

# Growth, Size at Sexual Maturity, and Egg-Per-Recruit Analysis of the Abalone *Haliotis fulgens* in Baja California

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**Abstract.** The growth rate and size at sexual maturity of *Haliotis fulgens* were measured at Bahía Tortugas, Baja California Sur. The parameters of the fitted von Bertalanffy growth equation were:  $K = 0.38$ ,  $L_{\infty} = 183$  mm. There was no significant difference in growth rate between the sexes. The length at which 50% of a sample reached sexual maturity was 105 mm. These data, with other published data on *H. fulgens*, were used to do yield-per-recruit and egg-per-recruit analyses. Maximum yields occurred at ages 4–7 years, according to the natural mortality rate chosen. At the current fishery size limit (145 mm), egg production levels are 6–17% and are considered to be dangerously low and inadequate to maintain recruitment.

## INTRODUCTION

Numerous abalone fisheries around the world have collapsed with increasing fishing pressure, and in some cases this has been attributed to the removal of too much of the parent stock (recruitment overfishing) (reviewed by BREEN, in press). In consequence, simple egg-per-recruit models have been devised to show the number of eggs produced under different fishing intensities and with different size limits (SLUCZANOWSKI, 1984, 1986; BREEN, in press; TEGNER *et al.*, 1989). Such models can be used in a population at equilibrium to specify size limits to maintain a

given level of egg production or, alternatively, to examine a fishery in retrospect to see what egg production level maintained the stock or, in the case of a collapsed fishery, led to such a collapse. In the absence of knowledge of the relation between breeding stock size and recruitment, egg-per-recruit analyses of many stocks, including collapsed ones, can give clues as to appropriate egg production levels.

The abalone *Haliotis fulgens* Philippi is taken commercially in Baja California where it comprises up to 85% of the abalone catch (TURRUBIATES *et al.*, 1987), but little is known of the parameters required to apply an egg-per-recruit model to the fishery. In this paper we describe an

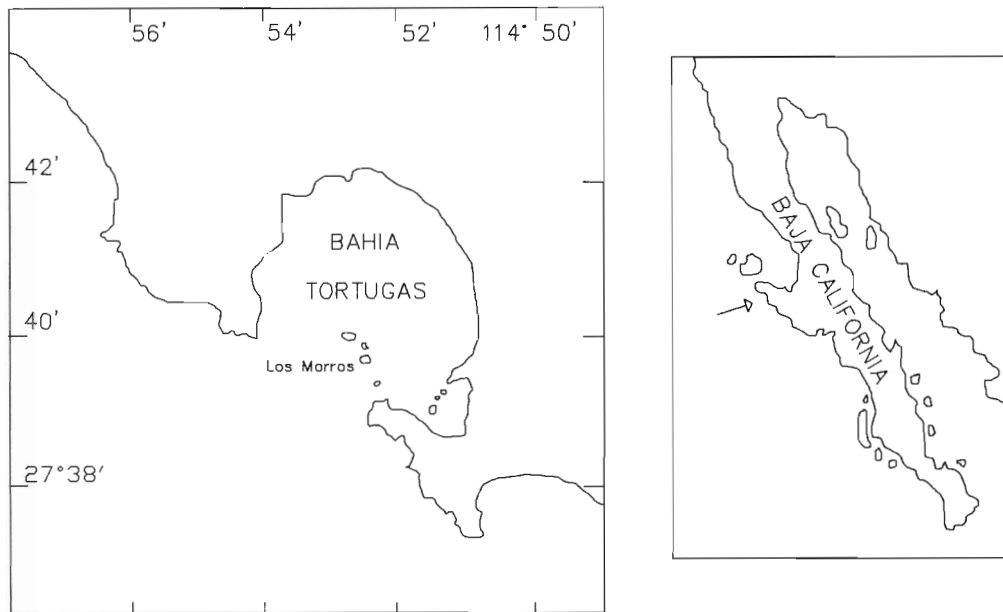


Figure 1

Map of Bahía Tortugas showing Los Morros Islands, and (on right) their location in Baja California.

experiment to measure the growth rate of *H. fulgens* at Bahía Tortugas, Baja California (Figure 1). We also attempted to measure the natural mortality rate,  $M$ , but the experiment failed, and we discuss it only to illustrate the problems of dealing with a cryptic species. We determined size at sexual maturity, and used these results and other published information to do yield and egg-per-recruit analyses for *H. fulgens*. We then apply the results to management of the fishery and suggest an appropriate size limit.

