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Possible criteria for reopening the Northern abalone
(*Haliotis kamtschatkana*) fishery in British Columbia

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Abstract

This paper reviews the literature for relevant biological and fishery characteristics of different abalone species, makes yield and egg per recruit calculations and suggests biological reference points, criteria for reopening a potential fishery, and possible rehabilitation and management actions for the northern abalone, *Haliotis kamtschatkana*, in British Columbia.

The biology of the *H. kamtschatkana* makes this species vulnerable to over exploitation. The northern abalone is slow growing, relatively long lived and sedentary, and has low or sporadic recruitment with accumulations of older individuals distributed in shallow water locations easily accessible to harvesters. The high market value, reduced availability, and the difficulty of enforcing the fishery closure since 1990 in a large mostly uninhabited coastal area, has encouraged illegal harvesting of northern abalone populations, hampering attempts to rebuild stocks to a level that would allow a sustainable legal harvest. Evidence to date, from surveys in the central coast of British Columbia and Queen Charlotte Islands, indicate that there has been insufficient recruitment during the last two decades to maintain estimated fishing rates (F) during 1976-90 when the legal fishery was open (mean F about 0.5) and during the closure 1990-94 (F ranged from 0.1 to 0.7 in some locations). Samples from abalone illegally harvested during 1995 suggested that poachers removed all sizes of available abalone with no regard to the minimum size limit of 100 mm shell length that was in force during the legal fishery. Without size and fishing rate controls, egg per recruit (EPR) analyses suggested that egg production, during the closed fishery, could probably be at or less (<30% EPR) than the level when the fishery was open (30 - 50 %EPR). Many of the long-term abalone fisheries around the world that have conserved $\geq 50\%$ EPR have been sustained; other fisheries that conserved lower egg production have suffered poor recruitment, stocks have declined and many fisheries closed. However, because of the difficulties of showing a stock-recruitment relation, predicting how environmental / ecosystem changes influence abalone stock dynamics, and ongoing poaching problems, there are no guarantees that various rebuilding / rehabilitation strategies will work.

Criteria required to reopen a northern abalone fishery could not be fully resolved in this paper due to lack of information on the frequency and patch size of adult abalone required to maintain sufficient recruitment for a healthy abalone population. Likely criteria for reopening a sustainable northern abalone fishery would require further research to determine the optimal distribution and density of spawners and recruits, distance of larval transport, genetic stock discreteness and how these factors would effect the geographic scale of fisheries management.

Rehabilitation of northern abalone populations should include (1) continued fishery closure until stocks rebuild, (2) reduction of illegal harvest through increased publicity and adoption of new detection and enforcement methodologies (e.g., DNA analysis), and (3) experimental manipulation, in well monitored management areas, to determine the efficacy of brood stock transplant and juvenile seed restocking methodologies.

Résumé

Le document fait état d'un examen des publications traitant des caractéristiques biologiques et halieutiques de diverses espèces d'ormeaux. On y trouve des calculs sur le rendement et le nombre d'oeufs par recrue et des propositions de points de référence biologiques, de critères pour une éventuelle réouverture de la pêche ainsi que de mesures de rétablissement et de gestion pour l'ormeau nordique (*Haliotis kamtschatkana*) en Colombie-Britannique.

La biologie de *H. kamtschatkana* rend cette espèce très vulnérable à la surexploitation. L'ormeau nordique croît lentement, vit relativement longtemps, est sédentaire et présente un recrutement lent ou sporadique. Les concentrations d'animaux plus âgés se trouvent en eaux peu profondes, ce qui facilite la récolte. La valeur élevée de ces animaux, leur rareté et la difficulté de faire respecter la fermeture de la pêche depuis 1990, dans une région côtière en grande partie inhabitée, a favorisé la récolte illégale de l'ormeau nordique et ainsi nuï aux tentatives de rétablissement des stocks à un niveau permettant une récolte légale soutenue. Les relevés effectués au large de la côte centrale de la Colombie-Britannique et autour des îles de la Reine-Charlotte ont montré que le recrutement des deux dernières décennies a été insuffisant pour assurer le maintien des taux de pêche estimés (F) pour la période de pêche légale de 1976-1990 (F moyen de 0,5 environ) et pour celle de 1990-1994 où la pêche était interdite (F variant entre 0,1 et 0,7 en certains endroits). Des échantillons prélevés de captures illégales en 1995 portent à croire que les braconniers ont récolté des ormeaux de toutes tailles sans tenir compte de la taille limite minimale de 100 mm de longueur de coquille qui était appliquée pendant la pêche légale. En l'absence de contrôles portant sur la taille et le taux de récolte, les analyses du nombre d'oeufs par recrue (OPR) indiquent une production d'oeufs pendant la période de fermeture (< 30% OPR) qui était sans doute inférieure à celle existant pendant la période de pêche légale (30 - 50 % OPR. Bon nombre des pêches de l'ormeau à long terme pratiquées ailleurs dans le monde où un OPR d'au moins 50 % a été maintenu ont aussi été maintenues. Les pêches où la valeur de l'OPR a été inférieure ont souffert d'un recrutement insuffisant, les stocks se sont appauvris et bon nombre de ces pêches ont été fermées. La difficulté d'établir une relation stock-recrutement, de prévoir la façon dont les variations de l'environnement ou de l'écosystème influent sur la dynamique des stocks d'ormeaux et la poursuite du braconnage fait que rien ne prouve que les diverses stratégies de rétablissement ou de restauration pourront réussir.

Les critères à respecter pour réouvrir la pêche de l'ormeau nordique n'ont pu être définis dans le document à cause de l'absence de renseignements sur la fréquence et la taille des concentrations d'ormeaux adultes nécessaires pour assurer un niveau de recrutement suffisant au maintien de populations saines. La définition de tels critères de réouverture de la pêche exigerait des recherches ayant pour objet de déterminer la distribution et la densité optimales des géniteurs et des recrues, la distance de déplacement des larves, le caractère discret des caractéristiques génétiques des stocks et la façon dont ces facteurs influeraient sur la superficie devant être gérée.

La restauration des populations d'ormeau nordique devrait comporter 1) le maintien de la fermeture de la pêche jusqu'au rétablissement des stocks, 2) la réduction de la récolte illégale de par une meilleure publicité et l'adoption de nouvelles méthodes de détection et d'application (analyse de l'ADN, etc.) et 3) des expériences, dans des zones de gestion bien contrôlées, afin de déterminer l'efficacité des méthodes de repeuplement de par la transplantation de géniteurs et l'introduction de juvéniles.

2.0 INTRODUCTION

Abalone, archaeogastropod molluscs of the Haliotidae family, are mostly found on shallow (intertidal to 30m) shorelines of temperate and tropical seas (Mottet 1978). Abalone have been exploited by man for thousands of years for the mollusc's large edible foot and colourful bowl-shaped shell. Although important to many coastal communities and economies, in recent years, the low capital cost of fishing, high market value and low biological productivity of abalone have made abalone vulnerable to over exploitation. Most modern-day abalone fisheries throughout the world have experienced increased landings, subsequent declines, and many have resulted in complete closure to fishing and in one case the prospect of species extinction (Table 1).

The "northern" or "pinto" abalone, *Haliotis kamtschatkana*, is found from Sitka Island, Alaska to Baja California and generally occurs in patchy distribution on exposed and semi-exposed coasts in British Columbia (B.C.). In B.C., northern abalone has been a traditional food of first nations and a target of recreational divers and a small commercial dive fishery until 1990. The biology and fishery of the northern abalone was reviewed by Sloan and Breen (1988) and Farlinger and Campbell (1992). Surveys at index sites in southeastern Queen Charlotte Islands and the north central coast of B.C. indicated that the abundance of northern abalone had declined more than 75% during the period of 1978-84 and remained low until 1994 (e.g., Winther et al. 1995; Thomas and Campbell 1996). Faced with stock depletion and the possibility of abalone population collapse the northern abalone fishery was closed in December, 1990, to first nations, recreational divers and commercial fishers, due to conservation concerns. The objective of the coastwide closure was to allow depleted populations of northern abalone to rebuild. Over six years have elapsed since the fishery closure and managers and user groups have requested an evaluation of the current northern abalone stock status in B.C.

The objectives of this paper are to suggest appropriate criteria which could be used in consideration of reopening a northern abalone fishery in B.C. This paper reviews relevant biological and fishery characteristics of different abalone species, makes yield and egg per recruit calculations and suggests biological reference points that could be relevant to the northern abalone and potential fishery in B.C. Possible rehabilitation of northern abalone populations and management actions are discussed.

3.0 HISTORY OF FISHERY

3.1 Summary of harvest and management

The ancient tradition of harvesting of abalone by First Nations along the northwest coast of North America (Holm 1965) was usually carried out at low tide where exposed abalone were picked by hand and subtidal abalone were harvested with a long pole terminating in a hook. The first non aboriginal fishery began in the early 1900's where abalone were harvested using long poles armed with hooks or by diving (Thompson 1914). With the advent of SCUBA in the 1950's a recreational fishery began and landings from a small commercial abalone fishery were recorded. Little is known about the extent of First Nations and recreational harvesting, although

the level is thought to be well below the commercial harvest during the last four decades (Sloan and Breen 1988). The commercial northern abalone fishery and management in B.C. is well documented (e.g., Breen 1986; Sloan and Breen 1988; Farlinger 1990; Elner 1991; Farlinger and Campbell 1992). Commercial landings were sporadic prior to the early 1970's after which total annual landings increased dramatically to a maximum of 481.4t in 1977, due to increases in market demand and technological improvements enabling exploitation in remote areas (Table 2) (Fedorenko and Sprout 1982; Farlinger 1990). Thereafter, with evidence of resource depletion, landings declined under a quota management system to 47 t in 1985-90 (Table 2). A minimum size limit (of 101.6 mm shell length (SL) during 1908-81 and 100 mm SL during 1981-90) was enforced for all three fishery categories from 1908 until 1990 (Farlinger and Campbell 1992). Surveys during 1978 to 1990 (see survey section) indicated that northern abalone stocks were being over exploited so harvest for all three fishery categories were officially closed in 1990 and have remained closed due to conservation concerns in B.C.

3.1.1 Illegal harvest

Poaching of the northern abalone has probably occurred during the last two decades and has been difficult to quantify and control. The illegal harvest of this high market value (recent unconfirmed reports of >Can \$45 / kg) shellfish has made northern abalone a lucrative product. How much poaching of northern abalone has affected the overall exploitation and landings when the commercial fishery was open in B.C. is unknown. Since the fishery closure in 1990, there probably has been a significant illegal harvest of northern abalone (evidenced by numerous seizures of many thousands of poached abalone and legal court convictions of poaching) in B.C. The negative influence that the unknown annual illegal landings have had on attempts to rehabilitate northern abalone stocks in B.C. may be substantial, but this is difficult to determine (see also sections on survey density 3.3.2 and mortality estimates 4.3.3). The unknown illegal harvest makes the use of landings data suspect for use in the stock assessment of northern abalone in B.C. The combined high unit value and difficulty of enforcing a fishery closure in a large (mostly uninhabited) coastline suggests that poaching pressure is a serious hindrance to northern abalone stock recovery.

