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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
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ABSTRACT

A consolidated life history of greenspotted rockfish, *Sebastes chlorostictus,* is compiled from past studies and recent data from the Southwest Fisheries Science Center's Groundfish Ecology Cruise program in central California. Our data indicate similar growth rates for males and females; the von Bertalanffy parameters for both sexes combined are L_∞ = 457 mm fork length (FL), k = 0.062 yr^{-1} and t_0 = -1.16 yr. The estimated length-weight relationship is $W = 0.00001032L^{3.108}$ (weight in grams), and the estimated annual natural mortality rate (M) is roughly between 0.04 and 0.07 yr^{-1}. Length at 50% maturity is 262 mm FL, and fecundity ranges from 14,000 to 414,000 eggs. Linear models provide the best fit of absolute fecundity data with length and weight. In central California, females spawn from March to August, peaking from April to June. Commercial landings of greenspotted rockfish declined from a peak of 430 metric tons (mt) in 1991 to <1 mt in 2003. Reduced landings since the late 1990s are due in part to management restrictions. Mean lengths from California commercial market samples show a declining trend from 1978-2004. The observed life history characteristics of *S. chlorostictus* (slow growth, sedentary adults, extreme longevity, and late maturity), combined with declines in mean length, may indicate that this species is vulnerable to overexploitation.

INTRODUCTION

Greenspotted rockfish (*Sebastes chlorostictus)* range from Copalis Head, Washington to Isla Cedros, Baja California in depths of 30-363 m (Eschmeyer *et al.*, 1983). Also known as chinafish, bosco and chucklehead, this species is considered abundant from Mendocino County (Northern California) to northern Baja California and is most common in depths of 90-179 m (Love *et al.*, 2002). Greenspotted rockfish is a benthic species that occurs over a wide range of habitats and has a reported maximum length of 47.2 cm (Love *et al.*, 2002).

Greenspotted rockfish are of modest importance in commercial and recreational fisheries. Greenspotted rockfish landings by the California recreational fishery have averaged 68 metric tons (mt) per year since 1980 (RecFIN, 2009). California commercial landings have averaged 113 mt per year since 1969 (CALCOM, 2009). To date, there has not been a stock assessment of greenspotted rockfish.

This study was initiated as part of the ongoing Groundfish Ecology Cruise program at the NOAA Fisheries SWFSC’s Fisheries Ecology Division in Santa Cruz, CA. This cooperative research program started in November 2001 and is intended to continue at least through 2010. New data are compiled from samples collected on monthly cruises by chartered commercial trawl and longline vessels. The objectives of the program are five-fold: (1) obtain monthly biological data on as many groundfish species as possible;

(2) develop basic life history data on as many species as possible; (3) examine various aspects of commercial fishing operations as they relate to research operations; (4) improve knowledge of commercial fishing by collaborating with the commercial fishing industry; and (5) compare various methods of fishing and surveying, including the use of remotely operated vehicles (ROVs) and different types of commercial fishing gear.

Several studies have described the maturity, fecundity, and growth of greenspotted rockfish (Barss, 1989; Chen, 1971; Lea *et al.*, 1999; Love *et al.*, 1990; Echeverria, 1987). In this paper, we review existing literature and compare the results of previous studies to findings from the Groundfish Ecology Cruise program. Our data include the first estimates of age and growth of this species using the break-and-burn technique for ageing (Chilton and Beamish, 1982). Additionally, we present the first estimates of natural mortality and fecundity for central California populations. We also include a discussion of landings and a synopsis of juvenile and adult life history information.

METHODS

COLLECTION OF SAMPLES

Samples were collected by monthly longline and trawl cruises between November 2001 and November 2004 from various locations in the Monterey Bay area. A total of 1,436 greenspotted rockfish were collected in 57 longline sets and 30 trawl tows that were positive for *S. chlorostictus*. Longline sampling gear consisted of 2/0 circle hooks with a 1.6 cm opening from tip to shank. Hooks were baited with squid and attached to 12-inch ganions spaced at 2-foot intervals. Sets were made with 3-5 skates of about 250 hooks each. Soak time was variable but was usually 1-2 hours. Trawl operations employed a commercial bottom trawl net equipped with rollers. The net had a 4.6 m vertical opening and a 41.2 m footrope. A net liner of 1.3 cm mesh was inserted in the cod end to retain small fish. Tows were generally made at about 2.5 knots for 1 hour.

All samples were returned to shore for processing. Fork length (FL) to the nearest millimeter and weight in grams were measured, and sex and maturity state were recorded. Otoliths were removed and stored dry in coin envelopes. Ovaries of females in late vitellogenesis were removed and stored in 10% buffered formalin.

AGE AND GROWTH

Age estimates were obtained for 150 fish using the break and burn technique (Chilton and Beamish, 1982). Otoliths were cross-sectioned through the core along the dorso-ventral axis with a Buehler Isomet low speed saw. The cut halves were then burnt over an alcohol flame and viewed at 20-40X magnification. Between-reader variability was determined using secondary age estimates of 130 otoliths examined by a different reader.

We model expected length at age using the von Bertalanffy (VB) growth equation,

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

where L_t (mm FL) is fish length at age t (yr), L_∞ (mm) is the population average asymptotic fork length, k (yr^{-1}) is the growth rate coefficient, and t_0 (yr) is the age-intercept of the growth curve at 0 mm fork length.

To examine differences in growth between sexes, we compare a VB growth model with sex-specific parameters to a VB model for the combined sexes. For this comparison, parameters were estimated using maximum likelihood assuming normally distributed errors and a constant CV for length at age (Cope and Punt, 2007). Models were fit to the average of two age reads, and a final model was selected based on the Bayesian Information Criterion (BIC; Schwartz, 1978).

Parameters of the von Bertalanffy growth model are usually estimated with the assumption that ages are known exactly (Quinn and Deriso, 1999). Cope and Punt (2007) examined the effect of admitting ageing (observation) error when fitting growth curves. They found consistent bias in parameter estimates based on single age reads and recommended treating ages as random variables. We fit random-effects models to the sex-specific and combined-sex data using both primary and secondary age reads, characterizing the distribution of true ages with a gamma distribution (Cope and Punt, 2007).

Weight and length data from 634 fish were fit to the equation

$$W = aL^b \qquad (2)$$

where W = weight (g), L = fork length (mm), and a and b are parameters estimated by linear regression of the log transformations of fork length and weight (Ricker, 1958). We report values of the parameter a after back-transformation into arithmetic space using the bias correction term exp(σ^2/2). To compare our data with existing studies, this relationship was also described in units of total length (cm) calculated using the length conversion in Echeverria and Lenarz (1984):

$$TL = -0.723 + 1.028FL \qquad (3)$$

where TL = total length (mm) and FL = fork length (mm).

NATURAL MORTALITY

Annual natural mortality rates were estimated using three different methods (Table 1). We used the mean gonadosomatic index (GSI) from 83 late vitellogenic female greenspotted rockfish to estimate natural mortality using Gunderson’s (1997) method. GSI was calculated as gonad weight divided by somatic weight. Estimates of M were also calculated using Beverton’s (1992) method based on maximum age. Total mortality (Z=M+F) was estimated using Hoenig’s geometric mean regression(Hoenig, 1983).

Table 1. Different methods of estimating mortality of greenspotted rockfish from central California. M is natural mortality, v is Beverton's (1992) proportionality factor for Pacific *Sebastes*, GSI is gonadosomatic index, Z is total mortality, and t_{max} is maximum age.

Method	**Description**
Gunderson (1997)	$M = 1.79(GSI)$
Beverton (1992)	$M = v/t_{max}$, $v = 2.5$ (1.5, 3.5)
Hoenig (1983)	$\log_e(Z) = 1.71 - 1.084 \log_e(t_{max})$

MATURITY AND REPRODUCTION

Female maturity stages were assigned based on the external morphology of ovaries using criteria adapted from Gunderson *et al.* (1980) and Echeverria (1987). Females with ovaries in late vitellogenesis, containing eyed larvae, or in recently spawned condition were considered sexually mature. Females with small, undeveloped ovaries were considered immature. Ovaries in early vitellogenesis were excluded from maturity analyses due to ambiguity in distinguishing females at this stage from immature females. Additionally, we are uncertain whether or not females at this stage always complete parturition or sometimes undergo a process by which oocytes are resorbed just prior to yolk accumulation (Eldridge *et al.*, 1991; Nichol and Pikitch, 1994).

LENGTH AT MATURITY

The relationship between length and the proportion of mature females was described for 602 females using a binomial generalized linear model (GLM) with a logit link function (McCullagh and Nelder, 1989)

$$\mu = \frac{\exp(\alpha + \beta L)}{1 + \exp(\alpha + \beta L)} \tag{4}$$

where μ is the proportion of mature females at fork length L *(mm)* and α and β are coefficients of the linear predictor. Exploratory data analyses and the Bayesian Information Criterion (BIC) were used for model selection (Burnham and Anderson, 2002).