#### MATERIALS AND METHODS

By agreement with the local fishermen's cooperative, a study site on the inner shore of Los Morros Island was selected and closed to fishing. The shore here is composed of large boulders and blocks up to 2 m diameter close to shore and a deeply eroded reef of 1–2 m relief. The giant kelp, *Macrocystis pyrifera*, forms a dense forest to about 2 m depth and, beyond the forest, the seagrass *Phyllospadix torreyi*, coralline algae, and other red and brown algae dominate exposed rock surfaces to about 5 m depth where rock is buried by sand. *Haliotis fulgens* mainly occurred at the edge of the *Macrocystis* forest from 2 to 4 m depth.

Individuals of *Haliotis fulgens* between 70 and 140 mm shell length (SL) were measured and marked with plastic numbered tags riveted to the shell through the proximal pore-hole (PRINCE, 1991) in August 1987, November 1987, and May 1988, and placed within an area marked out with chain. In August 1988, one year after the initial tagging, the area was thoroughly searched for 35 hr diving time and marked individuals recaptured. Subsequent further searching for 9 hr increased the number of recaptures.

The abalone taken in August 1987 were sexed, by visual inspection of the gonad, prior to marking, and the data obtained were used to determine size at sexual maturity. In this species the gametes are mature from June to September and the sexes are readily distinguishable visually by color (GUZMÁN DEL PRÓO, in press); visual inspection is considered to give a reliable indication of the presence of gametes, but not the onset of spawning.

Growth rates were estimated by fitting von Bertalanffy growth curves to growth increment data by the method of FABENS (1965). For this calculation we excluded growth data where the period at liberty was less than a year, in order to avoid bias from differential seasonal growth.

A simple model was developed to examine the biomass yield (BEVERTON & HOLT, 1957) and production of eggs (SLUCZANOWSKI, 1984) during the life of a cohort. We used the following equations as inputs. In the absence of published fecundity estimates for *Haliotis fulgens* in Baja California we used: a mean fecundity ( $F$ ) of 2.67 million eggs at 172 mm length, derived from TUTSCHULTE (1976) and TUTSCHULTE & CONNELL (1988) for *H. fulgens* at Santa Catalina; a length-weight relationship of  $W = 2.72 \times 10^{-5} L^{4.3}$  (after GUZMÁN DEL PRÓO, in press); and a mean length at sexual maturity of 105 mm (this paper). We assumed fecundity was linear with total weight ( $W$ ) and derived the equation:

$$F = 0.0026W - 0.61.$$

In these equations  $W$  is expressed in g,  $L$  in mm, and  $F$  in millions of eggs.

Parameters of the von Bertalanffy growth equation are those given for females in this paper.

Table 1

Values of the parameters of the von Bertalanffy growth equation for *Haliotis fulgens* at Los Morros. The total number (32) includes 4 that were sexually immature.

Sex	<i>n</i>	<i>K</i> (yr <sup>-1</sup> )	SE	<i>L</i> <sub>∞</sub> (mm)	SE
Male	15	0.39	0.10	181.2	8.3
Female	13	0.41	0.09	179.9	8.1
Total	32	0.38	0.04	183.1	6.1

## RESULTS

### Growth and Size at Maturity

Annual increment data for mark-recapture data are plotted in Figure 2 and estimates of the parameters of the von Bertalanffy growth equation are given in Table 1 for males, females, and all data, which includes juveniles. The slight differences in growth rate between the sexes are not significant. We did not have data on the growth rate of *Haliotis fulgens* below about 80 mm in this study. However, TURRUBIATES (1989) found that the growth rate of juveniles was 35 mm per year for the first 2 years at a different site in Bahía Tortugas. Assuming that the mean length of *H. fulgens* is 70 mm at 2 years, a mean growth curve can be constructed for the Los Morros site (Figure 3).

A plot of the percent sexually mature individuals against size (Figure 4) shows that sexual maturity occurs between 70 and 140 mm SL. Fifty percent are sexually mature at about 105 mm SL, suggesting that sexual maturity is attained at about 3 years of age.

The sex ratio changes from 1:2 (males to females) for

those <120 mm SL to 1.17:1 for those >120 mm SL. The change in sex ratio with size is significant (Cochran's Test:  $\chi^2 = 4.07$ ;  $P < 0.05$ ) and unless differential mortality occurs, suggests a slightly faster growth rate of males than females because of the higher proportion of mature females in smaller size classes.

