988 to 1998 in water depths of 1–20 m off Sonoma and Mendocino counties (Table 1). Some cohorts were sampled throughout their first year after first settlement, thus providing specimens of known age. We measured each specimen, determined sex, and removed otoliths. All fish lengths (either TL or SL) were standardized to FL for comparisons (by using equations from Echeverria and Lenarz, 1984).

Table 1

Number of specimens collected by year for blue rockfish (*Sebastes mystinus*) from three different sampling methods.

Year	Recreational catch	Diver spears	Midwater trawls
1978	12		
1980	64		
1981	214		
1982	215		
1985	31		
1986	77		
1988		109	35
1989		217	11
1990		206	38
1991		157	34
1992		122	7
1993		190	8
1994		138	
1995		18	
1997	15	43	
1998	27	45	

Otolith examination

Ages were estimated by counting the number of translucent zones from the surface of whole otoliths for young blue rockfish (less than 5 years of age) and by using the break-and-burn method (Chilton and Beamish, 1982) for fish greater than 5 years old. Whole otoliths were viewed through a dissecting microscope at 20–40× magnification with reflected light. For the break-and-burn method, whole otoliths were broken in half through the core, and one broken section was burned and viewed through a dissecting microscope at 20–40× magnification. Two readers determined ages independently by counting the number of translucent zones observed in both whole and broken-and-burnt otoliths. The precision of age estimates was compared by using the average percent error (APE; Beamish and Fournier, 1981). Otolith diameter was measured from the dorsal to the ventral edge through the core of the otolith. The diameter of the otolith at each presumed annual growth increment was measured from a video image of the cross section of a broken section of the otolith from the dorsal edge to the ventral edge of the translucent zone along a transverse axis through the core.

Validation of growth increments

Validation of growth increments as being produced annually was conducted in four parts. First, we conducted an edge analysis (Pearson, 1996) to determine if only one translucent zone formed along the edge of the otolith during a year. We identified the leading growth edge as either "opaque" or "translucent" on otoliths collected throughout the year to determine when the translucent zone was formed. An examination of edge analysis data was conducted on each age class from 1 to 44 years to determine if only one opaque and one translucent zone formed annually, and if they had formed, then these ages were considered validated.

Second, to identify the first annual growth increment, the average diameter of otoliths from known age one-year-old fish was compared to the average diameter of the first translucent zone from older fish. We determined the length of one-year-old fish at the time of translucent zone completion (as determined by the edge analysis) by plotting fish length against Julian date of capture and then determined the best model that described this relationship.

Third, we determined the predicted otolith diameter of a fish at the time of translucent zone completion. For this analysis, we used fish lengths from young-of-the-year (YOY; both pelagic and settled) and one-year-old blue rockfish for which ages were known by following a cohort through time. Fish length was plotted against total otolith diameter, and the best model for this relationship was determined. Using this relationship and the size of a one-year-old fish (established from the previous model), we calculated otolith diameter for one-year-old fish.

Fourth, mean diameters of the first, second, and third translucent zone of all otoliths from older fishes were measured. The diameters of these three translucent zones were compared to each other by using a Student's t test. If the first translucent zone corresponded to the diameter of an otolith at the time of completion of the first translucent zone and the first translucent zone was significantly different from the second and third zones, then the assumption that the first translucent zone was equivalent to the first annual growth increment was considered validated.

Growth

A von Bertalanffy growth curve was fitted to the fish length and age data. The form of the equation was

$$L_t = L_\infty (1 - e^{-k(t - t_0)}),$$

where L_t = fish length (mm FL) at age t;
L_∞ = maximum fish length (mm FL),
k = growth completion rate (per year);
t = age (years); and
t_0 = theoretical age (years) when the fish was length zero.

Parameters for the growth curve were calculated iteratively by using the method described by Schnute (1981). Growth models were developed separately for males and females to account for possible sex-specific growth rates (Echeverria, 1986). Growth curves were fitted for the entire sampling area and separately for the northern and southern areas to examine potential latitudinal trends in growth and by mode of collection. Growth curves were compared by using the extra sum of squares principle (Draper and Smith, 1981; Ratkowsky, 1983; Pearson and Hightower, 1991).