FECUNDITY

We estimated absolute fecundity for 49 fish using a gravimetric subsampling method similar to that used by Eldridge and Jarvis (1995). Rockfish ovaries lack uniform consistency due to dense central stromal tissue (Nichol and Pikitch, 1994). Since excess tissue can bias expansions of absolute fecundity, both the ovarian membrane and a portion of the central stromal tissue were removed. Ovaries were blotted dry and weighed to the nearest 0.1 mg. Three subsamples, each containing 200-300 oocytes, were removed from arbitrary locations in each of the two ovaries and weighed to the nearest 0.01 mg. The oocytes of each subsample were teased apart from the connective tissue with dissecting needles and counted under 10-20X magnification. Absolute fecundity was estimated for each fish by averaging the densities (eggs/gram) of the three subsamples, multiplying by the weight of each ovary, and then adding the total number of oocytes from the two ovaries together. Models for absolute fecundity were considered with either fork length or somatic weight as a covariate. Model selection was based on visual inspection of the residuals and BIC.

SEASONAL MATURITY

The ovarian maturity cycle of greenspotted rockfish was described using 367 mature females collected between January 2002 and November 2004. Individuals were pooled by month of capture and combined across years. Seasonal reproduction was determined by the percentage of females with ovaries in late vitellogenesis, containing eyed larvae, or in spent or recovering stages.

LANDINGS

Annual estimates of commercial landings in California and mean lengths of commercially landed fish were obtained from the CALCOM database (2009). Mean lengths and commercial landings were summarized by International North Pacific Fisheries Commission (INPFC) area (Figure 1). Landings in Oregon and Washington were extracted from the Pacific Fisheries Information Network (PacFIN, 2006). Estimates of recreational landings were obtained from the Recreational Fisheries Information Network (RecFIN, 2006).

Figure 1. International North Pacific Fisheries Commission commercial fishing areas for the U.S. west coast. Source: PFMC, 1998.

RESULTS AND DISCUSSION

RESEARCH CATCH

A total of 798 female and 614 male greenspotted rockfish were collected by the Groundfish Ecology Cruise program for this study. Individuals were caught between depths of 80 and 320 m and ranged in fork length from 116 mm to 482 mm (which is larger than reported in the literature) (Tables 2 & 3).

Table 2. Comparison of the number of sets, sets with greenspotted rockfish and number of greenspotted rockfish collected by the Groundfish Ecology Cruise program between November 2001 and November 2004, separated by gear type and depth strata (m).

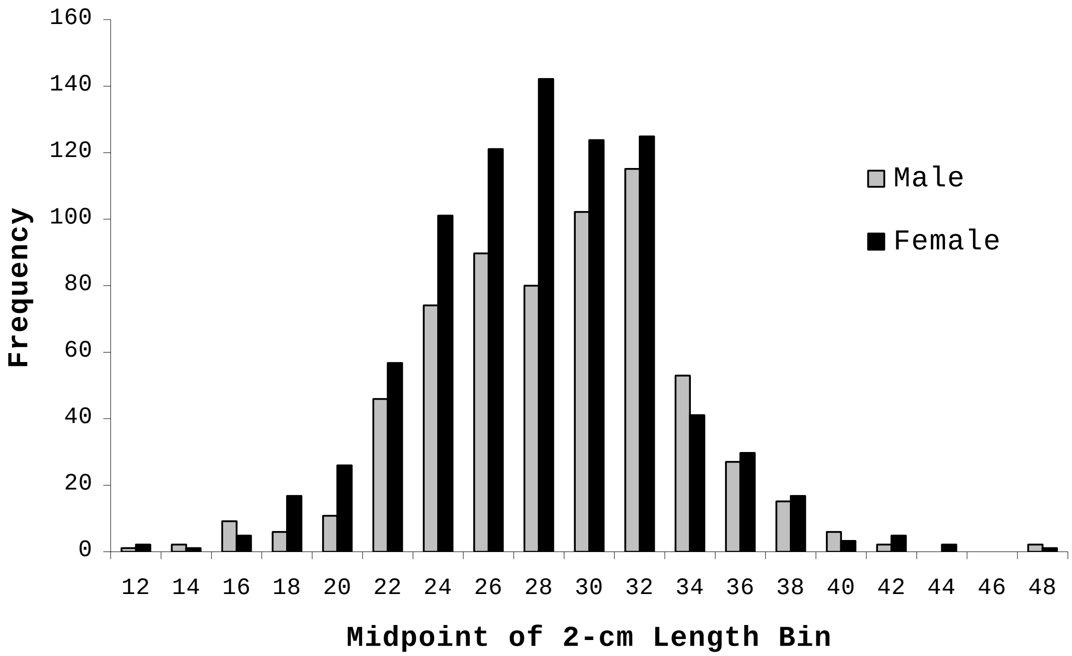
	Depth strata (m)							
	0-49	50-99	100-149	150-199	200-249	250-299	300-349	>350
Longline								
# of sets	28	44	20	2	1	0	2	35
# of sets w/ S. chloro	-	42	15	-	-	-	-	-
# S. chloro	-	878	325	-	-	-	-	-
Trawl								
# of sets	34	10	22	12	12	3	7	20
# of sets w/ S. chloro	-	1	13	7	5	3	1	-
# S. chloro	-	1	154	53	13	11	2	-

Table 3. Summary of the length composition by sex and gear type of greenspotted rockfish collected by the Groundfish Ecology Cruise program between November 2001 and November 2004. Individuals with undetermined sex not included (n = 21 and n = 3 for longline and trawl, respectively).

	Longline		Trawl	
	Males	Females	Males	Females
sample size	522	659	92	139
% of total	37.0%	46.7%	6.5%	9.8%
% by gear	44.2%	55.8%	39.8%	60.2%
min fork length (mm)	162	167	128	116
FL 10th percentile (mm)	235	233	166	175
mean fork length (mm)	291	286	250	255
median fork length (mm)	292	285	242	250
FL 90th percentile (mm)	343	335	332	349
max fork length (mm)	475	411	475	482
s.d. (mm)	42.3	41.1	67.8	66.5

Examination of the length frequency data shows similar size distributions by sex (Figure 2). We observed a sex ratio of 56% females which is similar to that reported by Pearson and Ralston (1990).

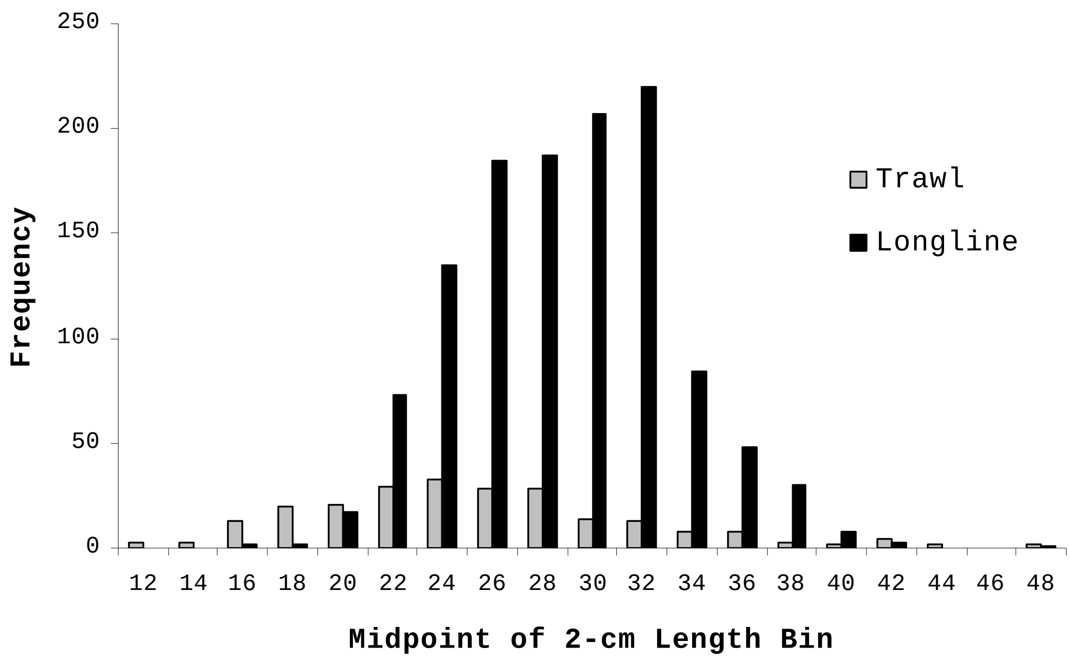
Figure 2. Size frequency distribution of greenspotted rockfish by sex, combined data from longline and trawl observations, collected by the Groundfish Ecology Cruise program between November 2001 and November 2004.



GEAR SELECTIVITY

A total of 234 fish were caught by trawl and 1,202 by longline. The bottom trawl accounted for a wider range of sizes but caught smaller fish on average (Figure 3). The variation in mean lengths among gear types may be attributed to differences in the size-specific selectivity and interactions between gear type and habitat preference. For example, mesh size in the liner of a trawl net and hook size on a longline are known to affect the minimum size of fish caught by each gear type (Ralston, 1982). In addition, the longline gear targeted areas of high relief and rocky substrate. The tendency to catch larger fish with longline gear could be the result of several factors: hook size may limit the capture of small fish, large fish might prefer large reef structure that is unsuitable for trawling, and the abundance of large fish in low-relief habitat may have been reduced by trawling. Trawling was restricted to terrain with low relief and relatively soft substrate. It is also possible that cobble, pebble, and mud provide more suitable habitat for smaller fish, making them more vulnerable to bottom trawling operations.

Figure 3. Size frequency distribution of greenspotted rockfish by gear type collected by the Groundfish Ecology Cruise program between November 2001 and November 2004.



AGEING CRITERIA

We found greenspotted rockfish to be a difficult species to age. Presumptive annuli were sometimes difficult to distinguish from false annuli or "checks" and occurred at irregular intervals.