Emigration from the study site was about 12% of those recaptured. Four individuals were found during extensive searching for 50 m beyond the marked boundary. The mean distance moved by these abalone was about 14 m (maximum 25 m) in a year, in each case in the direction of the approaching swell. In addition, fishermen reported three more tagged abalone that were estimated to have moved about 50 m.

### Egg-Per-Recruit and Yield-Per-Recruit Analysis

Egg-per-recruit analysis and biomass yield (Figure 5) are presented as a percentage of the maximum number of eggs produced by a cohort, or the maximum weight of the cohort, as the case is, for three rates of  $M$ —0.1, 0.2, and 0.3— for a range of ages at first capture.

We chose a high, fixed value of  $F$  for the analysis because this is the most realistic assumption of the intensity of fishing during the recent history of the fishery (see Discussion). It is also more useful for management because, in the future, control of fishing is likely to be more easily achieved by an output control, such as a size limit, than an input control, such as a direct control of effort.

The results show that egg production increases more or less monotonically from ages 5 to 10 years for the three chosen values of  $M$ , whereas biomass decreases from maxima at 4–8 years according to the value of  $M$ .

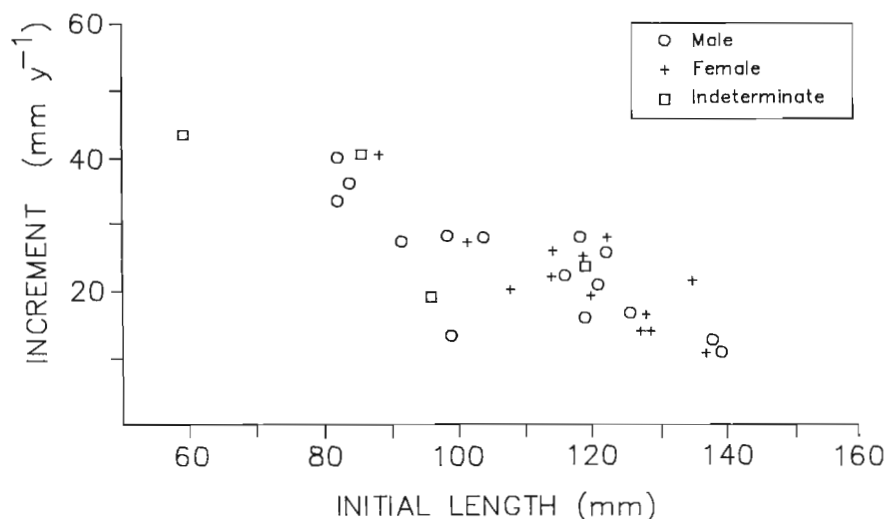


Figure 2

Plot of annual increment data for *Haliotis fulgens* at Los Morros for males, females, and those of indeterminate sex.