3.2 Catch per unit effort

Landings and effort (dive hours) were recorded on fisher logbooks throughout the last 14 years (1977-90) of the northern abalone fishery in B.C. (Elner 1991). Overall catch per unit effort (cpue) declined by about 46 % for the whole fishery during this period (Table 2). In contrast, density index surveys indicate > 70 % decline of northern abalone (see survey section). Problems with the use of cpue data as indices of stock abundance have long been recognized (p. 175, Hilborn and Walters 1992) especially in abalone fisheries (e.g., Breen 1992; Prince 1992). Cpue is likely to be an inaccurate indicator of abalone abundance, except under extremely high levels of exploitation, mainly because of the aggregative behavior of abalone making their catchability vary over time and space. Prince (1992) found that due to the visual nature of the fishery, *H. rubra* which often formed 'schools' were easily targeted by divers causing the catchability of abalone to increase as the stock density declined. Serial depletion of northern abalone in many areas of B.C. could be explained by the fishing strategy of exploiting the easily seen aggregations of emergent or 'exposed' abalone especially during spawning periods (Breen

and Adkins 1980a). Clearly the initial broad spatial-scale Leslie analyses conducted by Elner (1991) on northern abalone cpue logbook data should be considered with caution. However, the estimation of exploitation rates as high as 83 % in statistical area 7 could have reflected local serial depletion of abalone in some areas (Elner 1991). As Elner (1991) pointed out a more detailed analysis of the log book relative catch and effort data in conjunction with the independent abundance surveys on a fine spatial scale could be useful in understanding potential local regional and annual variability in production levels of northern abalone.

3.3 Surveys

The use of fishery independent surveys probably is the only way that a reasonably accurate assessment of the northern abalone stocks in B.C. can be made. Fortunately, a time series of northern abalone densities and size frequencies has been collected through surveys of southeastern Queen Charlotte Islands (QCI) and the Central Coast of B.C. (CC) during 1978-94 (see references in Table 3). Unfortunately, the general aggregated distribution of northern abalone and the time consuming dive surveying logistics makes biomass estimation of this species throughout B.C., on an annual basis, impossible. The survey conducted to date (using consistently the same standard 16 one m² quadrat survey method developed by Breen and Adkins (1979)) provide a time series of northern abalone densities at index sites in QCI and CC. Although there are a few surveys of southern B.C. (e.g., Quayle 1971; Breen et al 1978; Adkins 1996) they do not provide the extended coverage as the surveys in north B.C. Consequently only the surveys in north B.C. are discussed in this paper.

3.3.1 Size

Information from the literature was used to decide on the size categories. Abalone density was expressed as the number / m² for total (all sizes) and size categories of mature (≥ 70 mm SL), prerecruit (92-99 mm SL), new recruit (100-106 mm SL) and legal (≥ 100 mm SL) when the fishery was open. The smallest size that 100 % of abalone were mature was approximately 70 mm SL from gonad histological examination of northern abalone from QCI (Campbell et al. 1992). The "legal" size was set at ≥ 100 mm SL for all years to be consistent even though the legal minimum size was higher (101.6 mm SL) prior to 1981 (Farlinger and Campbell 1992) and there has been no legal fishery for northern abalone in B.C. since 1990. The prerecruit and new recruit sizes were estimated from abalone growth curves provided by Sloan and Breen (1988). Emphasis was made on mature northern abalone ≥ 70 mm SL because most (prerecruit and recruited) abalone of interest were easily found as emergent or exposed (visible on rocks) individuals. Attempting to find and count abalone < 70 mm SL, many of which are immature and cryptic, located in locations hard to reach (e.g., under rocks, in crevices), was time consuming and probably inaccurate using the current quadrat survey method (Campbell 1996).

Mean predicted weights were estimated by calculating weights (wt in g) from the equation $wt = 0.0001SL^{3.034}$ (after Sloan and Breen 1988) for each individual within each size category. Summary statistics on the different sizes of northern abalone surveyed in QCI and CC are presented in Table 4a,b. Generally the mean size of mature and legal sized abalone increased for QCI although there was no clear trend for each survey year (Table 4a). There were no differences between years in mean size of mature and legal sized abalone from CC (Table 4b).

Similar results were found in mean legal size for annual port samples although there were two peaks in 1987 and 1990 (Table 5).

3.3.2 Density

The mean density of northern abalone generally declined (except for a minor increase during 1985 - 87) for all size groups in the surveys of QCI and CC during 1978 - 94 (Table 3, Fig. 1, 2, 3, 4, 5). The frequency of samples (a sample normally consists of 16 one m² quadrats per site) indicates increasingly fewer sites with more than one abalone per m² during 1978 - 94 (Fig. 1). This indicates that there were significantly fewer locations during 1993-94 than during 1978-80 with critically important patches or sites of high densities (e.g., > 2 of abalone per m²) (see section on spawning and the importance of patch size).

Although for legal abalone there was a decrease in the density (Fig. 2) their average mean size did not decline (but increased slightly) (Table 4) which suggests serial depletion of legal sized northern abalone with little recruitment.

3.3.3 Pros and cons of surveys

The "Breen" survey method (Breen and Adkins 1979) used to assess northern abalone has provided a valuable time series of population density trends at indicator index sites in large remote areas throughout northern B.C. Considering the time consuming and logistical difficulty of surveying abalone at low densities over a large broad spatial scale the survey method has provided a consistent and logistically reliable procedure. However there is no perfectly reliable abalone survey method available and as with all survey methods used on abalone to date there are potential problems. For the "Breen" method, several authors have suggested that to improve the statistical precision and power to show changes in density between years sample sizes should be increased and or more efficient survey methods should be explored (e.g., Sloan and Breen 1988; Campbell 1996). Fig. 2 illustrates the overlapping confidence limits associated with the mean density estimates of legal sized abalone between surveys. Increases in sample size, with randomly placed samples in a larger area of the Central Coast are planned for future surveys. Although enumeration of scarce non-emergent abalone juveniles was part of the objectives of previous surveys, the "Breen" method was time consuming and probably not efficient in sampling small cryptic juveniles (< 50 mm SL). Other methods to estimate recruitment / settlement of small northern abalone juveniles, such as artificial habitats (Davis 1995), require evaluation.

Other survey methods used to assess abalone abundance have many problems (Breen 1992; McShane 1994). The free swim time search method (Shepherd 1985; McShane 1994) provides increased efficiency in covering large areas thereby increasing statistical precision of the relative density estimates, however, variability between and within divers (due to variability in diver experience, water visibility and swell, algal vegetation and abalone density aggregations) can influence searching time and bias in abalone density estimates (Shepherd and Partington 1995). The change-in-ratio method (Nash et al. 1994) requires the time interval between surveys be short so that growth and natural mortality effects on the relative abundance of the prerecruit and recruited abalone are negligible. Although tag/recapture methods may be useful in small

scale studies the behaviour of abalone such as their non random dispersal (Shepherd 1986b) and distribution in open and cryptic substrates could bias the random assumption of tag recapture in estimating population size (Ricker 1975). Hart et al. (1997a,b) compared several survey techniques (radial transects, catch-effort Leslie method, timed swims, change-in-ratio, mark-recapture Petersen's method) in 2.5 - 5.0 ha plots and concluded that the transect survey method (using 30 m² as the sample unit) with a stratified random sampling design was the safer and more robust alternative for surveying *H. rubra* stocks in Victoria, Australia. The change-in-ratio and mark-recapture (along with an equal catchability test) methods were also considered efficient but required more intensive data collection.

Clearly alternate survey methods still require development for northern abalone and will depend on the objectives and logistics involved. More than one survey method could be used in some studies to confirm abundance estimates. Adaptive sampling principles (Thompson 1992; Thompson and Seber 1996) have the potential to influence the way abalone populations are surveyed in the future. Temporal and spatial survey components may be critical in evaluating future reopening criteria and / or experimental management areas .

4.0 BIOLOGY

In this section a summary of relevant biological data on abalone is presented with an emphasis on recent findings since the review by Sloan and Breen (1988).

4.1 Reproduction

4.1.1 Size at maturity

Based on histological examination of gonads Quayle (1971) found northern abalone became sexually mature at about 50 mm SL (about 3 years old) in B.C. (Sloan and Breen 1988). Campbell et al (1992) found 50 % mature at about 55 mm SL and 100 % mature ≥ 70 mm SL for northern abalone on the southeastern QCI. In a histological examination of northern abalone gonads in Barkley Sound, 50 % maturity was at 45 mm SL for a "surf" abalone population exposed to heavy wave action and 52 mm SL for abalone in a relatively sheltered area (A. Campbell, B. Clapp and G. Jamieson unpublished data).

4.1.2 Fecundity

Fecundity of *H. kamtschatkana* in QCI was estimated by Campbell et al (1992) as the number of eggs in ripe ovaries. Fecundity for "surf" abalone in an exposed location, at the same shell length, were similar to that of abalone found in sheltered areas in Barkley Sound and from QCI; fecundity (f_j , in millions of eggs) of northern abalone for all areas combined was $f_j = 0.235 h_j^{3.5113}$ ($R^2 = 0.88$), where f_j is the number of eggs produced by a female at a length h_j (A. Campbell, B. Clapp and G. Jamieson unpublished data). These fecundities are probably slight overestimates since all eggs are probably not spawned.

4.1.3 Spawning and the importance of patch size

The spawning period for northern abalone usually occurs sometime during the April - August period (Quayle 1971; Sloan and Breen 1988; A. Campbell unpublished data). Northern abalone are synchronous spawners with groups of males and females in close vicinity to each other in shallow waters broadcasting their gametes into the water column (Breen and Adkins 1980a). Cues that cause mass spawning in abalone are environmental factors such as temperature changes (Sloan and Breen 1988), minor storms and typhoons (Sasaki and Shepherd 1995). Shepherd (1986a) suggested that abalone should be protected from fishing during the spawning season because of the vulnerability of these spawning aggregations to exploitation. Recent studies in abalone (Clavier 1992; McShane 1995a,b; Shepherd and Partington 1995) and sea urchins (Leviton et al 1992) have emphasized that dilution of gametes through reduced adult spawner densities can reduce fertilization success. If fertilization success depends on the aggregation density of abalone then exploitation rates on abalone aggregations may be important in influencing production of larvae. The size and frequency of patches required to maintain sufficient recruitment for a healthy population of northern abalone is unknown and requires study.