In other otoliths, presumed annuli were easy to identify and appeared at regular patterns. A comparison of the first and second age estimates of the primary reader showed 30% agreement to the year and 62% agreement within one year. Agreement between the primary and secondary reader was 9% to the year and 36% within one year, which is an indication of the difficulty in ageing this species. While our results provide a best estimate of ages for this species, other methods such as tag-recapture, radiometrics, or bomb carbon (Kerr *et al.*, 2005; Andrews *et al.*, 2002) may provide improved age estimates to describe growth.

Previous studies have described the difficulty in determining age from the surface of whole otoliths for this species (Chen, 1971; Echeverria, 1987; Lea *et al.*, 1999). Our surface age estimates tended to be lower than ages estimated from burnt otolith halves. Similar results were reported for Pacific Ocean perch (*S. alutus*) (Stanley, 1986) and shortbelly rockfish (*S. jordani*) (Pearson *et al.*, 1991). This bias was more prevalent in older fish; agreement between ageing methods was 73% ± 1 year for fish younger than 12 years and only 9% ± 1 year for fish older than 18 years. Otoliths from older fish were often thick and opaque, making accurate surface age estimates impossible. The outer annuli were compressed near the edge but were more visible in burnt otolith halves. Estimates of age from the surface of otoliths have been shown to underestimate true age and significantly increase size-at-age (Chilton and Beamish, 1982; Leaman and Nagtegaal, 1987; Munk, 2001). Additionally, the break-and-burn method has been accepted as a valid technique for estimating rockfish ages (MacLellan, 1997).

Our greenspotted rockfish ages have not been formally validated. A marginal increment analysis proved inconclusive due to difficulty in identifying edge type. This problem is associated with the slow and irregular growth of older rockfish (Six and Horton, 1977). Ages have been validated for other rockfish species including yellowtail rockfish (*S. flavidus*) (Kimura *et al.*, 1979), shortbelly rockfish (Pearson *et al.*, 1991), widow rockfish (*S. entomelas*) (Pearson, 1996) and blue rockfish (*S. mystinus*) (Laidig and Pearson, 2003).

ADULT LIFE HISTORY

Age and Growth

We found little difference between fitted von Bertalanffy growth curves for males and females (Figure 4). The BIC value for a combined-sex model is approximately 10 less than the BIC for a gender-specific model (Table 4), indicating that the data support the simpler combined-sex model over the gender-specific model (Burnham and Anderson, 2002). Males have been reported as being slightly larger than females, but this species is not considered sexually dimorphic (Mason, 1998; Lenarz and Echeverria, 1991).

Figure 4. Von Bertalanffy growth curves for male and female greenspotted rockfish from central California. Fitted curves are based on average age estimates from two readers.

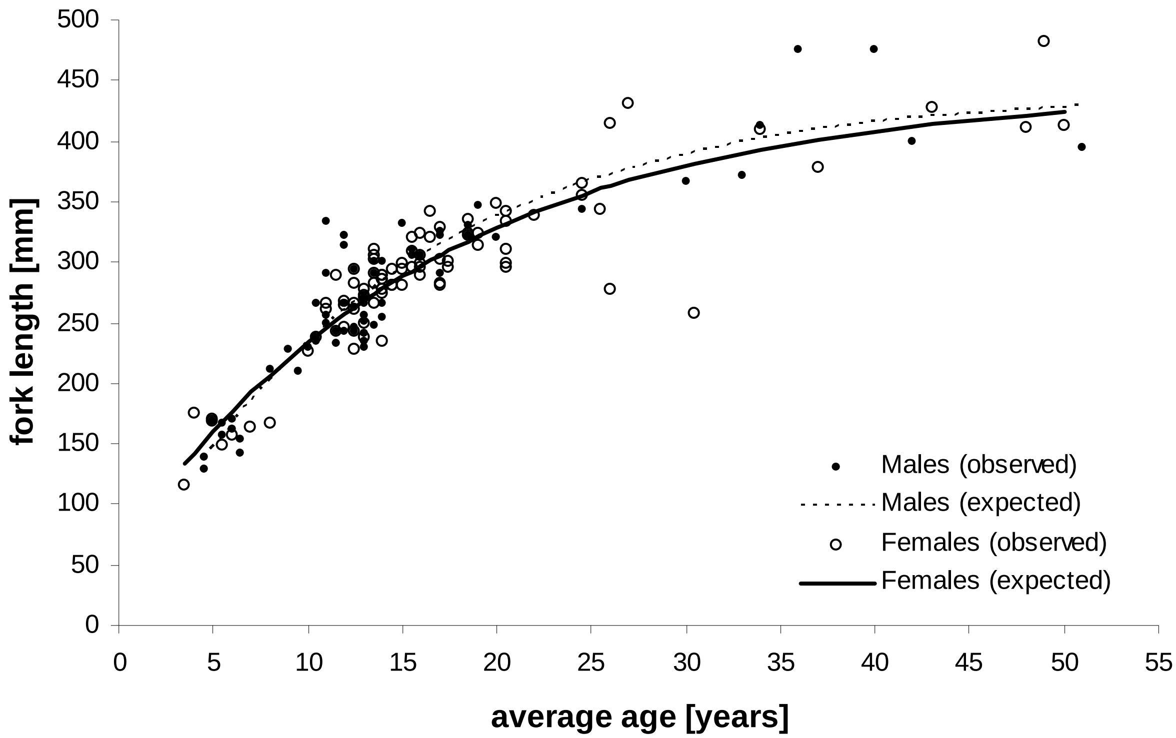


Table 4. Model comparison of gender-specific von Bertalanffy growth curves (with common CV) versus a combined-sex model.

Model	**n**	**parameters**	**BIC**
Combined-sexes	150	4	1422.2
Gender-specific	150	7	1432.2

The random effects model of Cope and Punt (2007) explicitly accounts for ageing error in the VB growth model. Using the greenspotted rockfish data (combined sexes), the random effects model predicts a larger L_∞, less negative t_0, and slightly smaller k relative to the standard nonlinear approach (Table 5).

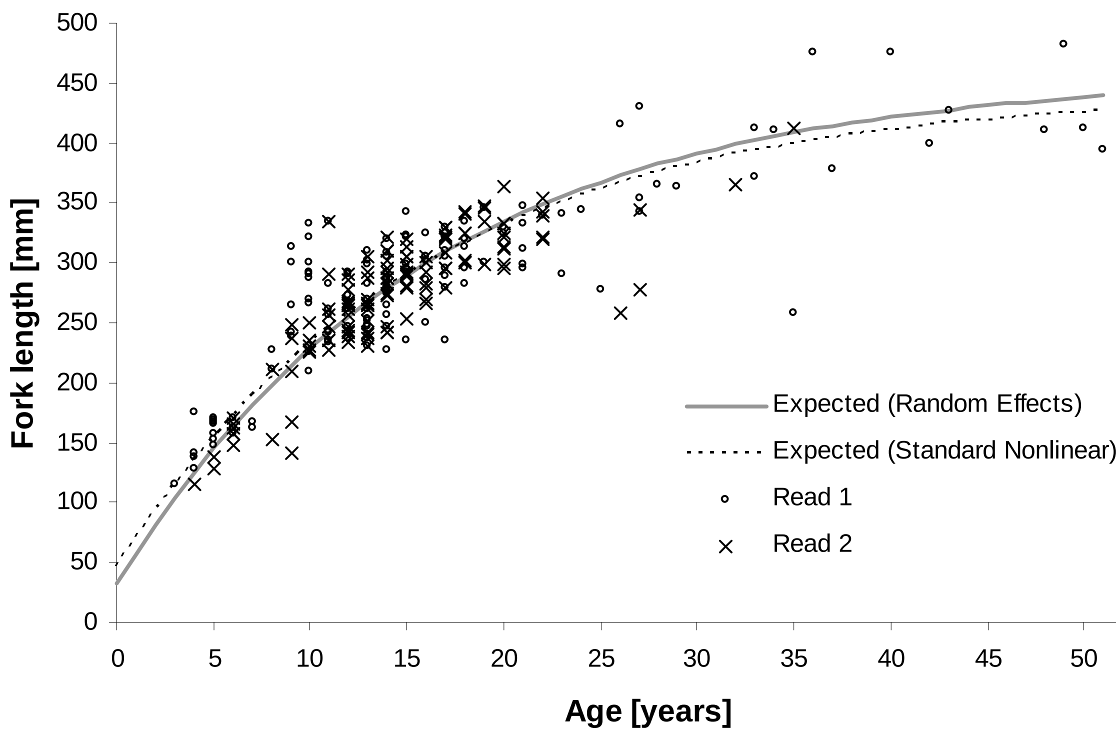
Table 5. Comparison of parameter estimates for von Bertalanffy growth models fit to greenspotted rockfish length and age data. The random effects models report CVs of length (CV_L) and age (CV_A) separately. Standard nonlinear models assume that CV_A=0. Ageing methods are break and burn (BB) and surface ageing.