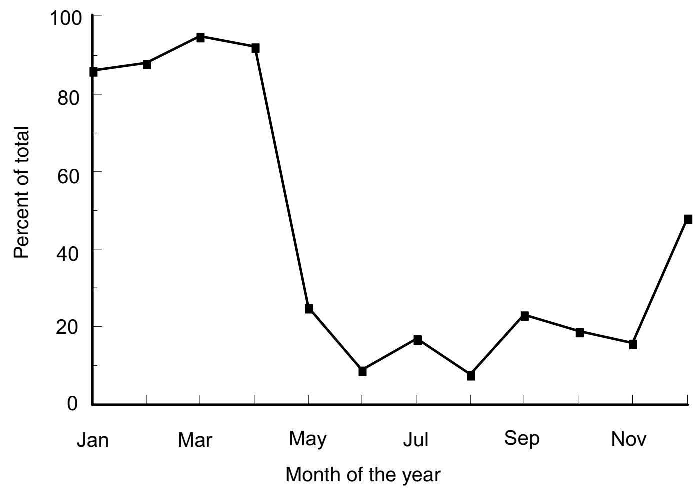

Figure 1

Percentage of blue rockfish (*Sebastes mystinus*) having a translucent zone along the otolith edge in each month (n=927).

Results

A total of 1980 blue rockfish were examined; 655 of these fish were caught by hook-and-line from CPFV, 133 pelagic juveniles were collected in midwater trawls offshore, and 1245 fish were speared. Maximum size of fish from the CPFVs was 365 mm FL for males and 444 mm FL for females. Maximum size of speared fishes was 360 mm FL for males and 412 mm FL for females. The oldest fish from the CPFVs were a 44-year-old male and a 40-year-old female, and the oldest speared fish were a 39-year-old male and a 41-year-old female. There was a 5.6% APE between readers. When ages were not in agreement, the readers would discuss the differences and if no consensus could be reached, the suspect otoliths were discarded.

Validation of growth increments

A subset (out of 1900 otoliths used for aging) of 927 (603 from CPFV and 324 from spearing) otoliths ranging from 1 to 44 growth increments was examined for edge analysis. Formation of the translucent zone followed a seasonal pattern for all otoliths combined (Fig. 1). A translucent zone developed from December through April, followed by an opaque zone that developed from May to November. Translucent zones in over 70% of the otoliths were completely formed by 1 May (or 120 Julian days), and formation of the opaque zone was complete by January in over 80% of the otoliths. From these results, we concluded that only one translucent and one opaque zone formed during a calendar year. Because only one translucent zone was shown to form each year, the annual periodicity of these zones was established. To complete the validation at each age, an edge analysis should be conducted for each age class individually (Campana, 2001). There were enough samples to conduct an edge analysis for females up to age 23 and males to age 25, and, in all instances, only one opaque and one translucent zone formed annually. Therefore, female blue rockfish were validated up to 23 years and males up to 25 years.

The length of a fish at the conclusion of translucent zone formation (determined from the edge analysis) was calculated. The first translucent zone was calculated to be complete on 1 May, one year after the assumed parturition on 1 January, or 365 Julian days + 120 Julian days = 485 days from parturition. The relationship between date of capture and FL was described with the linear equation: FL=0.16 × (date of capture) + 30.9 (n=99, r^2=0.91; Fig. 2). From this equation, a fish would be 108.5 mm FL at the time of completion of the first translucent zone (1 May, one year after parturition).

The relationship between fish length and otolith diameter (Fig. 3) was best described by the linear equation *otolith diameter* (mm) = 0.02 × (mm FL) – 0.02 (n=198, r^2=0.95). From this equation and a fish length of 108.5 mm FL at the time of the first translucent zone completion, an otolith diameter of 2.19 mm was the estimated size of the predicted translucent zone.

Diameters of the first and second translucent zones (n=509, df=508, P<0.001) and the second and third translucent zones (n=151, df=150, P<0.05) differed significantly. From a comparison of first, second, and third translucent zone diameters in the otoliths of all blue rockfish against fish length, the average observed diameter for the first translucent zone was 2.17 mm (Fig. 4), compared to the estimated diameter of 2.19 mm (from the above equation), the average observed diameter of the second zone was

3.00 mm, and the average observed diameter of the third zone was 3.67 mm (Fig. 4).

Growth

Growth between the sexes was significantly different ($P<0.05$); females grew faster and reached a larger maximum size than did males (Fig. 5). The von Bertalanffy growth model parameters for females were t_0 = –1.34 years, k = 0.149/year, and L_∞ = 400.16 mm FL and for males were t_0 = –0.95 years, k = 0.195/year, and L_∞ = 329.41 mm FL.