4.2 Early stages

After fertilization the planktonic phase of northern abalone has a short period (5 - 6 days) (Olsen 1984). Fertilized eggs sink to the substrate and subsequently hatch within days into free swimming lecithotrophic trochophore larvae which are phototactic (Olsen 1984). After approximately 40 hours these trochophore larvae metamorphose into a veliger larvae which remain as plankters for up to 4 days before settlement into juveniles occurs (Morse and Morse 1984). Evidence from recent studies have suggested that larval exchange in some abalone species may occur on small geographic areas (on a scale of hundreds of meters to several kilometers) (Tegner and Butler 1985a; Prince et al. 1987; McShane et al. 1988; McShane 1992b, 1995a,b). Little is known about the early juvenile stages (1-3 years) of the northern abalone in B.C. and requires further study (Sloan and Breen 1988).

4.3 Age and growth

4.3.1 Age

Growth checks caused by calcification at the perimeter of the shell and or rings laid down in the spire of the abalone shell have been used successfully to estimate age and growth in a number of abalone species (e.g., Sakai 1960; Shepherd et al. 1995; Day and Fleming 1992). However, the use of shell growth checks (which may be deposited annually) to indicate age should be validated by independent methods (e.g., tag recapture) for each population studied since the frequency of growth checks can vary annually between populations of a species (e.g., *H. rubra*) (McShane and Smith 1992). To date a direct method of aging *H. kamtschatkana* has not been developed. Marks in the cut and polished spires of the *H. kamtschatkana* shells have been observed, however, age validation experiments have yet to be attempted in B.C. (A. Campbell pers. observation). The lack of the ability to age northern abalone has generally impeded their quantitative assessments using age structured models.

Although age determination of individual *H. kamtschatkana* is not possible, estimates of the age at which northern abalone reach the recruit size of 100mm SL are between 6 to 8 years in B.C. (Quayle 1971; Breen 1986). "Surf" abalone at exposed sites in B.C. may never reach the recruit size of 100 mm SL (Sloan and Breen 1988). The largest northern abalone (164 mm SL) was considered to be between 15 and 50 year old (Breen 1980 a).

4.3.2 Growth rates

The considerable variation in growth rates found in many abalone species can be influenced by variation between sites, seasons, years and the quality (nutritional value) and quantity (availability) of algae (Day and Fleming 1992). Numerous tagging and size frequency analyses on *H. kamtschatkana* have shown large variation in growth depending on habitat type: fast growth for northern abalone in sheltered *Macrocystis* forests compared to slow growth in *Pterygophora* forests especially in exposed areas where the stunted growth of "surf" abalone can be found in B.C. (Quayle 1971; Schnute and Fournier 1980; Breen 1986; Emmett and Jamieson 1988; Sloan and Breen 1988). Fournier and Breen (1983) suggested that growth curves of northern abalone vary considerably between sites because of habitat-related mortality, growth rates and final size.

4.3 Mortality estimates

4.3.1 Natural mortality

Natural instantaneous mortality rates (M) for adult northern abalone from size frequency analyses was found to be 0.15 to 0.20 in some sites closed to fishing (Breen 1980; Breen 1986). M was estimated to be 0.15 to 0.27 from dead shell collection analysis (Emmett and Jamieson 1989). M for juvenile northern abalone (1-3 years) was found to be 0.36 (Olsen 1984 in Sloan and Breen 1988). Natural mortality may be caused by environmental factors (episodic high temperature, low salinity, storms), predators (e.g., sea otter, fish, crab, starfish, and octopus), starvation (lack of algae), competitors (e.g., red sea urchins) for space and food, parasites and disease (Sloan and Breen 1988; Shepherd and Breen 1992).

The prospect of the population expansion of the sea otter (*Enhydra lutris*), a major predator of *H. kamtschatkana* in B.C. (Watson and Smith 1996), in addition to human exploitation, poses a serious threat to future northern abalone populations.

4.3.2 Total mortality

Total instantaneous mortality rates (Z) between prerecruit and new recruit sizes were calculated from the survey density data (Table 3) using the formula $Z = -(\text{Log}_e(\text{new Recruits}) - \text{Log}_e(\text{Prerecruits}))$ (Ricker 1975). The average Z values for all years were 0.41 and 0.51 for QCI and CC, respectively, for the period 1978-96 (Table 3). These values are crude estimates and should be considered with caution since there probably are a number of different age classes overlapping through these two size categories. However, these estimates are within the range ($Z = 0.13$ to 0.54) of values estimated by Breen (1980b) using Heincke's method (Ricker 1975) and values ($Z = 0.05$ to 0.41) calculated by Breen and Fournier (1984) from size frequency

distributions.

4.3.3 Fishing mortality and poaching

Exploitation rates (u) of northern abalone in B.C., estimated from Leslie analysis of cpue data, were generally high (e.g., mean 44.6% and 41.2 % for areas 2E and 6, respectively, Table 2) for many years during 1977-1990 (Elner 1992). These u values probably should be treated with caution because the high values may be due to serial depletion of northern abalone in some small areas and not represent the overall management area. Assuming instantaneous natural and fishing mortality (F) rates occurred concurrently ($F = u Z / A$, Ricker 1975, where A is total mortality) mean $F = 0.544$ and 0.526 were estimated for management areas 2E (QCI) and 6 (part of CC), respectively, for the 1977 to 1990 period (calculated mean Z values were 0.41 and 0.51 , respectively, see section 4.3.2 and Table 3, and where $A = 1 - e^{-Z}$). These F values were within the range found by Breen (1986) who used stock reduction analysis to estimate $F = 0.18, 0.46, 0.66, 0.51$ and 0.30 for the northern abalone in B.C. from 1976 to 1980, respectively.

If we accept that the Z values calculated from the surveys are correct (Table 3) and assume natural mortality $M = 0.2$ ($F = Z - M$) then poaching (illegal fishing) F values (at least between the prerecruit and new recruit size groups) were at least 0.20 for QCI and from 0.14 to 0.70 in some areas of the central coast during the post fishery closure (1993-96) period. These results are not surprising considering the reports of seizures of illegally harvested northern abalone (including smaller than "legal" size, Table 6) and the decreasing densities recorded in the surveys (see sections 3.1.1 and 3.3.2).

These mortality values should be treated with caution because (1) natural mortality values were considered constant, but could have been higher or lower, and (2) the assumption that abalone come from one large broad scale population may be incorrect (instead there may be many small area scale populations with different growth and mortality characteristics). Attempting to determine mortality rates from abalone size frequencies from specific sites would have been logistically difficult because of the rarity of northern abalone.

4.4 Recruitment

Recruitment is defined in this paper as the number or density of abalone reaching the fishable size each year. Recruitment of northern abalone has declined in QCI and CC during 1978 - 94 (Fig. 4, 5, Table 3). Virtually nothing is known about the process of recruitment for northern abalone in B.C. There are a large number of complex factors that can influence the quantity and location of abalone recruitment (e.g., regional hydrodynamics and storms may influence the local entrainment or wide dispersal of the passively transported larvae during their short larval period prior to settlement; local mortality and growth rates may act differentially on cryptic juvenile and emergent adult abalone survival) (McShane 1992b, 1995a,b; Sasaki and Shepherd 1995).

4.5 Stock definition

A unit stock of northern abalone has to date been considered in the fisheries management

context as an abalone population within arbitrarily chosen geographic or management areas. Consequently most of the stock assessment surveys of northern abalone in B.C. have been on a broad geographic scale. However, evidence from recent studies have suggested that some abalone species may be made up of many populations in which stock recruitment relations may occur in small geographic areas (on a scale of hundreds of meters to several kilometers) based on gene exchange (Brown 1991; Brown and Murray 1992a,b) and larval exchange (Tegner and Butler 1985a,b; Prince et al. 1987; McShane et al 1988). Consequently Shepherd and Brown (1993) suggested that an abalone stock be considered as a metapopulation made of several local discrete populations that have limited larval interchange. This stock definition provides a framework for managing local abalone populations that may have variable demographic processes. Subdividing present fishing zones into smaller management units have been advocated for Australian abalone fisheries (Prince and Shepherd 1992). Demographic differences in the growth and mortality rates of northern abalone occur between locations (Sloan and Breen 1988). However, more research is required on the genetic variation and larval dispersal mechanisms to assist in defining stock sizes of northern abalone in B.C.

4.6 Stock and recruitment

If one considers populations can maintain themselves at a number of different equilibrium states then "overfishing" could be defined as any level or rate of fishing mortality that endangers the long-term ability of a stock to produce an optimal sustainable yield (Thompson 1993). The extreme case, "Recruitment overfishing" (Cushing 1977), whereby the size of spawning stock is reduced to such a low level that resulting production of recruits is insufficient to maintain the population, appears to be wide spread in many abalone fisheries, although difficult to prove (Table 1). The lack of proof for stock recruitment relationships has led to other theories that recruitment failure in abalone fisheries could have other causes than overfishing, e.g. high wave action, predation, environmental variation, pollution and disease (McShane 1995a). A relationship between the abundance of spawners and their progeny (Ricker 1975) has rarely been empirically demonstrated for abalone (McShane 1995b; Shepherd and Partington 1995) possibly because of the logistic difficulty of measuring the correct life history traits in the appropriate spatial scales. However, recent studies on abalone aggregation have been successful in showing a strong recruitment relation and the requirement of maintaining adult densities to ensure sufficient recruitment (McShane 1995a; Shepherd and Partington 1995). Shepherd and Partington (1995), using a Ricker stock recruitment curve, showed that there was a critical stock density threshold (0.15 m^{-2}) for the *H. laevisgata* in Waterloo Bay, S. Australia, below which the risk of recruitment failure was high. In addition, Shepherd and Brown (1993) showed that a "minimum viable population" of more than 800 individuals was required, anything less (or a critical density threshold of 0.3 m^{-2} , Shepherd and Partington (1995)) of *H. laevisgata* at West Island caused recruitment failure. These results supported the strength of the Allee effect or depensation (Allee et al 1949) in which reproductive success can be reduced due low fertilization of gametes when abalone are at low densities and are unable to aggregate.

Shepherd and Baker (1998) suggested that recruitment to an abalone fishery could be relatively poorer and more variable in small than in large abalone populations, in which case small populations would need to conserve relatively more egg production to prevent depletion. An important estimate of annual productivity of northern abalone was calculated as 6.5 % of the

original equilibrium stock size by Breen (1980b) based on mortality and growth rates and the assumption that recruitment was constant. Later Breen (1986) concluded recruitment was not constant, but that the original biomass (B_0) was about 1800t during 1976. Breen (1986) using a stock reduction analysis suggested that recruitment failure in *H. kamtschatkana* occurred independently of fishing pressure in B.C. He suggested that recruitment was lower than replacement levels during 1975-83 and that the stock would have declined by about a third for this period even without fishing (Breen 1992). Breen (1986) also examined the densities of prerecruits and new recruits from the survey data for 1978-83 (e.g., Table 3 this present paper) and calculated that these values were less than those required to maintain an equilibrium population at the pre-fishery density (Sloan and Breen 1988). Using $M = 0.20$ and an estimated prefishery density of 2.5 m^{-2} then the prerecruit and new recruit densities required would be 0.55 and 0.45 m^{-2} , respectively (Breen 1986). He concluded that because recruitment was well below the required values that recruitment (settlement) was not stable in the fishery and that recruitment failure occurred prior to the period of intense harvesting begun in 1976. Breen (1986) also suggested that historical evidence (e.g., a low abundance in Alaska during the early 1950's and in a B.C. 1955 commercial survey) (Livingstone for Alaska and Quayle in B.C. quoted in Breen 1986) compared to the high densities found in other surveys indicated that large variations in abundance of the northern abalone may occur over time. Breen (1986) and Sloan and Breen (1988) acknowledged that the causes of poor recruitment in northern abalone were not well understood. Changes in environmental factors during the 1970's to the 1990's in relation to possible changes in coastal ecosystems and *H. kamtschatkana* recruitment in northern B.C. have not been examined.