Model Description	n	t_0	k	L_∞	CV_L	CV_A	method
Standard nonlinear VB model							
Combined sexes	150	-1.74	0.064	442 (FL)	0.094	0	BB
Males	62	-0.74	0.071	440 (FL)	0.098	0	BB
Females	88	-2.42	0.061	442 (FL)	0.088	0	BB
Random effects VB model							
Combined sexes	150	-1.16	0.062	457 (FL)	0.074	0.161	BB
Males	62	-1.01	0.058	485 (FL)	0.058	0.194	BB
Females	88	-1.44	0.064	442 (FL)	0.078	0.132	BB
Lea *et al.* (combined sexes)	39	-0.2	0.128	444 (TL)	*	0	surface

* Lea *et al.* fit a constant variance model (value not reported)

Given the similarity in growth among sexes and uncertainty in age estimates, we recommend the random effects VB model for combined sexes as an appropriate description of length at age for greenspotted rockfish (Figure 5). Our results predict a slightly larger asymptotic size and slower growth for *S. chlorostictus* relative to estimates in Lea *et al.* (1999). Lea *et al.* fit their length data to single age estimates using a least squares algorithm (Tomlinson and Abramson, 1961). Differences in reported parameter estimates between studies may therefore be attributable to changes in growth, bias in parameter estimation, or both.

Figure 5. Von Bertalanffy growth curves for greenspotted rockfish (sexes combined) from central California. The random effects model (solid line) accounts for ageing imprecision. The standard nonlinear model (dashed line) is fit to average ages assuming they are known exactly.



The previously estimated maximum age of 33 years was based on surface ages (Echeverria, 1987). The maximum age estimated in this study, using break and burn ages, is 51 years. Lea *et al.* (1999) reported a k value of 0.128 yr^{-1}. We estimate k to be 0.062 yr^{-1}, suggesting that growth is considerably slower. Wilson (1985) similarly found the break-and-burn technique strongly altered von Bertalanffy growth parameter estimates of splitnose rockfish (*S. diploproa*) and canary rockfish (*S. pinniger*), which had been based on surface ages.

Length-weight Relationship

The length-weight relationship (weight in grams, fork length in millimeters) for greenspotted rockfish from central California was estimated as

$$W = 0.00001032L^{3.108} \tag{6}$$

with a RMSE of 0.198 around the linear regression of $\log_e$-transformed variables and an R^2 of 0.86. In order to compare our results with those of Love *et al.* (1990), we converted our fork length measurements to total length (cm) using the conversion in Echeverria and Lenarz (1984). Our result

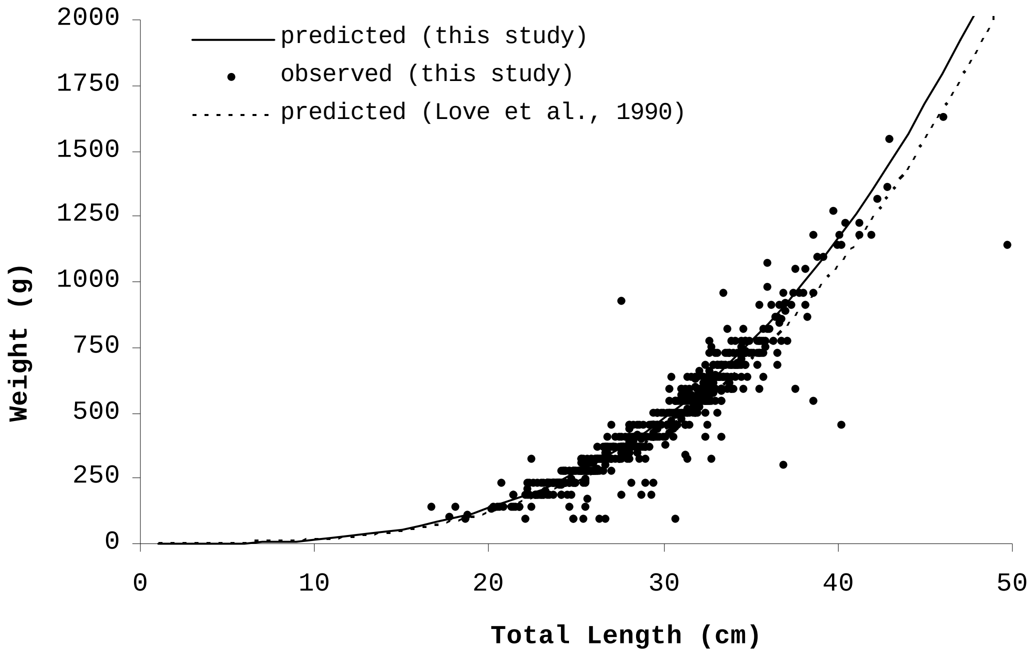
$$W = 0.01258TL^{3.1002} \tag{7}$$

is very similar to that of Love *et al.* (1990)

$$W = 0.00905TL^{3.1632} \tag{8}$$

for southern California (Figure 6). Both studies found this relationship to be indistinguishable between sexes. Lea *et al.* (1999) reported separate length-weight relationships for males and females; however, the sample size for their estimate was only 34 fish.

Figure 6. Comparison of the length-weight relationships of greenspotted rockfish (sexes combined N=634) from central California (this study) and southern California (Love *et al.*, 1990, N=354). Note: for comparison, we converted our lengths to total length (cm) using the conversion from Echeverria and Lenarz (1984).



Natural Mortality

We estimated total mortality (*Z*) to be 0.078 yr^{-1} using Hoenig's (1983) method and our maximum observed age of 51 years (Table 6). Our estimate of natural mortality using Gunderson's (1997) method was 0.057. This mortality rate suggests that <1% of individuals in an unfished equilibrium population would live beyond age 80. Beverton (1992) reported the range of natural mortality for Pacific species of *Sebastes* to be 0.02 to 0.05. Applying Beverton's method to our observed maximum age (t_{max} = 51, v=2.5) suggests that natural mortality for greenspotted rockfish is approximately 0.049.

There is a great deal of uncertainty in estimating natural mortality for this species. Based on this set of mortality estimates, M is likely to be between 0.05 and 0.08.

Table 6. Mortality estimates for greenspotted rockfish from central California. Z is total mortality, M is natural mortality, and t_{max} is maximum age.

Method	**Mortality estimate**
Gunderson (1997)	M = 0.057 (GSI = 0.0317)
Beverton (1992)	M = 0.049 (0.029,0.069)
Hoenig (1983)	Z = 0.078 (observed t_{max} = 51)

MATURITY AND REPRODUCTION

Length at Maturity

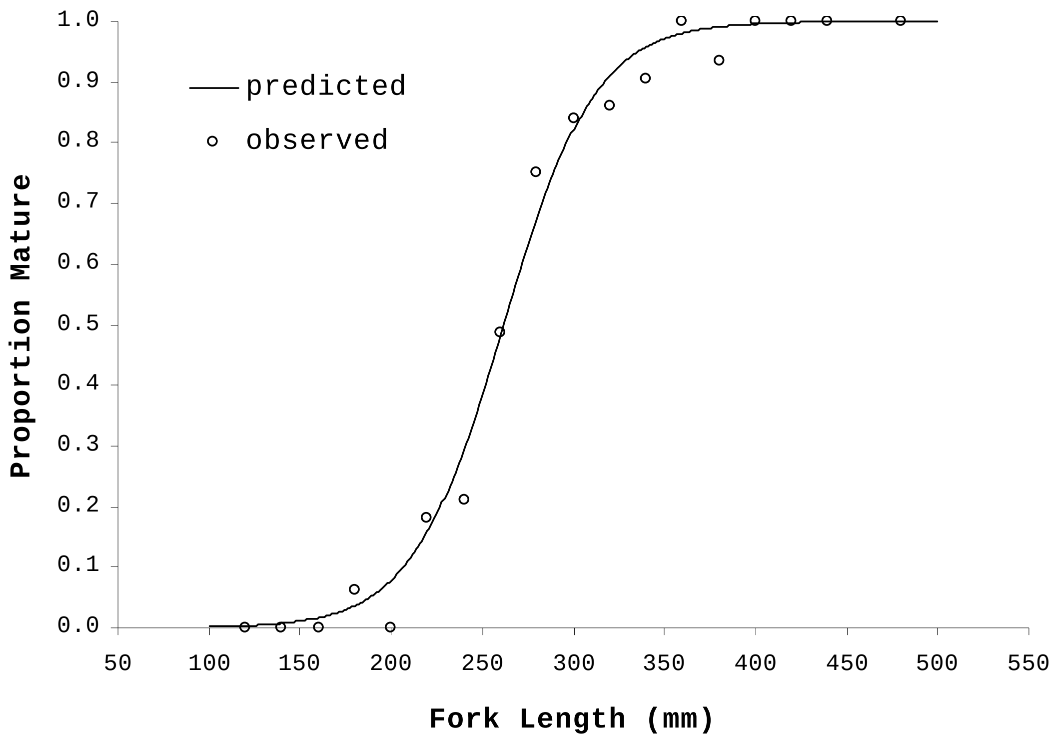
Our estimates of fork length at 50% maturity for female greenspotted rockfish varied slightly according to the type of sampling gear used (longline or trawl). There is evidence (Figure 3) of differences in size selectivity among sampling gears, but the sample size for the longline gear was more than 4 times that of the trawl. Since BIC values for the binomial GLM suggest only weak evidence (BIC differences <2) for including sampling gear in the model, we feel that the model with no gear effect adequately describes length at maturity (Equation 9, Table 7, Figure 7).

$$\mu = \frac{\exp\left(-10.449 + 0.0399L\right)}{1 + \exp\left(-10.449 + 0.0399L\right)} \tag{9}$$

Table 7. Predicted fork length (FL) and standard error (S.E.) at percent maturity of greenspotted rockfish from central California.