Growth models for both sexes were not significantly different ($P>0.05$) between the southern CPFV and northern speared samples (Fig. 6). The models representing males were virtually identical, with parameters for the CPFV model of t_0 = –0.94 years, k = 0.195/year, and L_∞ = 331.66 mm FL, and for the speared model of t_0 = –0.99 years, k = 0.194/year, and L_∞ = 323.14 mm FL. There was no significant difference between females; t_0 = –1.94 years, k = 0.107/year, and L_∞ = 430.74 mm FL for the CPFV samples and t_0 = –1.14 years, k = 0.166/year and L_∞ = 393.34 mm FL for the speared. Females from CPFV were larger at ages after 15 years than those that had been speared.

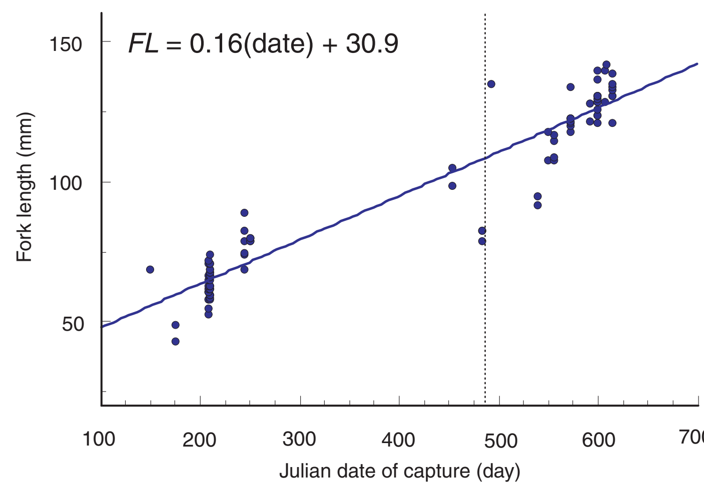

Figure 2

Growth of blue rockfish (*Sebastes mystinus*) collected nearshore during their first 1.5 years. Solid line is the fitted linear growth model (n=99; r^2=0.91). Vertical line represents 1 May, one year after the parturition date of 1 January (i.e. 365 +120=485 days).

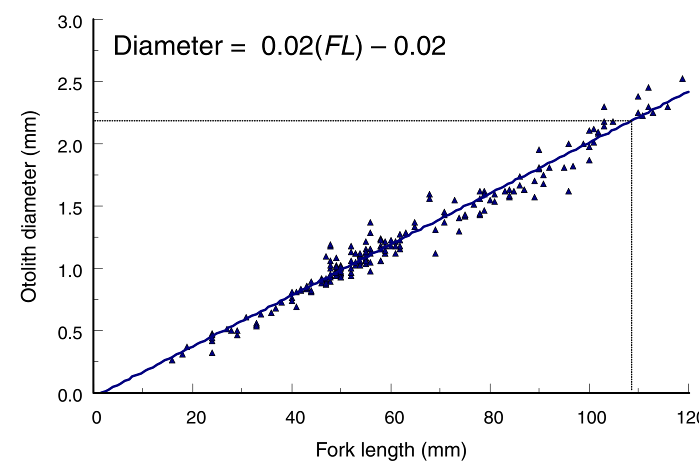

Figure 3

Change in otolith diameter with fish length for young-of-the-year and one-year-old blue rockfish (*Sebastes mystinus*). Solid line is the fitted linear model (n=198; r^2=0.95). Dashed line represents an estimated total otolith diameter of 2.19 mm for a fish of 108.5 mm FL (i.e. fish length at time of translucent zone completion).

Discussion

We estimated the age (using the break-and-burn technique) of blue rockfish to be greater than that reported in earlier studies. Aging the scales of blue rockfish, Miller and Geibel (1973) reported maximum ages of 24 and 17 years for females and males, respectively, whereas the oldest of either sex reported by MacGregor (1983) was only 13 years. Based on modal progression of length distributions, the estimate of the oldest individuals of either sex calculated by Karpov et al. (1995) was 17 years. In a study of blue rockfish off Newport, Oregon, McClure (1982) examined otolith surfaces and determined that the oldest female was 16 years, and the oldest male was only 12 years. In aging males to 44 years and females to 41 years, our study more than doubled the recorded maximum ages for blue rockfish, demonstrating the value of the break-and-burn section method for accurate age determination.