Initial attempts to look for a stock and recruitment relation in the northern abalone are indicated in Fig. 6. Clearly a lot more data points (or years, decades) are required to obtain a more complete picture to determine if there is a stock and recruitment relationship for northern abalone using these type of data. However, two important points emerge from Fig. 5 and 6. The first, a small recruitment pulse was observed for CC and QCI in the mid 1980's which is probably due to successful settlement from the progeny of high adult densities of the late 1970's. The second, apart from the increase in recruitment for mature northern abalone densities $> 1.6 \text{ m}^{-2}$, recruitment increased only slightly for densities $< 1.6 \text{ m}^{-2}$ (Fig. 6). The evidence to date indicates that there has been insufficient recruitment during the last two decades to maintain the high level of exploitation observed to date on northern abalone in B.C. These data suggest that the current density of adult northern abalone are on the left side of the steep ascending limb of a stock-recruitment curve which makes northern abalone highly susceptible recruitment overfishing. The northern abalone is close to or below what Shepherd and Partington (1995) called the critical stock density threshold for *H. laevis* in Waterloo Bay (0.15 m^{-2}) and at West Island (0.3 m^{-2}), S. Australia, (Shepherd and Brown 1993), below which the risk of recruitment failure was high or actually did occur. The critical stock density threshold for northern abalone is unknown, but all the current evidence indicates we are well below this threshold. If we accept Breen's (1986) calculation of replacement requirements of prerecruit and new recruit densities to be 0.55 and 0.45 m^{-2} , respectively, then the threshold would be well below the $> 2.0 \text{ m}^{-2}$ mature northern abalone required. Myers et al. (1995), examining 128 finfish stocks, indicated that the population collapses at the levels observed to date, could not be attributed to depensatory dynamics and that the effects of overfishing were generally reversible, by reducing fishing mortality rates allowing remaining stocks to rebuild, unless environmental/ecosystem changes

altered the stock dynamics.

5.0 EGG AND YIELD PER RECRUIT ANALYSES

5.1 Assumptions, rationale and methods

Differences in growth and mortality rates are known to affect the yield productivity in weight and egg production of local populations of the same abalone species (e.g., McShane 1991; Nash 1992; McShane and Naylor 1995; Shepherd and Baker 1998). Estimating egg production under different growth and mortality rates is important in helping to understand how to protect a minimum amount of reproduction through regulation of size limits and fishing rates. Although yield per recruit (YPR) and egg per recruit (EPR) analyses have been conducted on *H. kamtschatkana* (Breen 1986; Sloan and Breen 1988) the models used were simple and only considered one growth rate (Breen 1992). Subsequently Tegner et al (1989), using Sluczanowski's (1986) approach, developed an egg per recruit model to analyze *H. rufescens* and *H. corrugata* from southern California. This model included some variability in length about the mean length-at-age. To determine the effect of different growth rates and size at maturity on egg per recruit we developed a computer program that adopted the same approach, but slightly modified a few of the equations, of Tegner et al (1989) so that different size at maturity ogives and maximum size limits could be examined (see Appendix 1 for modified equations). The egg per recruit model assumes that recruitment is constant, that the eggs produced by all sizes of mature females are equally viable and fertilized. No adult density effects on fertilization success are included in this model. Emphasis is made on egg per recruit analyses, although the effect of growth and mortality rates were also calculated with a yield per recruit analysis using equation 10.20 of Ricker (1975).

Of interest to management are the implications of possible changes in various size regulations including having a maximum size under different fishing rates should any fishery of northern abalone be legally allowed again. The egg per recruit analyses can provide useful biological reference points to indicate at what level of exploitation and size limits that egg production can be maintained above a threshold and below which the risk of recruitment overfishing would be high (Shepherd and Baker 1998). The purpose of using maximum legal sizes in addition to the minimum legal recruit sizes in the egg per recruit analyses was to examine the effect of protecting large abalone on egg production.

In the egg and yield per recruit analyses, two hypothetical populations of *H. kamtschatkana*, fast- and slow- growing, are considered. The von Bertalanffy growth equation for the "fast" or normal growth was obtained from northern abalone in a *Nereocystis* habitat from Gilbert Island and that for the "slow" growth was obtained from stunted "surf" northern abalone in a *Pterygophora* habitat from Newberry cove (Breen 1986; Sloan and Breen 1988) (Table 7). Size at maturity ogives were obtained from a histological examination of northern abalone gonads in Barkley Sound, one representing what we assumed to be a "fast" or normal growth northern abalone from a relatively sheltered area and the other a "surf" abalone population exposed to heavy wave (A. Campbell, B. Clapp and G. Jamieson unpublished data) (Table 7). Nash (1992) suggested that sexual maturity of *H. rubra* was attained at a given age, not at a give

size. We could not age northern abalone directly, but showed that the "surf" northern abalone matured at a smaller size than the northern abalone from the relatively sheltered area and assumed the difference was a result of differential growth rates. The fecundity / shell length relationship (Table 7) was assumed to be the same for both the "slow" and "fast" growing populations and that fecundity measured as the number of eggs in a ripe ovary is essentially a potential number that could be produced since not all eggs are probably spawned (Campbell et al 1992) (see also section 4.1.2). Although M , growth rates and maximum size could change between simulations, for each simulation these values were assumed to be constant (including some variation about the average growth) for all northern abalone sizes while the minimum legal (recruit) size and fishing mortality rate were changed at a predetermine increment (Table 7).

5.2 Results and discussion

The results of the YPR and EPR analyses are shown for the "fast" and "slow" growth northern abalone populations in Fig. 7 and 8, respectively. EPR are represented as a percentage of the total egg production of an unfished northern abalone population. Note that increases of natural mortality and reduction in growth rate between simulations caused a significant decrease in egg production of the unfished population (Table 8). Consequently caution is required when making comparisons of the relative %EPR simulations between different M and growth rates. Assuming $F = 0.5$ and a minimum size limit (MLS) of 100 mm SL when the fishery was open then %EPR ranged from 30 to 60 % with the different M values of 0.1 to 0.3 for "fast" growth northern abalone (Fig. 7). These values have a wider range, but are similar to those (35 - 50 %) reported for northern abalone at $M = 0.02$ by Sloan and Breen (1988). For areas with "slow" growth abalone over 95% EPR of the small potential number of eggs would be produced since most abalone would not reach the 100 MLS (Fig. 8, Table 8).

Since the fishery closed in 1990, we can assume there has been no respect by poachers for the 100 MLS and that all "emergent" northern abalone > 70 mm SL could potentially be exploited (e.g., Table 6). During the closed fishery, at a recruit size of 70 mm SL and $F = 0.5$ (see section 4.3.3) the %EPR ranged from 10 to 30 % with the different M values of 0.1 to 0.3 for "fast" growth northern abalone (Fig. 7). Even if poaching F was lower (e.g., 0.2 with a recruit size of 70) %EPR was only 30 - 50 %. (Fig. 7). Similarly for "slow" growth northern abalone harvested at a 70 MLS and $F = 0.5$ % EPR would be significantly reduced from $>95\%$ to 30 - 60 % depending on the M value (Fig. 8). Clearly without control of poaching fishing pressure and no size limit controls of northern abalone one can conclude (based on EPR analyses alone) that potential egg production was probably no higher (even less) with poaching and a closed fishery than when the fishery was open. Whether the poaching that probably occurred when the commercial fishery was open also included fishing abalone below legal size is unknown.

To increase egg production greater than 30 - 60 % EPR using a 100 MLS one would have to reduce F to about 0.05 to reach 80 - 90 % EPR (at $M = 0.1$ to 0.3 for "fast" growth northern abalone) (Fig. 7). Having a maximum size of 120 mm SL (along with 100 MLS, $F = 0.5$ and $M = 0.2$) would achieve a similar result (about 85 % EPR) (Fig. 9B), but would be higher than just increasing to 120 MLS (about 70 % EPR) at the same mortality rates (Fig. 7E). Reducing maximum sizes would increase %EPR at equivalent F and MLS values (Fig. 9). As expected

there were no changes to %EPR for "slow" growth abalone when applying maximum sizes > 100 mm SL (Fig. 8).

6.0 BIOLOGICAL REFERENCE POINTS (BRP's)

A number of studies on finfish populations have considered a variety of BRP's that could be used as thresholds to identify overfishing (e.g., Mace and Sissenwine 1993; Thompson 1993; Mace 1994; Myers et al 1994; Myers and Pepin 1994). Whether any of these BRP's are applicable is difficult to determine for a species such as northern abalone where the stock recruitment relation and required brood stock size for optimal harvest is unknown. However, the following BRP's support the justification for closure of the northern abalone fishery.

6.1.1 Egg production

Shepherd and Baker (1998) attempted to use thresholds of egg production in EPR models as a substitute for spawner stock size to estimate risk of overfishing given different F levels (Mace and Sissenwine 1993). Shepherd and Baker (1998) concluded 50%EPR and 40%EPR thresholds were appropriate BRP's for intermediate - and large - sized metapopulations, respectively, of *H. laevis* in South Australia; they suggested that 80%EPR thresholds could be required for many of the small metapopulations that had collapsed. Shepherd and Baker (1998) noted that many of the long-term abalone fisheries around the world that had conserved $\geq 50\%$ EPR had been sustained to date (Table 1). Clearly, for northern abalone, the 30 - 50%EPR (Breen 1986; this study) (assuming $M \leq 0.2$) has been insufficient to maintain productive populations in B.C. if we assume there is a stock recruitment relation. If there is no stock recruitment relation for northern abalone and recruitment is highly sporadic and variable depending on different environmental events (e.g., climate changes due El Nino or regional ocean currents), then the need to conserve a larger potential for egg production (e.g., >70%EPR) for all metapopulation sizes is advisable to prevent depletion or take advantage of even small favorable environmental events for an already depleted population.

6.1.2 Abundance

Myers et al. (1994) suggested minimum biomass (abundance) reference threshold levels (e.g., the stock size corresponding to (a) 50 % of the maximum predicted average recruitment and (b) 20 % of virgin stock size) could be used to indicate recruitment to a fish stock was seriously reduced. Clearly northern abalone stocks were below these two thresholds when the fishery was closed (see Sections 3 and 4.6).