% Mature	Fork length (mm)	S.E. (mm)
5%	188	7.4
25%	234	4
50%	262	2.8
75%	289	3.1
95%	335	6.1

Figure 7. Predicted proportion of mature female greenspotted rockfish at length (solid line) and observed proportion mature (by 20-mm length bin circles).



Our estimate of length at 50% maturity (262 mm FL) is consistent with previous reports for female greenspotted rockfish from California. Echeverria (1987) reported fork length at 50% maturity as 273 mm in northern and central California. In southern California, fork length at 50% maturity is reported to be 215 mm (Love *et al.*, 1990).

Fecundity

Absolute fecundity ranged from 14,107 eggs for a female of 242 mm fork length to 414,222 eggs for a female of 378 mm. We found that absolute fecundity is best predicted as a linear function of somatic weight, which explains 85% of the variability in these data (Table 8; Figures 8 and 9). However, our study did not include females greater than 378 mm fork length. The absence of larger individuals in this study may account for the superior fit of the linear model, due to truncation of the natural size range.

Table 8. Parameter estimates and model selection criteria for models of absolute fecundity (y; 1000s of eggs) at length/weight of greenspotted rockfish from central California. *It is inappropriate to compare linear models for y and log(y) using R^2. †Models in which somatic weight is a covariate were fitted to a subset of the data used in models based on fork length. Secondary analysis of this subset using fork length as a covariate confirmed that somatic weight is the best predictor of absolute fecundity.

Covariate	**model ($\varepsilon \sim N(0,s^2)$)**	**parameter estimates a**	**b**	**s**	**R^2**	**BIC**
Fork length	$y = a + bL + \varepsilon$	-549.0	2.423	33.29	0.88	486.5
	$y = aL^b e^{\varepsilon}$	1.457×10^{-11}	5.256	0.2823	n/a*	512.6
Somatic weight	$y = a + bW + \varepsilon$	-40.86	0.4002	36.11	0.85†	480.0†
	$y = aW^b e^{\varepsilon}$	9.312×10^{-3}	1.5612	0.3045	n/a*	497.0

BIC scores for power function models were calculated using nonlinear predictors for the untransformed response variable, assuming lognormally distributed errors. This allows for direct comparison with linear models that assume Gaussian errors (Burnham and Anderson, 2002).

Figure 8. Linear and power function models of absolute fecundity vs. fork length of female greenspotted rockfish from central California.

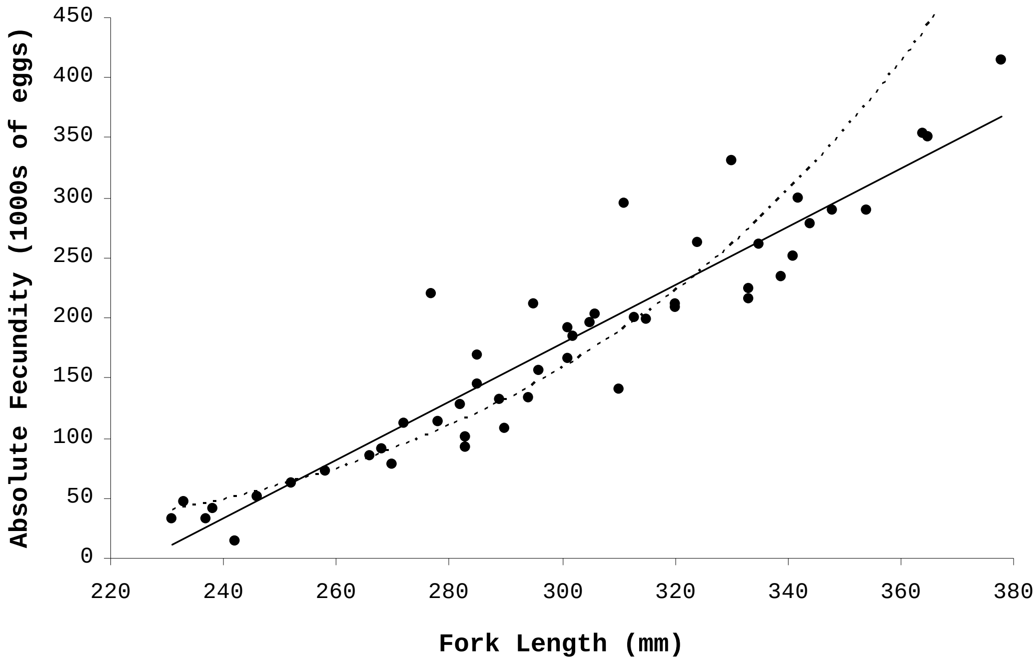
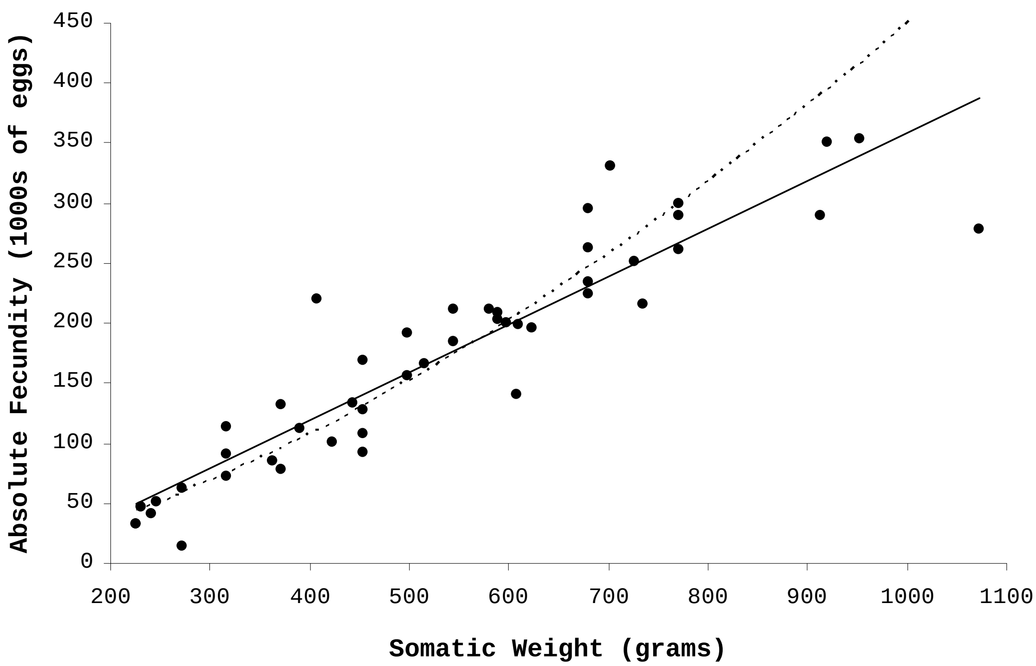


Figure 9. Linear and power function models of absolute fecundity vs. somatic weight of female greenspotted rockfish from central California.



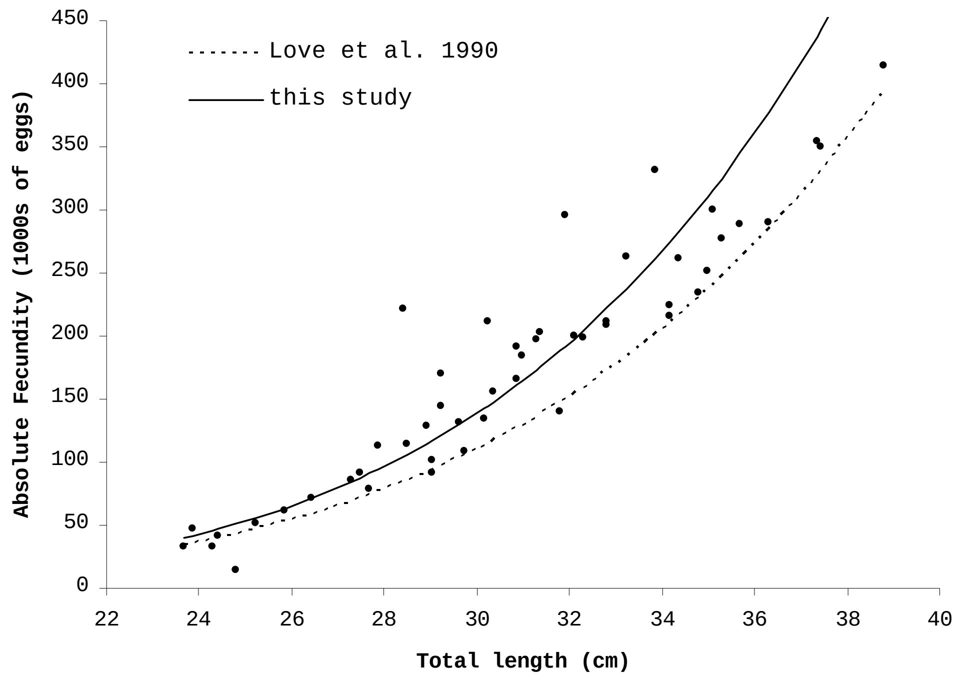
The reported value for the proportionality coefficient, a, is the exponentiated intercept term from the linear model for log(y), bias-corrected by the multiplicative factor exp($0.5s^2$), where s^2 is the estimated mean squared error of the model.