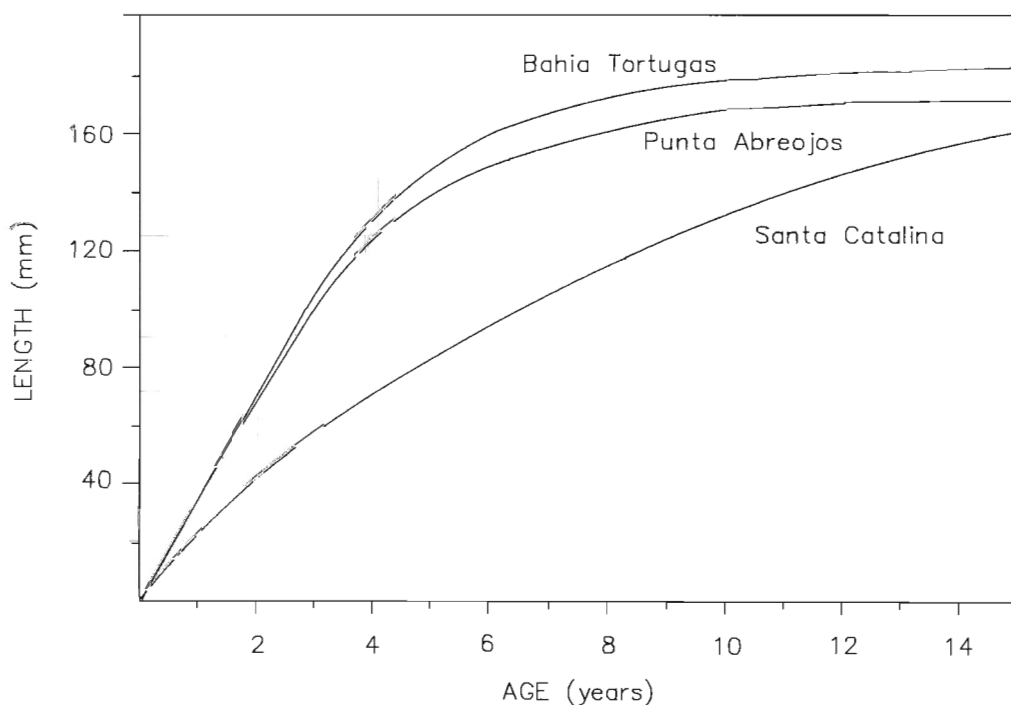


Figure 3

Growth curves of *Haliotis fulgens* at Los Morros (Bahía Tortugas) (this study), Punta Abreojos (GUZMÁN DEL PRÓO & MARIN, 1976), and Santa Catalina, California (TUTSCHULTE & CONNELL, 1988).

## DISCUSSION

### Growth, Size at Maturity, Sex Ratio, and Mortality

Previously published growth rates of *Haliotis fulgens* are given in Table 2 (see review by DAY & FLEMING, in press) and compared graphically in Figure 3. The growth rates of *H. fulgens* are almost identical at Punta Abreojos and Los Morros, and both are much faster, especially at smaller sizes, than that recorded by TUTSCHULTE & CONNELL (1988) at Santa Catalina Island. This is consistent with GUZMÁN DEL PRÓO's (1989) statement that the growth rate of abalone decreases with increasing latitude along the Californian peninsula. Compared with the growth rates of other abalone species (DAY & FLEMING, in press) this species in central Baja California must rank among the fastest growing abalone in the world.

The size at sexual maturity from our data occurs over a wide size range (70–140 mm), an only slightly greater range than that given by TUTSCHULTE & CONNELL (1981), 61–128 mm, although these authors suggested a much slower rate of growth. Our values are also less than that given by GUZMÁN DEL PRÓO (in press) in his review of earlier work; 50% of the population was mature at 141 mm SL. Size at sexual maturity has been suggested to be age-dependent rather than size-dependent (PRINCE, 1989), and this accords with our experience (SHEPHERD & LAWS,

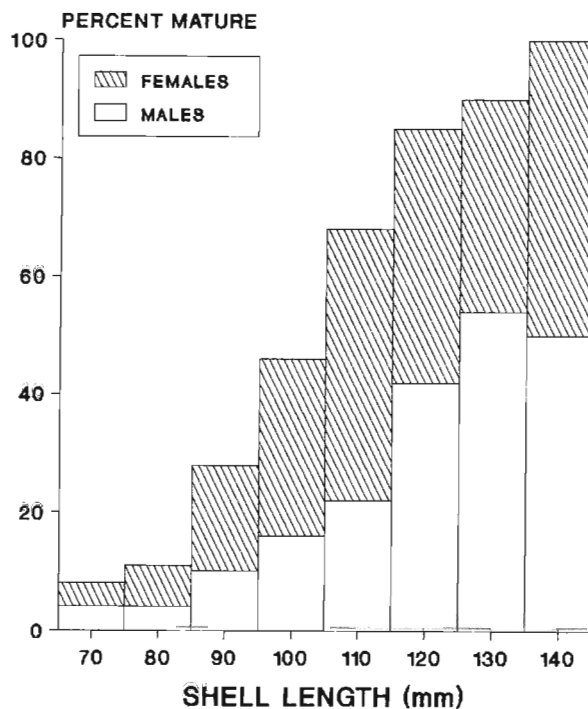


Figure 4

Percentage of sexually mature *Haliotis fulgens* with size.