7.0 CRITERIA FOR REOPENING

There are no published guidelines in determining criteria for reopening closed abalone fisheries. The Fisheries Resource Conservation Council (FRCC 1995) suggested some stock status indicators (e.g., abundance indices of spawners and recruits) for reopening a closed fishery which possibly could be used for the northern abalone. The objectives of the northern abalone

fishery closure were to reduce or stop fishing mortality so that stock size and recruitment could increase and rebuild to a level that would allow sustainable harvest. Considering that the time from settlement to recruitment for the northern abalone requires at least 6 - 8 years the rebuilding of stocks could be expected to take several decades. The reopening criteria would depend on the management objectives and type (commercial, recreational or native) of fishery required in terms of target yield level, geographic area (metapopulation size) and the stock's long term productive capacity. The size of stock (metapopulation) can influence the productivity, egg production and resilience to exploitation (Shepherd and Baker 1998), much of which is unknown for the northern abalone. Consequently the following proposed reopening criteria must be considered as being arbitrary.

7.1 Spawner abundance

Assuming $\geq 50\%$ D_0 (initial density of a "virgin stock" or pristine population such as in the late 1970's) of spawners would be sufficient for brood stock target density, about 1.0 mature (≥ 70 mm SL) or 0.25 legal (≥ 100 mm SL) northern abalone per square meters would be required for reopening (Fig. 3, 2). These density measurements are assuming a broad area scale survey is used for at least two to three years of sampling to insure population trends have increased and not caused by a recruitment pulse or measurement error. These thresholds generally agree with Shepherd and Partington (1995) who considered a critical spawning stock density threshold in small areas for *H. laevigata* in Waterloo Bay (0.15 m^{-2}) and at West Island (0.3 m^{-2}), S. Australia, (Shepherd and Brown 1993), below which the risk of recruitment failure was high.

7.2 Spawner distribution

There should be widespread geographic distribution of spawners within the area under consideration (e.g., management area, metapopulation) to ensure substocks have sufficient adults to provide successful fertilization for seed stock to repopulate depleted areas. The patch size, in terms of optimal density and distribution required to sustain northern abalone fishery is unknown.

7.3 Recruit abundance

Option 1. Assuming $\geq 50\%$ D_0 (initial density of a "virgin stock" or pristine population such as in the late 1970's) the target density would be about 0.26 and 0.14 of prerecruit and new recruit (respectively) northern abalone per square meters that would be required for reopening (Fig. 4, 5). Also assume same survey conditions as in section 7.1.

Option 2. Assuming $\geq 50\%$ of maximum predicted average recruitment (Myers et al. 1994) threshold requirement and an estimated prefishery prerecruit and new recruit densities being 0.55 and 0.45 m^{-2} , respectively (Breen 1986), then the target reopen density should be $\geq 0.26 \text{ m}^{-2}$ for prerecruits and $\geq 0.23 \text{ m}^{-2}$ for new recruits. Also assume same survey conditions as in section 7.1.

7.4 Environmental and ecological considerations

Optimal habitat would be required sufficient semi - and sheltered hard rock boulder substrate and food algal with long term prospects of no pollution, no major natural predators (sea otters), competitors (red sea urchins?) and no disturbances or degradation of habitat. The recovery and expansion of sea otters (Watson and Smith 1996) will mean that there should be no expectation of reopening an abalone fishery in areas that have or predicted to have sea otter populations within a certain time frame (e.g., 10 - 20 yr).

7.5 Fishing mortality rates and size limits

If some form of fishery is prosecuted low F and high size limits should be considered. In consideration of the egg per recruit calculations (Section 5) an increase in the MLS (100 to 120 mm SL) or a maximum legal size (120 mm SL) should be considered along with a low fishing rate (maximum $F < 1.0$) or a max F of $< 80\%$ of M (Thompson 1993) to ensure that %EPR is at least 70 - 80 % (Fig. 7E).

8.0 IMPLICATIONS FOR REHABILITATION

Continued closure of the fishery should be a major objective to reduce or stop fishing mortality so that northern abalone stock size and recruitment can increase and rebuild to a level that would allow sustainable harvest. The following additional actions should be considered to help rehabilitate this species.

8.1 Spatial scale

Understanding the spatial scale of stock units or metapopulations of northern abalone to be exploited is important for developing appropriate management strategies. The Australian experience suggests that a small spatial scale of monitoring and management is appropriate because of the high biological variability between abalone populations and susceptibility to sequential over-exploitation of abalone sub stocks (Prince and Shepherd 1992; Prince et al. in press). Although broad scale monitoring is useful to determine overall health of the stock and maintaining a times series of data, additional more intensive local fine scale surveys should be conducted to determine variability within and between areas of key biological variables of northern abalone. Appropriate survey methodology will be important to any successful application of small scale experimental management activities. A genetic evaluation should be conducted to help determine genetic variability and extent of genetic discreteness or spatial scale of northern abalone stocks.

8.2 Discourage poaching

Although enforcement efforts are catching poachers, the following additional approaches should be considered to reduce illegal fishing pressure. Public education and information on poaching problems should be increased. Obtaining a COSEWIC (Committee on the status of endangered wildlife in Canada) classification of "Threatened" ("a species likely to become

endangered if limiting factors are not reversed”) and “Vulnerable” (“a species of special concern because of characteristics that are sensitive to human activities or natural events”) or “Endangered” (“a species facing imminent extirpation or extinction”) for the northern abalone would help emphasize to the public the serious problems this species has. The combination of environmental factors, predation by the expanding sea otter populations and exploitation by man has potentially serious implications to placing the northern abalone on the endangered species list in B.C.

8.3 Genetic studies

Developing genetic studies to help enforcement and courts identify location and species of abalone found in illegal seizure and in restaurants would discourage illegal abalone trade more effectively. In addition, a genetic evaluation should be conducted to determine the spatial scale of genetic variability for northern abalone which would help in stock delineation and management.

8.4 Experimental management areas

Well monitored small scale experimental management studies should be encouraged in several locations to provide information on resource and rebuilding characteristics, and the effectiveness of manipulation of brood stock and juvenile recruitment abundance. Local community participation, especially in cooperation with first nations, should be encouraged in monitoring and protecting local abalone populations through experimental management areas. Prince et al. (1998) have advocated Territorial User Rights Fisheries (TURF) for protecting abalone populations. A form of TURF management was recently implemented to reduce poaching in the heavily exploited gastropod *Concholepas* fishery in Chile (Castilla et al. 1998). Creating more marine protected areas or refuges have also been suggested (Shepherd and Brown 1993; Tegner 1993). Refuge design to effectively assist northern abalone must consider the population biology, the local oceanographic regime, distances or spatial scales of brood stock sources and subsequent recruitment and feasibility of monitoring populations and enforcement (Tegner 1993).

8.4.1 Seed restocking

Production and restocking of juvenile abalone seed has been an intense activity in Japan since the late 1970's (e.g., Saito 1984; Kojima 1995) and to lesser extent in California (Tegner and Butler 1985b) and New Zealand (Schiel 1992, 1993). Although the release of larvae into the wild does not seem cost effective, the probability of the release of juveniles being cost effective may depend on the habitat choice and mortality factors involved (Schiel 1992, 1993). The efficiency of juvenile seed operations, however, remains questionable. Survival and recapture rates can vary considerably (Kojima 1995) requiring efforts to artificially increase survival by introduction of artificial habitats (Davis 1995) or having intense fishing pressure to control predators (e.g., octopus, crab, fish and spiny lobster) in Japan (Tegner and Butler 1989; Kojima 1995). Werner et al (1995) suggested dispersal of seed juveniles due to stress of handling, lack of food and exposure to new environment may explain the loss of seed abalone in some reseeded operations.

To date, no land based aquaculture facility for northern abalone in B.C. has successfully produced juvenile seed for restocking in the wild. This will require a concerted effort in terms of a critical mass of dedicated biologists and technicians and considerable long term funding. Problems to be addressed would include (1) implications of obtaining brood stock from depleted wild abalone populations, and (2) possible disease (Altstatt et al. 1996), sabellid polychaete infestation (Culver et al. 1997) and genetic transfers associated with transplanting abalone from one area to another (artificial holding facilities included).

8.4.2 Brood stock transplants

Brood stock transplanting, to increase the density of adults and probability of successful fertilization and recruitment, in an area have been attempted in closed fishing areas in California (Tegner 1992). The effectiveness of this approach depends on the number and longevity of the transplanted abalone, the survival and the amount of dispersal of the larvae (Tegner 1992; Tegner 1993). Protecting the transplanted northern abalone adults from poaching and sea otter predation will also be an important factor.

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FIGURE LEGENDS

- Fig. 1. Frequency distributions of samples with different densities (number per square meter) of total northern abalone (all sizes) from all sites of each Queen Charlotte Island and Central Coast survey during 1978-94.
- Fig. 2. Mean density of legal (≥ 100 mm SL) northern abalone from surveys in the (A) Queen Charlotte Islands (after Winther et al. 1995) and (B) Central Coast of B.C. (after Thomas and Campbell 1996). Vertical lines are approximate 95 % confidence intervals (± 2 S.E.). Numbers near dots indicate the number of sample sites
- Fig. 3. Mean density of "mature" abalone (≥ 70 mm SL) from surveys in the Queen Charlotte Islands (after Winther et al. 1995) and Central Coast of B.C. (after Thomas and Campbell 1996). The reopen density target was arbitrarily set at slightly higher than 50 % of peak densities during the 1970's.
- Fig. 4. Mean density of prerecruit northern abalone (92 - 99 mm SL) from surveys in the Queen Charlotte Islands (after Winther et al. 1995) and Central Coast of B.C. (after Thomas and Campbell 1996). The reopen density target was arbitrarily set at slightly higher than 50 % of peak densities during the 1970's.
- Fig. 5. Mean density of new recruit northern abalone (100 - 106 mm SL) from surveys in the Queen Charlotte Islands (after Winther et al. 1995) and Central Coast of B.C. (after Thomas and Campbell 1996). The reopen density target was arbitrarily set at slightly higher than 50 % of peak densities during the 1970's.
- Fig. 6. Relation between "mature" (≥ 70 mm SL) and estimated new recruit (100 - 106 mm SL, eight years later) northern abalone densities from surveys in the Queen Charlotte Islands (QCI) (after Winther et al. 1995) and Central Coast of B.C. (CC) (after Thomas and Campbell 1996). The numbers associated with the survey location indicate the year of the survey for the "mature" northern abalone densities (e.g., QCI84 = Queen Charlotte Islands 1984 survey) associated with new recruit northern abalone densities from the same area eight years later.
- Fig. 7. Yield per recruit (g) and egg per recruit (percentage of total eggs produced by an unfished population) analyses for the northern abalone using fast growth parameters and different natural mortality rates (A and D) $M = 0.1$, (B and E) $M = 0.2$ and (C and F) $M = 0.3$, respectively. See text, Appendix 1 and Table 7 for explanation and parameters used in the analyses.
- Fig. 8. Yield per recruit (g) and egg per recruit (percentage of total eggs produced by an unfished population) analyses for the northern abalone using slow growth parameters and different natural mortality rates (A and D) $M = 0.1$, (B and E) $M = 0.2$ and (C and F) $M = 0.3$, respectively. See text, Appendix 1 and Table 7 for explanation and parameters used in the analyses.