A comparison of the absolute fecundity-length models from this study and Love *et al.* (1990) suggests fish from central California are more fecund over the range of observed lengths than those from southern California (Figure 10). Love *et al.* described the fecundity of greenspotted rockfish from southern California using the equation:

$$F = 5.0 \times 10^{-6} TL^{4.9712} \quad (10)$$

where F is absolute fecundity (1000s of eggs) and TL is total length in centimeters. To obtain this estimate they used 19 females to a maximum length of 390 mm. These results suggest that this species has moderate to high fecundity relative to other species of rockfish (Love *et al.*, 1990).

Figure 10. Comparison of the relationship between absolute fecundity (1000s of eggs) and total length (cm) of female greenspotted rockfish from central California N=49 (current study, power function) and southern California N=19 (Love *et al.*, 1990). Note: for comparison purposes, we converted our lengths to total lengths (cm) using the conversion from Echeverria and Lenarz (1984).



Estimates of linear models for the mean number of eggs per gram somatic weight as functions of length and weight are presented in Table 9. For *S. chlorostictus*, the mean number of eggs per gram increases as a function of size (i.e. larger females contribute more to egg production, on a per-gram basis, than smaller females). Figures 11 and 12 illustrate the fit of these models to fork length and somatic weight, respectively.

Table 9. Parameter estimates and model selection criteria (R^2 and BIC) for models of mean eggs per gram (z) of somatic weight as a function of fork length and total weight for female greenspotted rockfish from central California.

model	**parameter estimates**				
(ε~N(0,s^2))	**a**	**b**	**s**	**R^2**	**BIC**
$z = a + bL + \varepsilon$	-163.0	1.570	70.46	0.40	534.6
$z = a + bW + \varepsilon$	185.3	0.2248	77.3	0.28	551.6

Figure 11. Linear model of mean eggs per gram of somatic weight vs. fork length for female greenspotted rockfish from central California.

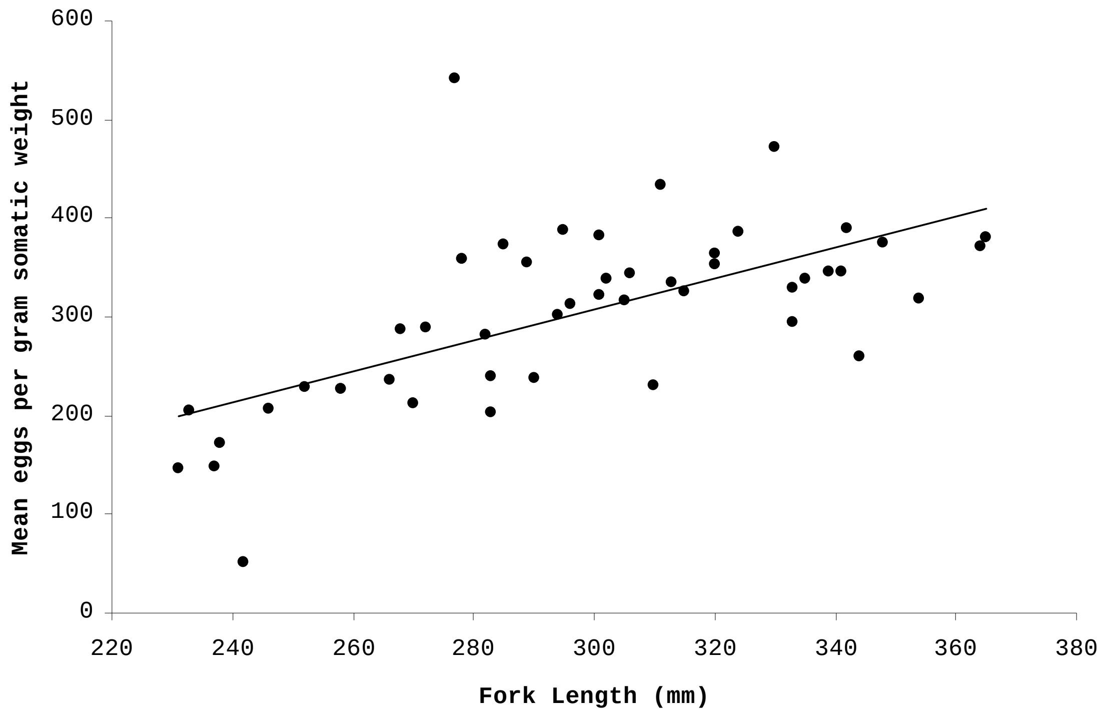
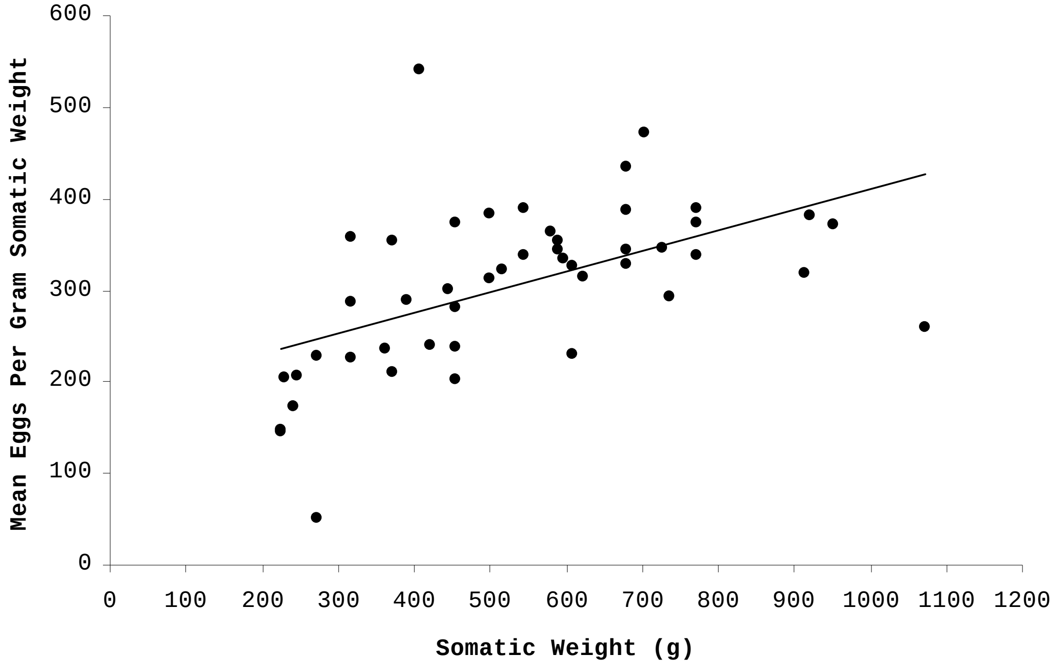


Figure 12. Linear model of mean eggs per gram of somatic weight vs. somatic weight for female greenspotted rockfish from central California.



Seasonal Maturity

We observed ovaries containing eyed larvae from June through August. Although data for April, May, and December were sparse, the presence of a small percentage of spent/recovering females in March and high percentage in June indicates that peak parturition probably occurs between April and June (Figure 13). The timing of seasonal maturity from this study is compared with results from two other studies in Table 10. Spawning females were found from February through July in southern California, peaking in April (Love *et al.*, 1990). In northern/central California, parturition was observed from April through September peaking in May (Echeverria, 1987). Barss (1989) observed parturition in May in a very small number of females from Oregon. It is possible that a larger sample size would reveal the same geographic trend observed in California.

Figure 13. Seasonal maturity of female greenspotted rockfish from central California illustrated by the percent frequency of females in late vitellogenesis, eyed larvae, or spent/recovering stages. Sample sizes are shown above the bars. Note: data for April, May and December were sparse.

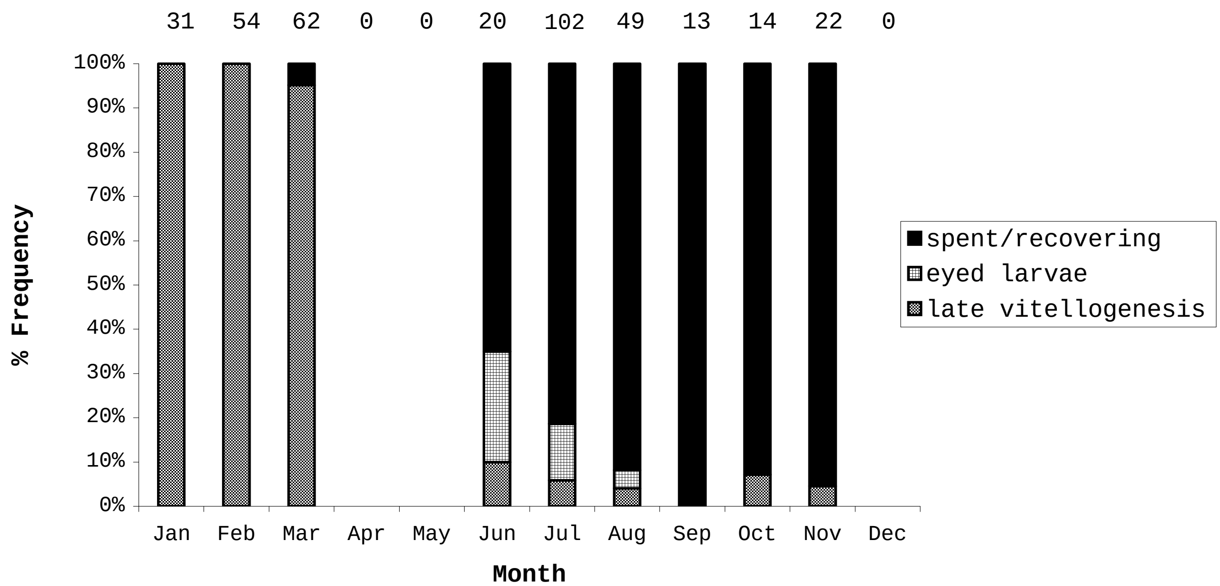


Table 10. Comparison of the reproductive season of female greenspotted rockfish from northern California (Echeverria, 1987) central California (this study), and southern California (Love *et al.*, 1990).