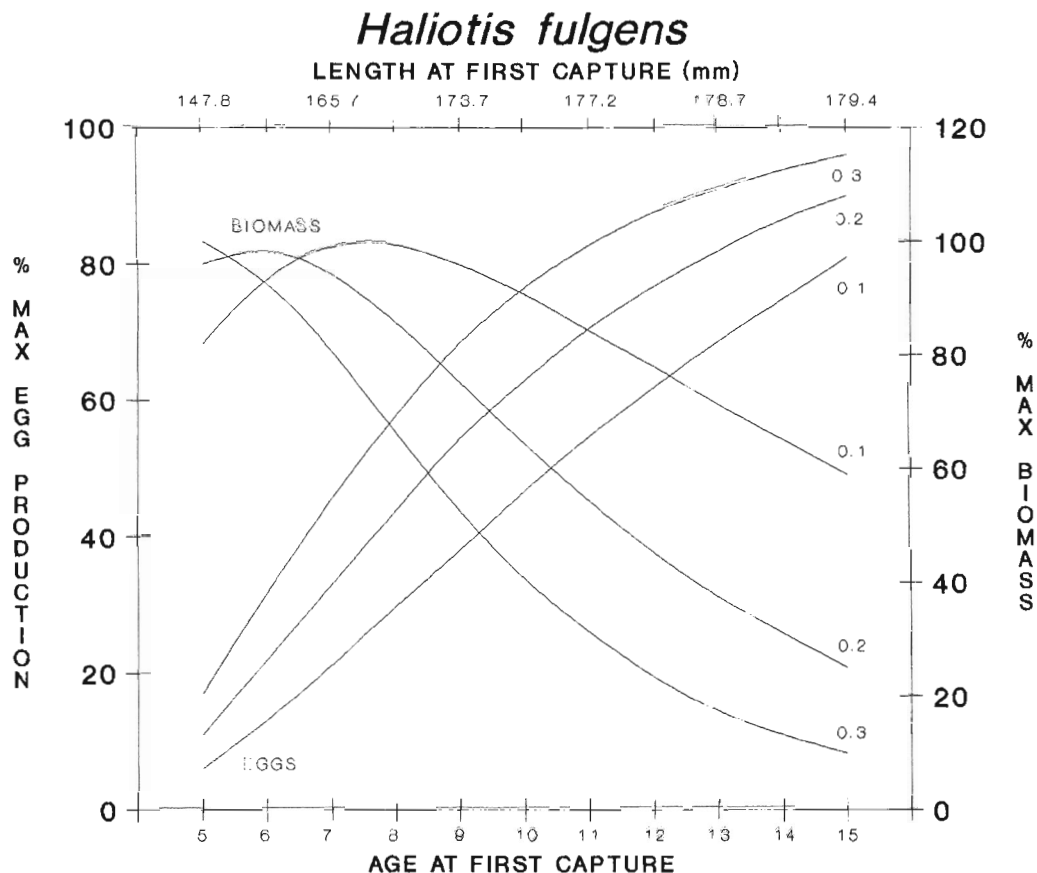


Figure 5

Yield-per-recruit and egg-per-recruit curves for *Haliotis fulgens* at  $M$  values of 0.1, 0.2, and 0.3, for high values of  $F(= 8)$ .

1974; GUZMÁN DEL PRÓO, in press). Because growth rates can vary greatly between reefs, the size at sexual maturity would also be expected to be variable between sites.

The significance of a changing sex ratio with size is still not clear (see TUTSCHULTE & CONNELL, 1981). SHEPHERD & HEARN (1983) suggested that differential growth between the sexes was the most likely cause of changing sex ratios. This implies that allocation strategies may vary between the sexes in a population, a possibility that deserves further study.

Our tagging experiment was conducted in a way that allowed for measurement of the natural mortality rate ( $M$ )

by the BEINSEN & POWELL (1979) method. However, of the 533 marked abalone released only 10% were recaptured; the obtained value of  $M'(0.31)$  did not differ significantly from zero, and is of no value. The experiment illustrates the problems encountered when the recapture rate is low. The low recapture rate was due partly to the cryptic nature of *Haliotis fulgens* in a deeply creviced habitat that contained many large boulders that could not be overturned, partly to the abundance of *Phyllospadix* and algae which made searching difficult, and partly to low visibility due to red tide. A low searching efficiency is not inconsistent with a high value of  $F$ ; the former applies to

Table 2

Parameters of the von Bertalanffy growth equation for *Haliotis fulgens* at different sites.