Fig. 9. Egg per recruit (percentage of total eggs produced by an unfished population, i.e., 68.75×10^8 eggs, see Table 7) analyses for the northern abalone using fast growth parameters, $M = 0.2$ and different maximum legal sizes (A) 130 mm SL, (B) 120 mm SL and (C) 110 mm SL. See text, Appendix 1 and Table 7 for explanation and parameters used in the analyses.

Table 1. Status of abalone fisheries around the world and egg production (% EPR) conserved where estimated. "Overfished" status may also mean recruitment failure due to other postulated causes. ^a includes *H. corrugata* in Mexican abalone fishery (but not EPR analyses). ^b S. California only, N. California fishery open.

Species	Area	Status	% EPR	References
<i>H. discus</i> and other species	Japan	Declined, massive enhancement attempts		e.g., Moma (1990), Yamada et al. (1994), Kojima (1995)
<i>H. cracherodii</i> ("black")	California	Overfished, closed, disease caused recent mass mortalities		Davis et al (1992), Davis (1993), Richards and Davis (1993), Haaker et al. (1992), Freidman et al. (1993), Lafferty & Kuris (1993), Gardner et al. (1995), Altstatt et al. (1996)
<i>H. corrugata</i> ("pink")	California	Overfished, closed	51 - 75	Tegner et al. (1989), Parker et al. (1992)
<i>H. fulgens</i> ("green")	California Mexico ^a	Overfished, closed Depleted	6 - 17	Parker et al. (1992) Shepherd et al (1991), Prince and Proo (1993)
<i>H. iris</i> ("paua")	New Zealand	Harvest rate probably not sustainable	18	Schiel (1992), Schiel & Breen (1991)
<i>H. kamtschatkana</i> ("northern"/"pinto")	Alaska Canada	Closed Overfished, closed	20 - 50	D. Woodby (pers. comm.), Farlinger & Campbell (1992) Winther et al. (1995), Thomas & Campbell (1996), This study
	Washington	Closed		A. Bradbury (pers. comm.)
<i>H. laevisgata</i> ("greenlip")	S. Australia	Some populations stable others declined	27 - 83	Prince and Shepherd (1992), Shepherd and Baker (in press)
<i>H. mariae</i>	Oman	Declined	2 - 29	Johnson et al. (1992), Shepherd et al. (1995)
<i>H. midae</i>	S. Africa	Declined		Tarr (1992)
<i>H. roei</i>	W. Australia	Small fishery		Prince and Shepherd (1992)
<i>H. rubra</i> ("blacklip")	S. Australia	Reasonably stable	40 - 55	Sluczanowski (1986), Prince and Shepherd (1992)
	Tasmania	Reasonably stable	40 - 70	Nash (1992)
	Victoria	Reasonably stable	≥ 50	McShane (1992a), Sanders and Beinssen (1996)
<i>H. rufescens</i> ("red")	California ^b	Overfished, closed ^b	35 - 48	Tegner et al. (1989), Davis et al (1992)
<i>H. sorenseni</i> ("white")	California	Overfished, closed, possible extinction		Davis et al. (1996)
<i>H. tuberculata</i> ("ormer")	Europe	Declined		Clavier (1992)

Table 2. Annual abalone landings, catch per unit effort of diving and quota for whole of British Columbia and annual landings for three management areas where abalone were surveyed, 1977 - 90.

Year	British Columbia			Area 2E	Area 6	Area 7
	Landings (tonnes)	Kilograms per hour	Quota (tonnes)	Landings (tonnes)	Landings (tonnes)	Landings (tonnes)
1977	481.4	43.5		258.8	36.6	5.6
1978	403.9	34.2		101.1	134.9	10.9
1979	208.6	32.7	227	32.1	82.3	11.7
1980	104.6	31.4	113	16.2	44.0	1.9
1981	93.6	34.2	94	21.3	38.1	1.8
1982	82.1	31.2	94	13.6	25.3	0.9
1983	53.1	34.5	71	17.4	7.4	0.5
1984	57.7	31.0	59	14.0	7.7	
1985	45.2	31.6	47	4.4	10.8	
1986	45.7	24.3	47	6.4	4.0	
1987	46.4	26.9	47	14.3	10.8	
1988	47.3	23.2	47	19.2	4.9	2.7
1989	46.9	23.9	47	11.4	7.3	0.1
1990	47.3	23.6	47	12.6	6.5	0.8

Table 3. Crude estimates of average total mortality rate (Z) from density of prerecruits (92 - 99 mm SL) and new recruits (100 - 106 mm SL) from all and comparable sites of abalone surveys (Breen method) of large scale areas. The 1995-96 surveys by Cripps and Campbell (in prep) were of transects in two small abalone beds (Dallain Point and Higgins Pass respectively). a or b = comparable sites throughout the years in general survey area; data from Winther et al (1995) or Thomas and Campbell (1996). c = prerecruits (94 - 101 mm SL) and new recruits (102 - 107 mm SL); data from Thomas and Campbell (1996). d = number of transects in abalone bed. $Z = -(\text{Log}_e(\text{New Recruits}) - \text{Log}_e(\text{Prerecruits}))$.

Year	Z	Mean Density (number per square meter)		Number of Sites	References
		Prerecruits	New Recruits		
Southeastern Queen Charlotte Islands					
1978-79	0.59	0.250	0.138	33	Breen and Adkins (1979, 1981)
	0.66	0.272	0.140	28a	
1984	0.78	0.064	0.029	70	Boutillier et al. (1985)
	0.68	0.075	0.038	28a	
1987	0.02	0.056	0.054	71	Carolsfeld et al. (1988)
	0.28	0.070	0.053	28a	
1990	0.15	0.047	0.041	69	Thomas et al. (1990)
	0	0.037	0.037	28a	
1994	0.40	0.027	0.018	69	Winther et al. (1995)
	0.45	0.033	0.021	28a	
Central coast of British Columbia					
1978-80	0.28	0.350	0.264	49	Breen et al. (1978, 1982), Adkins & Stefanson (1979),
	0.61	0.46	0.25	11ac	Breen and Adkins (1980b, 1981, 1982)
1983	0.59	0.18	0.10	25bc	Boutillier et al (1984)
	0.74	0.23	0.11	11ac	
1985	0.58	0.25	0.14	25bc	Farlinger and Bates (1986)
	0.22	0.20	0.16	11ac	
1989	0.69	0.082	0.041	26	Farlinger et al. (1991)
	0.98	0.08	0.03	25bc	
	0.77	0.13	0.06	11ac	
1993	0.56	0.062	0.035	28	Thomas and Campbell (1996)
	0.69	0.06	0.03	25bc	
	0.51	0.05	0.03	11ac	
1995	0.34	0.038	0.027	30d	Cripps and Campbell (in prep.)
1996	1.00	0.049	0.018	32d	Cripps and Campbell (in prep.)

Table 4a. Mean shell length and predicted mean total weight of an abalone from size frequency data of surveys on abalone from southeastern Queen Charlotte Islands, 1978 - 94. Mean weights were estimated from $wt = 0.0001SL^3.034$ (Sloan and Breen 1988) calculated for each abalone.

Details	Queen Charlotte Islands				
Year	1978-79	1984	1987	1990	1994
Total Number					
All sizes	2491	738	832	720	725
Adults ≥ 70 mm SL	1111	364	485	371	436
Prerecruits 92 - 99 mm SL	193	76	66	63	67
New Recruits 100-106 mm SL	96	39	63	52	46
Legals ≥ 100 mm SL	243	110	222	121	169
Percent of Total all sizes					
Adults ≥ 70 mm SL	44.60	49.32	58.29	51.53	60.14
Prerecruits 92 - 99 mm SL	7.75	10.30	7.93	8.75	9.24
New Recruits 100-106 mm SL	3.85	5.28	7.57	7.22	6.34
Legals ≥ 100 mm SL	9.76	14.91	26.68	16.81	23.31
Percent of Total ≥ 70 mm SL					
Prerecruits 92 - 99 mm SL	17.37	20.88	13.61	16.98	15.37
New Recruits 100-106 mm SL	8.64	10.71	12.99	14.02	10.55
Legals ≥ 100 mm SL	21.87	30.22	45.77	32.61	38.76
Mean Shell Length in mm (s.e)					
All sizes	66.6 (0.5)	69.5 (1.0)	77.5 (1.1)	71.2 (1.0)	77.7 (1.0)
Adults ≥ 70 mm SL	89.2 (0.4)	92.9 (0.8)	98.8 (0.9)	93.4 (0.9)	96.4 (0.8)
Prerecruits 92 - 99 mm SL	95.2 (0.2)	95.5 (0.3)	95.0 (0.3)	95.6 (0.3)	95.9 (0.3)
New Recruits 100-106 mm SL	102.7 (0.2)	102.7 (0.3)	103.3 (0.3)	103.1 (0.3)	103.2 (0.3)
Legals ≥ 100 mm SL	110.9 (0.6)	111.0 (0.8)	116.2 (0.8)	112.9 (1.1)	114.7 (0.9)
Maximum SL in mm	141	140	146	152	150
Mean Weight in g (s.e)					
All sizes	49.1 (1.0)	57.2 (2.1)	79.8 (2.7)	61.6 (2.4)	76.4 (2.6)
Adults ≥ 70 mm SL	89.7 (1.4)	100.9 (2.6)	125.8 (3.3)	104.9 (3.2)	115.6 (3.2)
Prerecruits 92 - 99 mm SL	100.9 (0.5)	101.3 (0.9)	100.3 (0.9)	102.3 (0.9)	103.4 (1.01)
New Recruits 100-106 mm SL	127.0 (0.8)	127.0 (1.2)	129.2 (1.0)	128.6 (1.0)	129.0 (1.1)
Legals ≥ 100 mm SL	163.4 (2.8)	163.6 (3.9)	190.5 (4.0)	175.0 (5.4)	182.5 (4.4)

Table 4b. Mean shell length and predicted mean total weight of an abalone from size frequency data of surveys on abalone from southeastern Central Coast of British Columbia, 1978 - 93. Mean weights were estimated from $wt = 0.0001SL^{3.034}$ (Sloan and Breen 1988) calculated for each abalone.