Age data were validated by using an edge analysis and the first translucent zone was validated as corresponding to the first annual growth increment. Campana (2001) pointed out that there are problems in using edge analysis as a validation tool. Specifically the extension of younger, validated ages to older, nonvalidated ages. In our study, we validated ages up to 23 years for females and up to 25 years for males; ages of older fish could not be positively validated. Therefore, caution must be taken when using the older ages.

The growth rates of blue rockfish in our study were similar to those estimated by others in California, but slower than conspecifics off Oregon (Fig. 7). MacGregor (1983) examined blue rockfish from southern California and determined the combined male and female growth

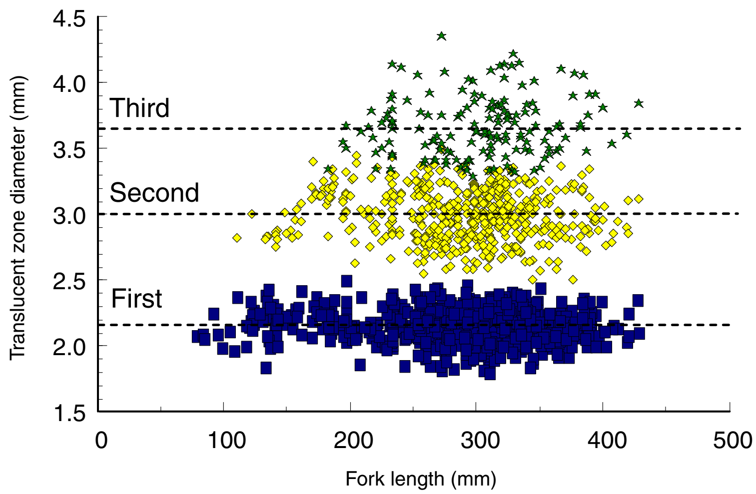

Figure 4

Diameter of the first, second, and third translucent zones in otoliths from blue rockfish (*Sebastes mystinus*) at various lengths. Dashed lines represent the mean diameters.

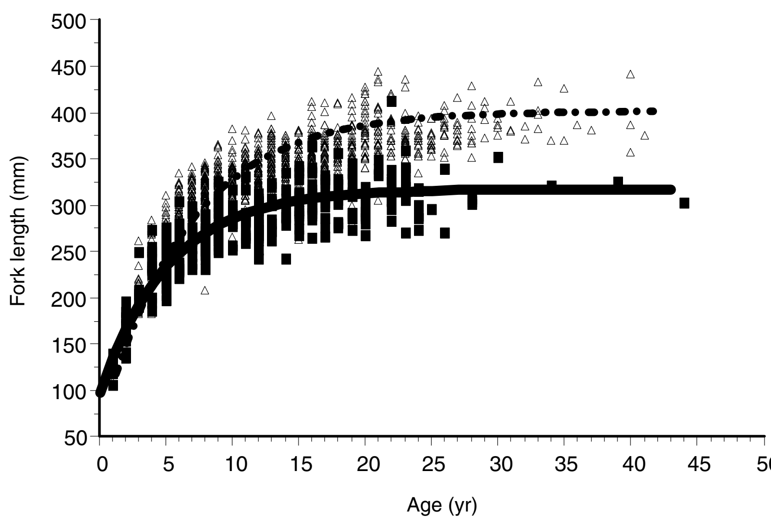

Figure 5

Von Bertalanffy growth models for all male (solid line) and female (dashed line) blue rockfish (*Sebastes mystinus*). (n=348 for males and n=1348 for females.)

rate and calculated k (instantaneous growth rate) to range from 0.13–0.16/years, which was comparable to k in our study (0.2/year for males and 0.15/years for females; mean k=0.17/year). Karpov et al. (1995) calculated k for the combined male and female growth rate from modal progressions studies to be 0.12/year. This also was similar but less than the k from our present study. On the other hand, McClure (1982) estimated a much faster growth rate for blue rockfish off Oregon, with a k for males of 0.23/years and for females of 0.31/year. Although the Oregon fish were larger at age (Fig. 7), maximum sizes from Oregon and California were similar; the largest specimen from Oregon was 460 mm FL (McClure, 1982) and the largest individual from our study was 444 mm FL.