Source	**Area**	**Spawning months**	**Peak parturition**	**Multiple broods**
Echeverria	north/central CA	April-September	May	no
this study	central CA	March-August	April-June	no
Love *et al.*	southern CA	February-July	April	yes

Multiple broods per season were noted for southern California females (Love *et al.*, 1990). However, there was no evidence of multiple broods in individuals from central or northern California

(Echeverria, 1987). Love *et al.* (1990) noted that coastal upwelling occurs earlier in southern California, leading to increased food availability and earlier egg development in southern populations. It is possible that environmental factors leading to an earlier reproductive season in southern California are also responsible for multiple broods in that region. Further research is needed to determine whether northern populations occasionally attempt a second brood and possibly resorb their eggs as a result of environmental changes late in the reproductive season.

Habitat

Greenspotted rockfish are found over a variety of depths and substrates. Yoklavich *et al.* (2000) used manned submersibles to quantify deepwater rock habitat and fishes in Soquel Canyon in northern Monterey Bay. They counted 426 greenspotted rockfish at densities of 0.2 to 5.6 fish per 100 m^2. It was the fourth most abundant species, comprising 6.9% of the total number observed, and was also among the 4 most abundant species in 4 of the 6 deep-water assemblages identified in the study. Small individuals were common over mostly flat relief made up of combinations of large-grain pebbles, cobble and mud. Large individuals were common over rocky outcrops and locally associated with ridges, caves and overhangs. The large individuals were particularly abundant in sites having little or no fishing pressure. A similar survey was performed at the Big Creek Marine Ecological Reserve in central California (Yoklavich *et al.*, 2002). In this area greenspotted rockfish occurred over similar deep, sloping habitats of mostly bedrock and cobble. They were almost absent at depths less than 100m and common (1.5%-3.1% of total) at depths greater than 100m.

In southern California, Love *et al.* (2000) used a research submersible to survey fish around seven oil platforms in the Santa Barbara Channel area. The greenspotted rockfish was among the most common species, and 383 fish accounted for 8.0% of the total observed. This species was not present on the two shallower platforms (49-72 meters), but their density increased with depth from 3.54 to 25.72 fish per 100 m^2 on the other platforms (97-224 m). Large individuals were almost always seen on the bottom, very close to the platform. Small individuals were often seen away from the platform, and juveniles were usually hidden in the shell mounds at the structure’s base. Love *et al.* (1990) suggested that smaller fish occured away from the platform to avoid predation by the larger fish in the structure. A few juveniles were found midwater on the platform, but all ages, from young-of-the-year to adults, were present at the base of the platform.

Movement

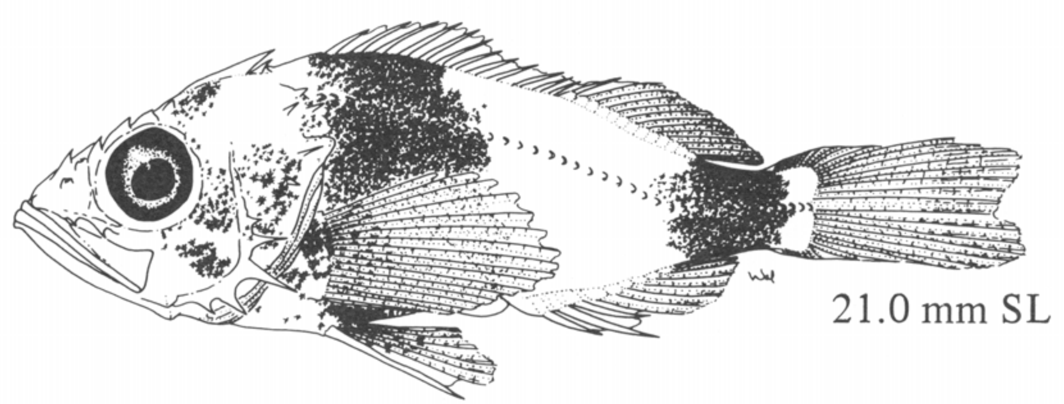
Available evidence suggests that the greenspotted rockfish is a sedentary species showing almost no vertical movement and limited horizontal movement. Starr *et al.* (2002) placed acoustic transmitters in 6 greenspotted rockfish and tracked their movement with an array of 6 receivers moored to the flank of the Soquel Canyon in northern Monterey Bay. The fish exhibited two patterns of small horizontal movements. In one pattern the fish made a few short trips to the mouth of the canyon but spent 94% of the time within an area of 0.58 km^2. The other pattern consisted of more frequent larger movements, sometimes covering the entire 1.6 km^2 study area. These movements are believed to be foraging trips along the canyon edge; 90% of them lasted less than 5 hours. These individuals exhibited almost no vertical movement. They remained within 3m of the bottom 99% of the time except for a few instances when a fish swam down 20-40 m and returned within 2 hours. One fish moved 90 m vertically in the 18 hours it was recorded before it left the study area for 67 days.

EARLY LIFE HISTORY

There is little information available on the early life stages of the greenspotted rockfish. Species identification is a major challenge when studying pelagic larvae and juveniles. For some species, meristic frequencies are the only practical way to identify juveniles (Laidig and Adams, 1991). However members of the subgenus *Sebastomus*, which includes greenspotted rockfish, share morphological characters such as number of fin rays and head spines and pigmentation patterns, which make them difficult to identify (Chen, 1971; Kendall, 1991). Recently, DNA sequence analyses and morphological characters were used to successfully differentiate other members of the *Sebastomus* group from greenspotted rockfish (Rocha-Olivares *et al.*, 2000). The geographic distribution and reproductive season of adults must also be considered when identifying pelagic juveniles (Kendall, 1991).

Rockfish larvae are born with well-developed eyes, jaws, fins and digestive tract and metamorphose into pelagic juveniles (Wourms, 1991). As they grow, they begin feeding on copepod nauplii and invertebrate eggs, progressing to adult copepods, euphausiids, and other pelagic invertebrates (Moser and Boehlert, 1991). The pigment pattern of a pelagic juvenile at 21 mm standard length shows less than three vertical pigment bands with a patch of pigment on the caudal peduncle (Figure 14). The duration of the pelagic stage is unknown and there is no information available on recruitment size, depth or temporal pattern for this species.

Figure 14. Pigmentation patterns of a pelagic juvenile greenspotted rockfish from Laroche (unpublished data) in Matarese *et al.*, 1989.



FISHERIES

Commercial

Commercial landings of *S. chlorostictus* in California totaled about 2,800 mt between 1980 and 2005 (CALCOM, 2009). Oregon contributed an estimated 10.7 mt, and no landings were reported in Washington (PacFIN, 2006). Landings were greatest in the Monterey INPFC area from 1987 to 1997, comprising about 73% of all commercially landed greenspotted rockfish (Figure 15). Prior to 1987, landings were highest in the Conception INPFC area. Eureka landings were relatively minor, peaking at about 25 mt in 1989. Estimates of Eureka landings in 1981 and 1991 are imprecise, and therefore we excluded them from Figure 15. Phillips (1939) found that greenspotted rockfish constituted about 0.7% of the commercial catch in fish markets in Monterey during the late 1930’s. Statewide landings have gradually declined from a peak of about 240 mt in 1991 to less than one mt in 2007 (Figure 15).

Reduced commercial landings from the late 1990s through the present are due in part to management restrictions on shelf rockfish (PFMC, 2004). Between 1978 and 1988, Pearson and Ralston (1990) noted a small decrease in mean length (less than 2%)of greenspotted rockfish from northern and central California. Examination of more recent data indicates this was the beginning of a long-term pattern of declining length (Figure 16).

Figure 15. Annual commercial landings (metric tons) of greenspotted rockfish in California between 1969 and 2007 by INPFC area. Source: CALCOM, 2009.