Year	1978-80	1989	1993
Total Number			
All sizes	2181	223	485
Adults ≥ 70 mm SL	1428	170	313
Prerecruits 92 - 99 mm SL	243	32	62
New Recruits 100-106 mm SL	189	17	39
Legals ≥ 100 mm SL	442	42	81
Percent of Total all sizes			
Adults ≥ 70 mm SL	65.47	76.23	64.54
Prerecruits 92 - 100 mm SL	11.14	14.35	12.78
New Recruits 100-106 mm SL	8.67	7.62	8.04
Legals ≥ 100 mm SL	20.27	18.83	16.70
Percent of Total ≥ 70 mm SL			
Prerecruits 92 - 99 mm SL	17.02	18.82	19.81
New Recruits 100-106 mm SL	13.24	10.00	12.46
Legals ≥ 100 mm SL	30.95	24.71	25.88
Mean Shell Length in mm (s.e)			
All sizes	77.6 (0.5)	80.1 (1.5)	75.5 (1.2)
Adults ≥ 70 mm SL	92.2 (0.4)	90.7 (1.1)	90.8 (0.8)
Prerecruits 92 - 99 mm SL	95.4 (0.1)	95.9 (0.4)	95.6 (0.3)
New Recruits 100-106 mm SL	102.8 (0.1)	102.8 (0.5)	102.2 (0.9)
Legals ≥ 100 mm SL	109.5 (0.4)	110.4 (1.3)	108.7 (0.8)
Maximum SL in mm	139	140	126
Mean Weight in g (s.e)			
All sizes	70.5 (1.2)	73.9 (3.5)	66.1 (2.3)
Adults ≥ 70 mm SL	98.2 (1.3)	93.8 (3.7)	93.4 (2.4)
Prerecruits 92 - 99 mm SL	101.5 (0.5)	103.1 (1.3)	102.2 (0.9)
New Recruits 100-106 mm SL	127.2 (0.5)	127.2 (1.8)	127.1 (1.1)
Legals ≥ 100 mm SL	156.7 (1.7)	160.8 (6.5)	152.6 (3.5)

Table 5. Summary of mean shell length of harvested northern abalone from annual port sampling at Prince Rupert (after Farlinger 1990).

Year	Statistical District	Overall Mean SL (mm)	Number of abalone
1985	1,3,5,6,8	111	425
1986	1,3,6	112	829
1987	1,2E,3,6	115	557
1988	1,3,5,6	111	723
1989	1,2E,3,5,6	112	1552
1990	1,2E,6	117	477

Table 6. Summary statistics of shell length (SL) data of samples from many thousands of poached abalone seized in the Port Hardy area.

Date	Shell length (mm)			Total number	Percent of total	
	Mean	minimum	maximum		< 100 mm SL	> 120 mm SL
March 1995	125	96	163	443	2.0	64.6
April 1995	109	85	150	845	10.2	15.7
May 1995	108	90	138	177	18.1	13.6

Table 7. Input parameters used in the egg per recruit and yield per recruit model for "fast" and "slow" growing northern abalone. See Tegner et al (1989) and Appendix 1 for model equations.

Parameter description	Fast growth	Slow growth	Source
Min length for first recruitment	60.0	60.0	
Max length for first recruitment	140.0	100.0	
Step size for length	5.0	5.0	
Maximum length for exploitation	none, 110, 120, or 130	none, 110, 120, or 130	
Min and Max fishing mortality, increment	0.0 and 1.0, 0.1	0.0 and 1.0, 0.1	
Von Bertalanffy growth equation			Breen (1986)
Growth coefficient, K	0.204	0.195	
Max length, L_{∞} in mm	137.3	95.2	
Hypothetical age, t_0	0.0	0.0	
Length (L in mm)-weight (W in g) relation, $W = a L^b$, where a and b are	0.0001 and 3.034	0.0001 and 3.034	Sloan and Breen (1988)
Min and Max age (years) of recruitment to stock, increment	1 and 3, 0.1	1 and 3, 0.1	
Maximum age (years)	25	25	
Instantaneous Natural Mortality, M, values	0.1, 0.2, 0.3	0.1, 0.2, 0.3	
Initial number of females	1000	1000	
a and b constants for standard deviations varying with age equation 3	8.0 and 0.25	8.0 and 0.25	Tegner et al. (1989)
Fecundity (f_i) shell length (h_i) relation, $f_i = a h_i^b$, where a and b are	0.235 and 3.5113	0.235 and 3.5113	Campbell et al. (1992) and Campbell et al. Unpubl. data
Proportion mature (P) shell length (L) relation, $P = L / (L + e^{(A-BL)})$, where A and B are	15.0059 and 0.2135	12.5514 and 0.1960	Campbell et al. Unpubl. data
Width (mm) for length interval j	5	5	

Table 8. Relative cumulated spawning potential (total number of eggs $\times 10^8$) for an unfished population ($EPR_{F=0}$) under different natural mortality and growth rates (M) when starting simulation runs with 1000 female abalone.

Growth rate	Natural Mortality Rate (M)		
	0.1	0.2	0.3
Fast	217.54	68.75	27.27
Slow	54.75	16.63	6.34

Appendix 1. Modified equations used in the Egg per recruit model

The basic assumptions and equations (1 - 6, inclusive, 8, 13 and 14) for an EPR model of abalone proposed by Tegner, M. J., P. A. Breen and C. E. Lennert. 1989. (Population biology of red abalones, *Haliotis rufescens*, in southern California and Management of the red and pink, *H. corrugata*, abalone fisheries. Fishery Bulletin 87: 313-339) were used unchanged in a computer program written in Turbo Pascal 7.0. The definitions of symbols can be found in Tegner et al (1989). The following provides a detailed description of changes made to the original equations 7, 11, 12, and 15 quoted in Tegner et al. (1989) to accomodate a size maturity ogive and when a maximum legal size was required in the calculations of the EPR model. (N.B. the letter "p" following equation number indicates that the original equation was replaced by this equation, whereas the letter "a" following equation number indicates the equation was an added feature to the program to replace the original equation if a maximum legal size analysis was required).

The Maximum Length for Exploitation is the size at which the animal can no longer be fished and is safe to continue producing eggs until it naturally dies. The animals are referred to as "postmaxlegals" that are larger than the maximum length for exploitation, or MLX.

The original Equation (9) is the proportion of prerecruits in the population, and is an integral from 0 to the minimum recruit length. Therefore the proportion of postmaxlegals ($QPostLegal_t$) in the population is an integral from MLX to infinity:

$$QPostLegal_t = \frac{1}{SD_t \sqrt{2\pi}} \int_{MLX}^{\infty} e^{-\left(\frac{(h-L_t)^2}{2SD_t^2}\right)} dh \quad (9a)$$

However, since the computer cannot handle infinity, we use an upper bound $= 2L_{\infty}$, and assumed that no animal ever grows larger than this length.

The number of postmaxlegals ($NPostLegal_t$) in each cohort is given by

$$NPostLegal_{t_{\infty}} = QPostLegal_t NV_{t_{\infty}} \quad (10a)$$

and the number of individuals exposed to the fishery, equation (11), changes to

$$NR_{t_{\infty}} = N_{t_{\infty}} - NPR_{t_{\infty}} - NPostLegal_{t_{\infty}} \quad (11p)$$

$NPostLegal_t = 0$ if there is no max size is requested.

The survival rate, original equation (12), determined by prerecruits being exposed to natural mortality, postmaxlegals being exposed to natural mortality, and recruits being exposed to both natural and fishing mortality, changes to

$$S_t = \left[\left(\frac{NPR_{t_{\infty}}}{N_{t_{\infty}}} \right) e^{-M} \right] + \left[\left(\frac{NR_{t_{\infty}}}{N_{t_{\infty}}} \right) e^{-(M+F)} \right] + \left[\left(\frac{NPostLegal_{t_{\infty}}}{N_{t_{\infty}}} \right) e^{-M} \right] \quad (12p)$$

Before we can continue, we must set the number of individuals exposed to the fishery to equation (11), as this number is used in equation (14), and is the same regardless of the inclusion of a maximum length for exploitation.

The equation which determines the mature proportion ($MatProp_j$) at the length interval j of the population is

$$MatProp_j = \frac{L}{L + e^{(A-BL)}}$$

where L is the shell length (mm). The EPR program allows the user to set the constant values A and B .

Including a mature proportion changes original equation (7) to

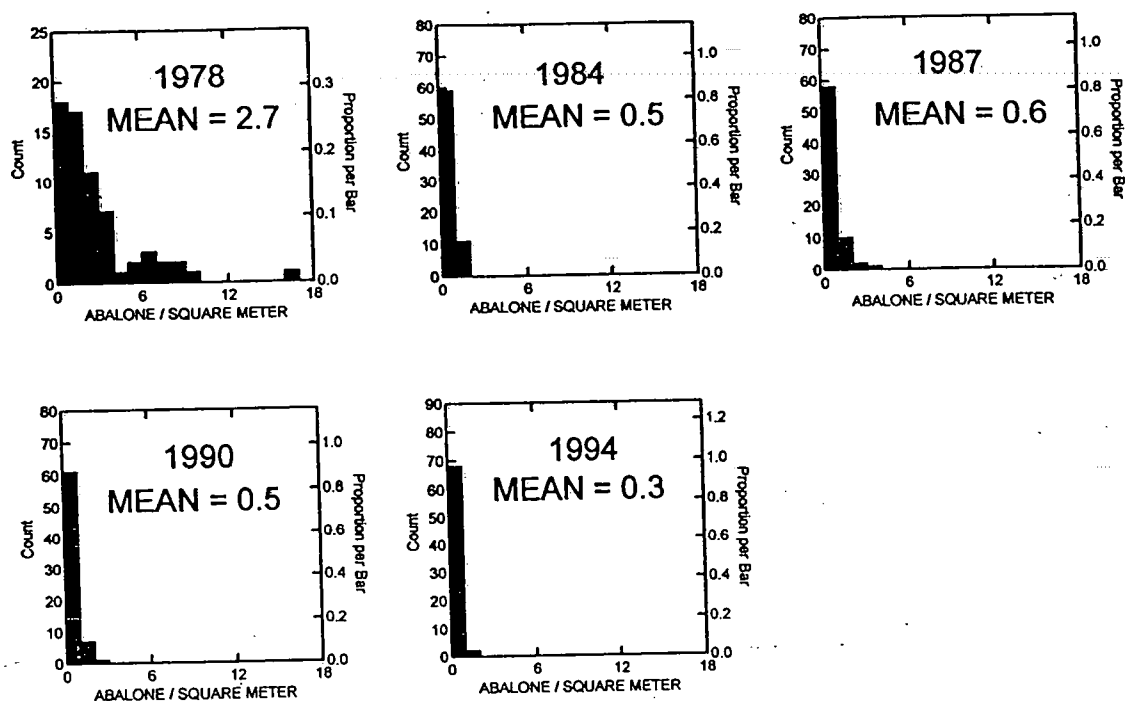
$$E_{max} = \sum_{j=m}^J NV_{\cdot j} f_j MatProp_j \quad (7p)$$

and similary changes equation (15) to

$$E = \sum_{t=1}^{\lambda} \sum_{j=m}^J N_{t,j} f_j \quad (15p)$$

These are the only places where the mature proportion of the population is used.