Place	Latitude	$K$ ( $\text{yr}^{-1}$ )	$L_{\infty}$ (mm)	Sex	Authority
Santa Catalina	37°N	0.10	205	both	TUTSCHULTE & CONNELL (1988)
Punta Abrejos	26°40'N	0.38	171	male	GUZMÁN DEL PRÓO & MARIN (1976)
Punta Abrejos	26°40'N	0.37	170	female	GUZMÁN DEL PRÓO & MARIN (1976)

the smaller, cryptic fraction of the population whereas the latter applies to the larger, more exposed fraction. Further, the study site may have contained more cryptic habitat than is typical of fished habitats. The problem of low searching efficiency was experienced by SHEPHERD *et al.* (1982) in measuring  $M$  for *H. rubra*, a species of similar cryptic habit. SHEPHERD & BREEN (in press) have discussed the problem and recommended a pilot experiment to obtain some idea of the likely movement and recapture rate.

Estimates of  $M$  for *Haliotis fulgens* range from 0.07 to 0.53 (reviewed by SHEPHERD & BREEN, in press) but we think the high values are not realistic for adult abalone. For the purpose of the egg-per-recruit analysis we use  $M$  values of 0.1–0.3, which should span the likely range of  $M$ .

### Implications for Management

The history of the Mexican abalone fishery in Baja California is described by GUZMÁN DEL PRÓO (in press), and salient features are summarized here. From the early 1960s the fishery was subject to high fishing pressure. From 1970 to 1985 the combined annual catch of *Haliotis fulgens* and *H. corrugata* in Zones II–IV (the mid-Baja California coast that includes Bahía Tortugas) declined to one-fifth, although the proportion of *H. fulgens* increased, indicating a proportionally smaller decline of that species. The density of *H. fulgens* apparently declined to one-third in the same period (GUZMÁN DEL PRÓO, in press). It seems reasonable to assume that the fishing mortality rate ( $F$ ) was high ( $>1.0$ ) during this period.

Size limits existed in name only until 1984, when a limit of 145 mm SL was enforced by requiring divers to land abalone in the shell. However, *Haliotis fulgens* has a cryptic habitat to at least 140 mm SL (TUTSCHULTE, 1976, unpublished), so that, even under intense fishing, few individuals  $<130$ –140 mm SL would have been taken. We conservatively assume that the age of first capture is 5 years ( $\approx 148$  mm SL).

On the basis of the above assumptions, egg production since 1970 would have been in the range of 6 to 17% of the maximum possible according to the chosen value of  $M$ . Intuitively, this seems extremely low, and raises the possibility that recruitment overfishing (reduction of parent stock to a level that adversely affects recruitment) may have occurred, and precipitated the decline in catch and density during the history of the fishery (GUZMÁN DEL PRÓO, in press). NASH (in press) presented evidence suggesting that at least 50% of the egg production potential should be maintained in an exploited stock. SLUCZANOWSKI (1984, 1986) suggested minimum levels of 40%. SHEPHERD (1991) found that recruitment failed in an isolated population, when the population density declined to around 32% of the virgin population and when the fraction of the population that aggregated for spawning fell to 6%. However, such values are at best suggestions only until the stock-recruitment relations in abalone are better known.

Until more information on natural mortality is available, it would be prudent to increase the size limit to around 165 mm SL to ensure 20–40% egg production. This measure would be certain to have serious social and economic implications, which would need to be explored.

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### LITERATURE CITED

- BEINSSSEN, K. & D. POWELL. 1979. Measurement of natural mortality in a population of blacklip abalone, *Notohaliotis ruber*. Rapports Precis-Verbal Reunion Conseil international pour la Exploration de la Mer 175:23–26.
- BEVERTON, R. J. H. & S. J. HOLT. 1957. On the dynamics of exploited fish populations. U.K. Ministry of Agriculture and Fisheries, Food and Fisheries Investigations (Ser.2) 19:1–533.
- BREEN, P. A. In press. A review of models used for stock assessment in abalone fisheries. In: S. A. Shepherd, M. J. Tegner & S. A. Guzmán del Prío (eds.), Abalone of the World: Biology, Fisheries and Culture. Blackwells: Oxford.
- DAY, R. W. & A. E. FLEMING. In press. The determinants and measurement of abalone growth. In: S. A. Shepherd, M. J. Tegner & S. A. Guzmán del Prío (eds.), Abalone of the World: Biology, Fisheries and Culture. Blackwells: Oxford.
- FABENS, A. J. 1965. Properties and fitting of the von Bertalanffy growth curve. Growth 29:265–289.
- GUZMÁN DEL PRÓO, S. A. 1989. Problemas y perspectivas de las investigaciones pesqueras sobre los abulones de Mexico. Pp. 297–305. In: Proceedings of the Workshop Australia-Mexico on Marine Science. Merida, Mexico.
- GUZMÁN DEL PRÓO, S. A. In press. A review of the biology of abalone and its fishery in Mexico. In: S. A. Shepherd, M. J. Tegner & S. A. Guzmán del Prío (eds.), Abalone of the World: Biology, Fisheries and Culture. Blackwells: Oxford.
- GUZMÁN DEL PRÓO, S. A. & A. MARIN. 1976. Resultados preliminares sobre crecimiento de abulon amarillo y azul (*Haliotis corrugata* y *H. fulgens*) en Punta Abreojos, B.C. Instituto Nacional de Pesca. INP/SC. No. 17:11 pp.
- NASH, W. J. In press. An evaluation of egg-per-recruit-analysis as a means of assessing size limits for blacklip abalone (*Haliotis rubra*) in Tasmania. In: S. A. Shepherd, M. J. Tegner