The difference in growth between studies may be attributed to a temporal difference in the collection of fish. Two thermal regime shifts have occurred in the Pacific Ocean over the past 25 years; one in 1977 and the other in 1989 (Hare and Mantua, 2000). The samples from our study came from two different thermal regimes, but the growth curves were not statistically different (Table 1). Therefore, these regimes did not appear to effect the growth of adult fish. Out of the four other surveys mentioned above, three came from one of these two regimes, and the fourth, Miller and Geibel (1973), came from an earlier regime. If there were any effects from the three different thermal regimes, it would seem clear that these differences would show up between samples from such varied regimes. However, the only study with different measures of growth was that from Oregon (McClure, 1982), with samples that were collected during the same regime as two of the other studies (MacGregor, 1983; and the present study). Therefore, thermal regime alone does not seem to have a major impact on the growth of blue rockfish, although further analysis is needed to confirm this point.

These differences in growth parameters between fish from California and Oregon may be attributed to differences in aging methods. Wilson and Boehlert (1990) found that estimates of growth based on aging of otolith surfaces were higher for *Sebastes pinniger*, but were similar to growth rates estimated from otolith sections for *S. diploproa*. The ages of *S. alutus* determined from otolith surfaces had poor correlation with ages from otolith cross-sections for fish older than 17 years, but there was close agreement for younger fish (Stanley and Melteff, 1987). Reading ages from the surface of an otolith may underestimate the age of a rockfish (Munk, 2001) and thus result in greater size-at-age and growth rate estimates. However, aging methods may not be the only factor influencing the growth discrepancies. Miller and Geibel (1973) and MacGregor (1983) both used scales to age blue rockfish (which also can underestimate the age of fish [Beamish and MacFarlane, 1987]), and, yet, their growth models more closely approximated the model produced by our study.

Faster growth estimated for blue rockfish off Oregon may reflect a latitudinal difference in growth. Fraidenburg (1980) examined length and age composition of *Sebastes flavidus* and reported evidence of a north-to-south cline of decreasing size-at-age. Pearson and Hightower (1991) studied *S. entomelas* and noted smaller *k* values and larger average maximum lengths with increasing latitude. Boehlert and Kappenman (1980) reported faster growth in the north for *S. diploproa* and no difference in growth with latitude for *S. pinniger*. They postulated that because the fish live demersally on the continental shelf, latitudinal variation in environmental factors may be insufficient to explain the difference in growth rates and that differential exploitation by the fishery may be a possible influence on growth. Blue rockfish live at relatively shallow depths where environmental and biological factors may have a greater influence on their populations.

Although blue rockfish display a possible latitudinal trend in growth rate between California and Oregon, within California no latitudinal trend in growth rates was observed. Specimens from both the southern CPFV sample and the northern speared sample areas had translucent zone completion by 1 May, which was consistent with the findings of Miller and Geibel (1973) using ages from scales. Individual fish in our study also had similar maximum ages and maximum fish lengths in the north and south areas.

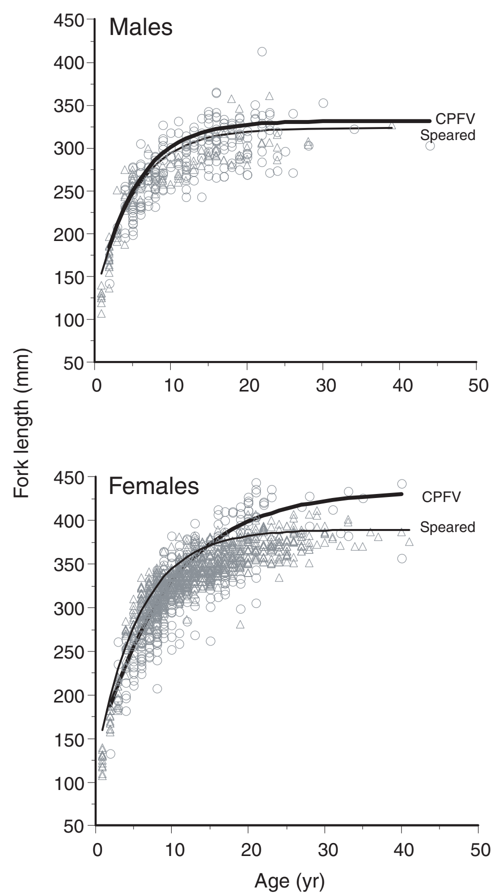

Figure 6

Von Bertalanffy growth models for male and female blue rockfish (*Sebastes mystinus*) from the CPFV (thick line) and speared samples (narrow line). Individual data points are plotted for blue rockfish from CPFV (open circle) and speared samples (open triangles).