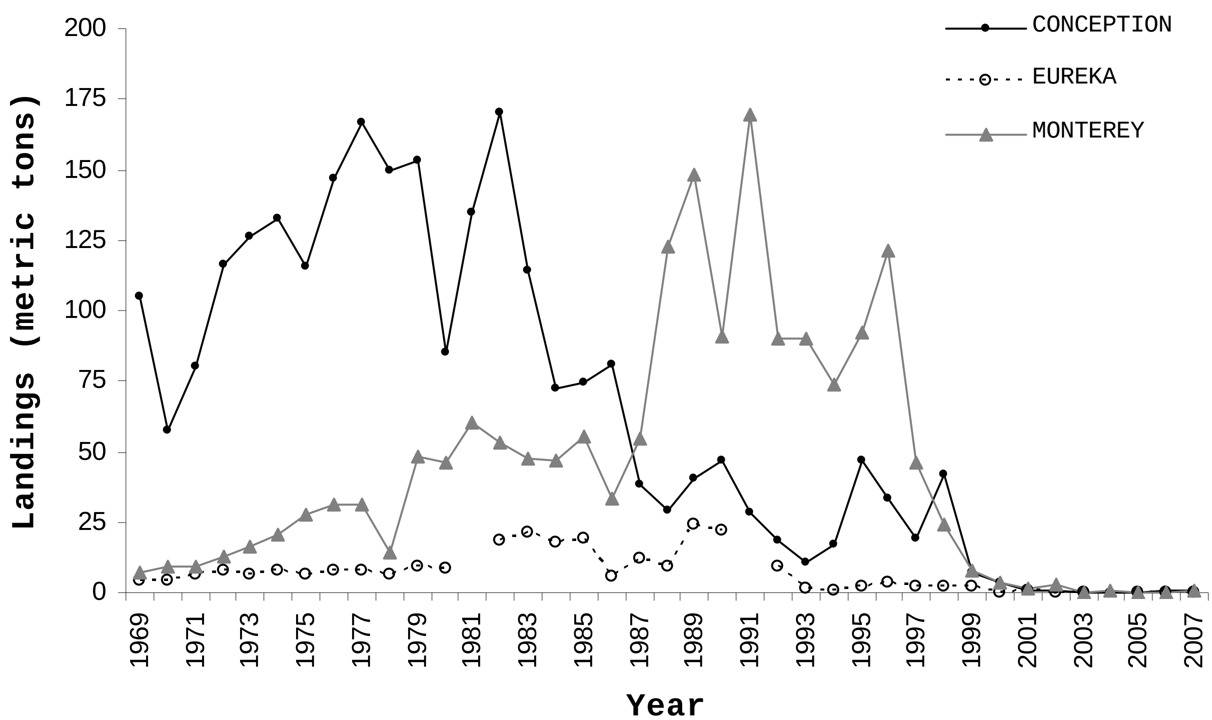
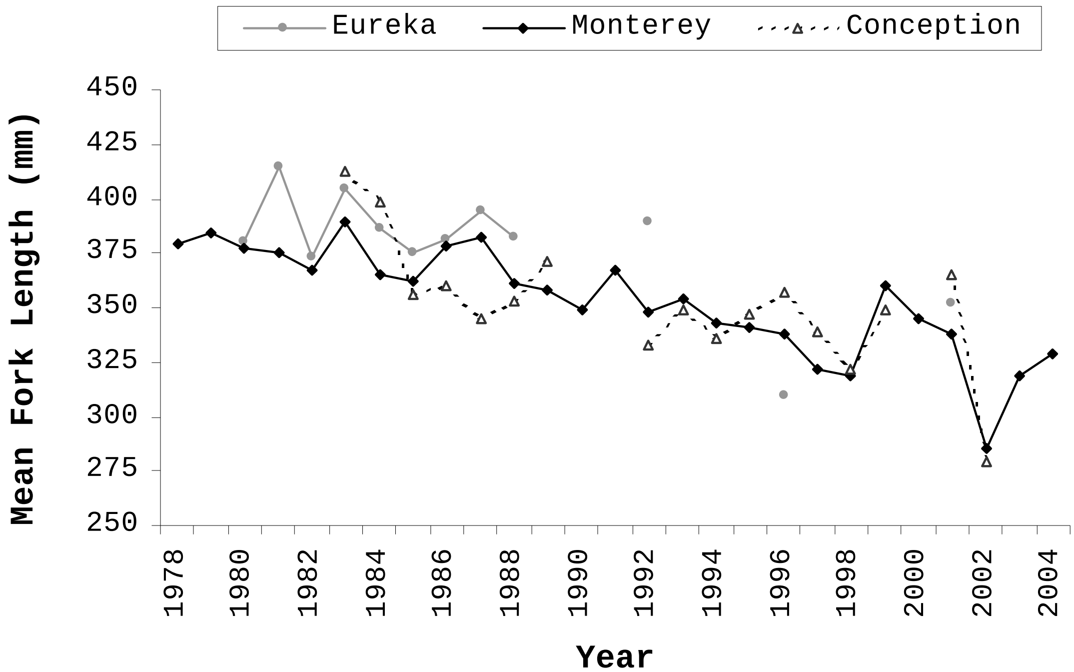


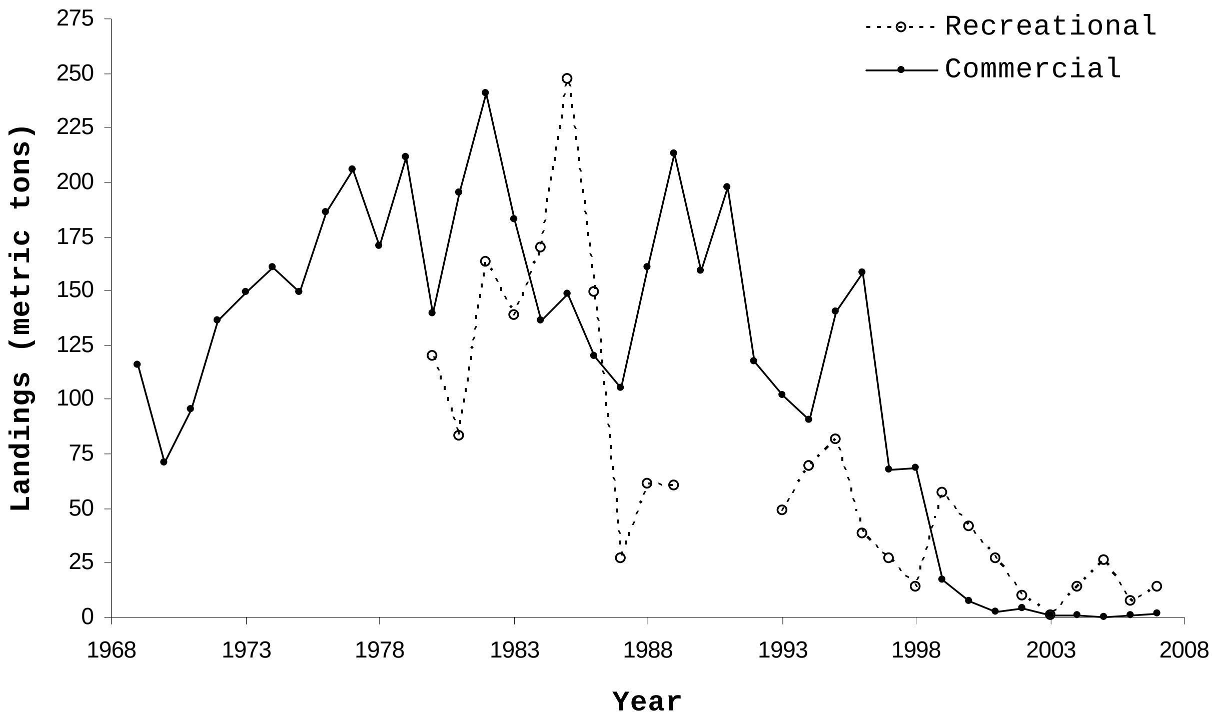
Figure 16. Annual mean fork lengths of greenspotted rockfish from California market samples by INPFC area. Only years and INPFC areas with at least 15 measured fish were used. Source: CALCOM, 2006.



Recreational

Greenspotted rockfish constitute an important component of the recreational fishery in California. Recreational landings totaled 1,730 mt from 1980 to 2005 with 67.5% of the landings occurring south of Point Conception. Recreational landings exceeded commercial landings from 1984 to 1986 and 1999 to 2007, more than doubling them in some years (Figure 17).

Figure 17. Comparison of estimated annual commercial (1969-2007) and recreational (1980-2007) landings of greenspotted rockfish in California. Note: no data available for recreational landings 1990-1992. Sources: CALCOM (2009) and RecFIN (2009).



Between 1981 and 1986 estimated annual landings from commercial passenger fishing vessels (CPFV) averaged 44.0 mt, which was about 92% of the total annual recreational catch for this species (Karpov *et al.*, 1995). Love *et al.* (1998) reported a decrease in mean length of CPFV-landed greenspotted rockfish in southern California from 308 mm from 1980-1989 to 252 mm from 1993-1996. They also reported a reduction in catch-per-unit-effort (CPUE) on CPFVs over the same period. In Monterey Bay CPFV landings, greenspotted rockfish are the eighth most abundant species and represent 3% of the total from 1959-1994. Mean length increased 1.8% from 1960 to 1977 and declined 4.1% from 1960 through 1994. This could reflect the shift to deeper water by CPFVs in the 1970s and the close proximity of deepwater fishing sites in the Monterey Bay (Mason 1998). Decreased mean lengths, reduced landings and CPUE have indicated population decline in other species of rockfish from the U.S. West coast (Ralston, 1998). Variable recruitment, growth, and changes in fishing areas or methods may also be contributing to these declines.

CONCLUSION

This study found the greenspotted rockfish to be a slow-growing species that lives much longer than previously reported. While not commercially targeted, both commercial and recreational landings have applied continual pressure on this stock. Decreases in landings and CPUE as well as declining length are consistent with patterns of increased fishing mortality and the removal of large, old fish. The moderately high fecundity of greenspotted rockfish may act as a buffer against overexploitation but could be offset by highly variable recruitment. Additional research is needed to determine if this species has recently had poor recruitment or if young fish are unavailable to our sampling gear. The characteristics of juvenile life history such as size, depth, and time of recruitment warrant further investigation. Also, further studies, such as tag-and-recapture, radiometric ageing, or otolith bomb carbon (Kalish, 1995), may be necessary to validate age in this species. The objective of this study was to consolidate the available information on greenspotted rockfish, however more data would assist future stock assessment efforts and effective management of this species.

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