- & S. A. Guzman del Próo (eds.), *Abalone of the World: Biology, Fisheries and Culture*. Blackwells: Oxford.
- PRINCE, J. D. 1989. The fisheries biology of the Tasmanian stocks of *Haliotis rubra*. Ph.D. Thesis, University of Tasmania, Hobart.
- PRINCE, J. D. 1991. A new technique for tagging abalone. *Australian Journal of Marine and Freshwater Research* 42: 101-106.
- SHEPHERD, S. A. 1991. A review of the concept of stock in abalone fisheries: implications for the role of refugia in conservation. American Fisheries Society. San Antonio, Texas (abstract only).
- SHEPHERD, S. A. & P. A. BREEN. In press. Mortality in abalone: its estimation, variability and causes. In: S. A. Shepherd, M. J. Tegner & S. A. Guzmán del Próo (eds.), *Abalone of the World: Biology, Fisheries and Culture*. Blackwells: Oxford.
- SHEPHERD, S. A. & W. S. HEARN. 1983. Studies on southern Australian abalone (genus *Haliotis*). IV. Growth of *H. laevigata* and *H. ruber*. *Australian Journal of Marine and Freshwater Research* 34:461-475.
- SHEPHERD, S. A., G. P. KIRKWOOD & R. L. SANDLAND. 1982. Studies on southern Australian abalone (genus *Haliotis*). III. Mortality of two exploited species. *Australian Journal of Marine and Freshwater Research* 33:265-272.
- SHEPHERD, S. A. & H. M. LAWS. 1974. Studies on southern Australian abalone (genus *Haliotis*). II. Reproduction of five species. *Australian Journal of Marine and Freshwater Research* 25:49-62.
- SLUCZANOWSKI, P. R. 1984. A management oriented model of an abalone fishery whose substocks are subject to pulse fishing. *Canadian Journal of Fisheries and Aquatic Sciences* 41: 1008-1014.
- SLUCZANOWSKI, P. R. 1986. A disaggregate model for sedentary stocks: the case of the South Australian abalone. *Canadian Special Publications in Fisheries, Aquatic Sciences* 92:393-401.
- TEGNER, M. J., P. A. BREEN & C. E. LENNERT. 1989. Population biology of red abalones (*Haliotis rufescens*) in southern California, and management of the fishery. *Fishery Bulletin* 87:313-339.
- TURRUBIATES, J. R. 1989. Edad, crecimiento y reproducción del abulón azul *Haliotis fulgens* Philippi 1845 (Mollusca: Gastropoda) de Bahía Tortugas, B.C.S. Tesis de Maestro en Ciencias, Instituto Politécnico Nacional, México D.F.
- TURRUBIATES, J. R., M. ORTIZ, F. LOPEZ, R. AYALA & B. GOMEZ. 1987. Informe de la temporada de pesca 1985-86 de abulón, *Haliotis* spp en la costa occidental de la Península de Baja California. Resúmenes de VII Congreso Nacional de Oceanografía, Ensenada, B.C. July 1987.
- TUTSCHULTE, T. C. 1976. The comparative ecology of three sympatric abalones. Ph.D. Thesis, University of California, San Diego. 355 pp.
- TUTSCHULTE, T. C. & J. H. CONNELL. 1981. Reproductive biology of the species of abalones (*Haliotis*) in southern California. *The Veliger* 23:195-206.
- TUTSCHULTE, T. C. & J. H. CONNELL. 1988. Growth of three species of abalone (*Haliotis*) in southern California. *The Veliger* 31:204-213.