No latitudinal trend in growth rates was observed over the 280 km between the centers of the two sampling areas. Although growth rates varied throughout their study area from Half Moon Bay in the north to Morro Bay in the south, Miller and Geibel (1973) likewise observed no latitudinal trend in growth for blue rockfish.

Blue rockfish have average maximum ages and growth rates when compared to other rockfish species. Maximum ages for rockfishes (*Sebastes* spp.) range from 12 years for the relatively small calico rockfish to 205 years for rougheye rockfish, one of the largest species (Cailliet et al., 2002; Love et al., 2002). According to Love and Johnson (1998), of the 38 species most accurately aged, most lived to more than 40 years. Love et al. (1990) found growth rates for three species that share the blue rockfish habitat (black, k=0.12–0.21/year; yellowtail, k=0.16–0.20/year; and widow rockfish, k=0.14–0.22/year) to be similar to that for blue rockfish (k=0.17 years). Mean k values for rockfish varied

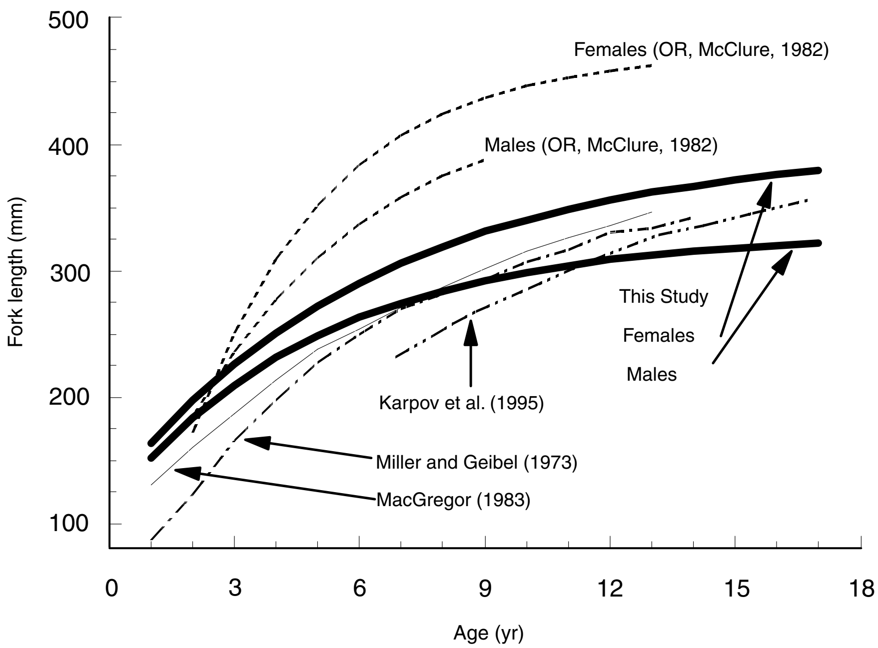

Figure 7

Growth models from five published studies of blue rockfish (*Sebastes mystinus*).

from 0.04/year for female silvergrey rockfish to 0.62/year for the shorter-lived dwarf Puget Sound rockfish, with the average range of k values occurring from 0.1 to 0.3/years (Love et al., 1990; Beckman et al., 1998). This considerable longevity and relatively slow growth rate have significant effects on the ability of many rockfish stocks to withstand exploitation.

The age and growth relationships described in this study indicate that both recruitment of blue rockfish to the fishery and their maturity occur at younger ages than previously reported. Blue rockfish enter the fishery at a size of approximately 200 mm (Miller et al., 1967; Miller and Geibel, 1973). This length equates to ages of 2–4 years as determined in our study compared to 3–5 years as estimated by Miller et al. (1967). The new estimates for age at which 50% of individuals are mature (using fish lengths from Miller and Geibel, 1973) are even more striking: our estimated age at 50% maturity is 5–6 years for males and 5 years for females, whereas estimates from Miller and Geibel (1973) and Echeverria (1986) were 7 years for males and 7–8 years for females. Similarly, the youngest mature males and females in these early studies were 4–5 years, whereas we estimated the age to be 3 years.

The changes observed in our study in age-at-length, maximum age, recruitment age, and age at 50% maturity have important implications for stock assessments. Accurate information on age composition, weight-at-age, age specific availability to the fishery, and maturity-at-age is crucial to the proper functioning of the stock synthesis model (Methot, 1990), which is used for Pacific coast groundfish. If incorrect age data are used, it could lead to erroneous estimates of population size, and subsequently to either overfishing or an unnecessary reduction in allowable catch.

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