TOTAL ABALONE QUEEN CHARLOTTE ISLANDS



TOTAL ABALONE CENTRAL COAST

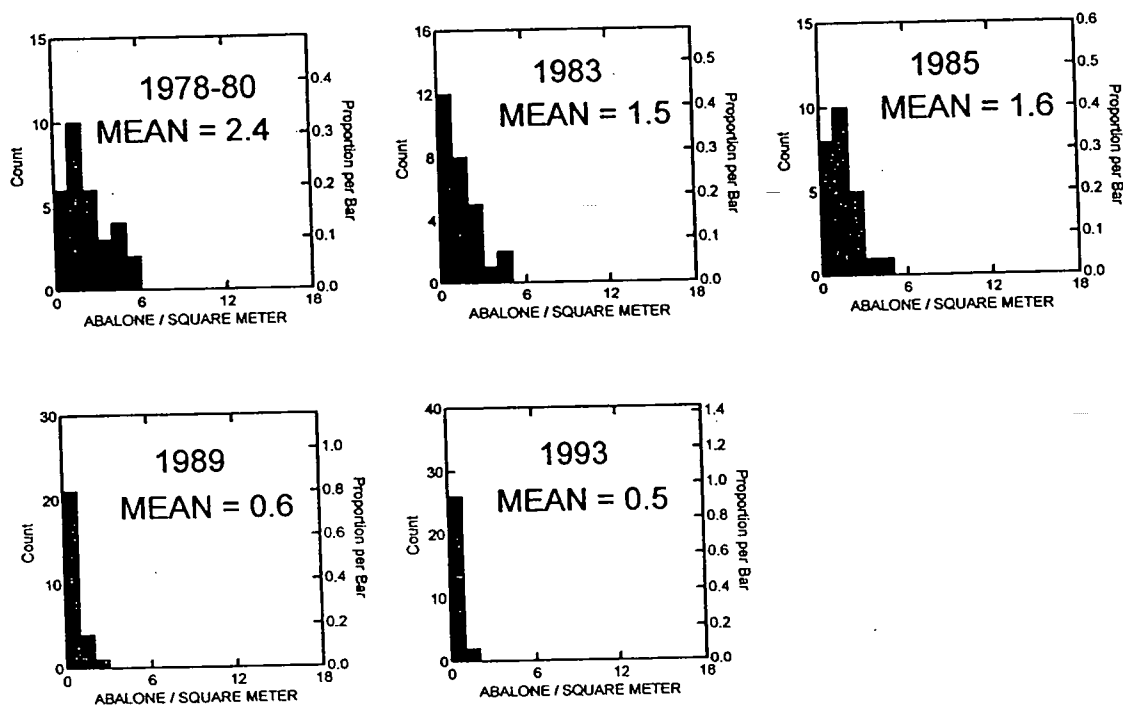


Fig. 1 Frequency distributions of samples with different densities (number per square meter) of total northern abalone (all sizes) from all sites of each Queen Charlotte Island and Central Coast survey during 1978-1994.

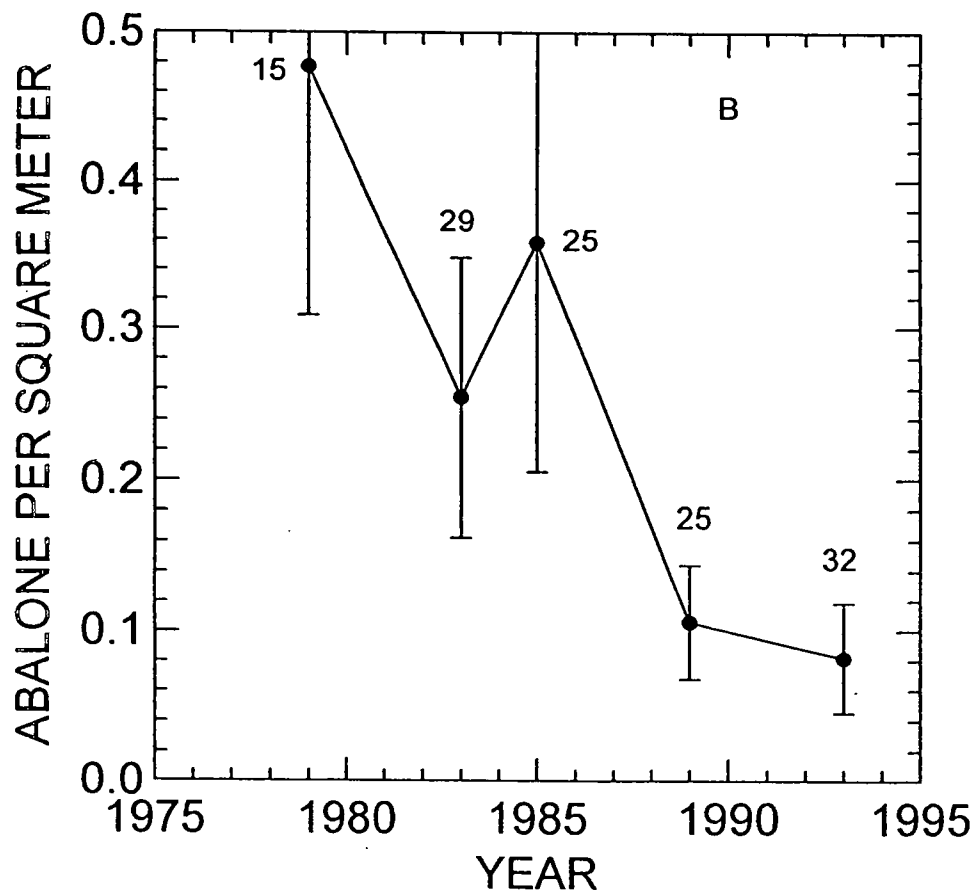
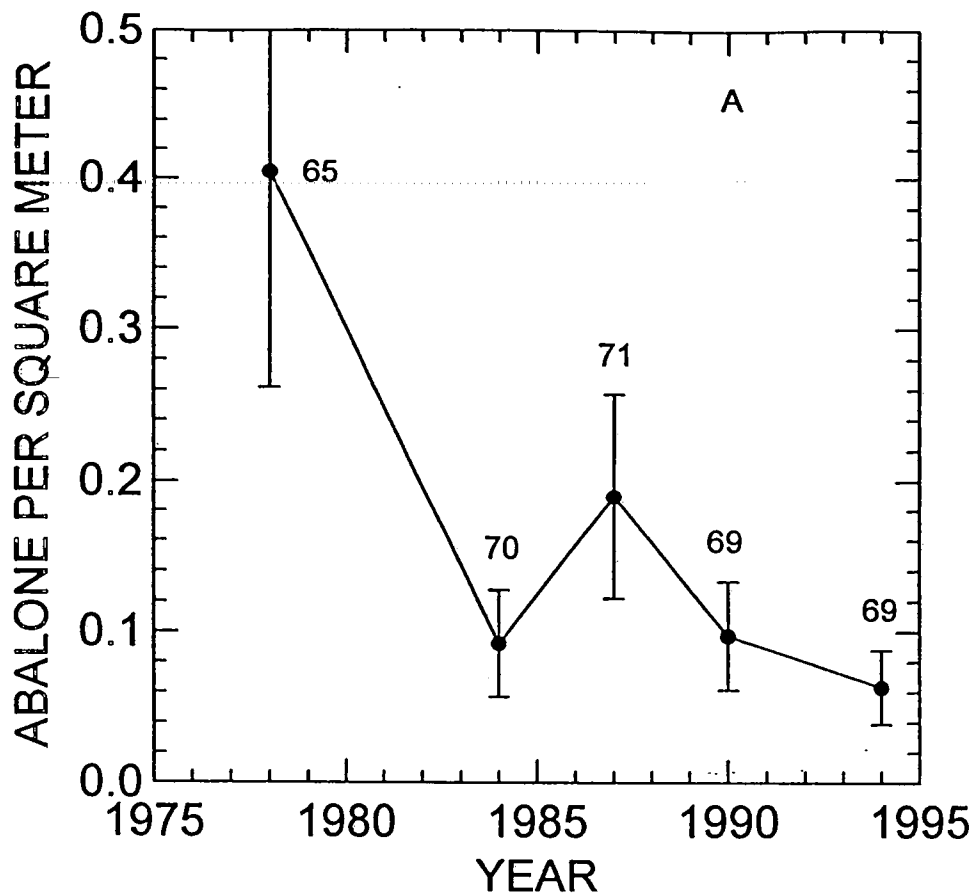


Fig. 2 Mean density of legal (≥ 100 mm SL) northern abalone from surveys in the (A) Queen Charlotte Islands (after Winther et al. 1995) and (B) Central Coast of B.C. (after Thomas and Campbell 1996). Vertical lines are approximate 95% confidence intervals (± 2 S.E.). Numbers near dots indicate the number of sample sites.

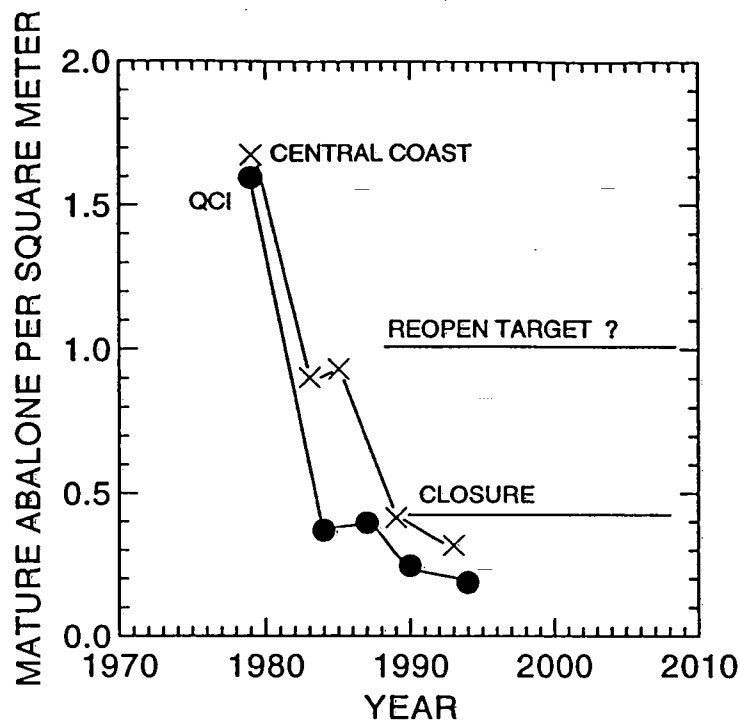


Fig. 3 Mean density of "mature" abalone (≥ 70 mm SL) from surveys in the Queen Charlotte Islands (after Winther et al. 1995) and Central Coast of B.C. (after Thomas and Campbell 1996). The reopen density target was arbitrarily set at slightly higher than 50% of peak densities during the 1970s.

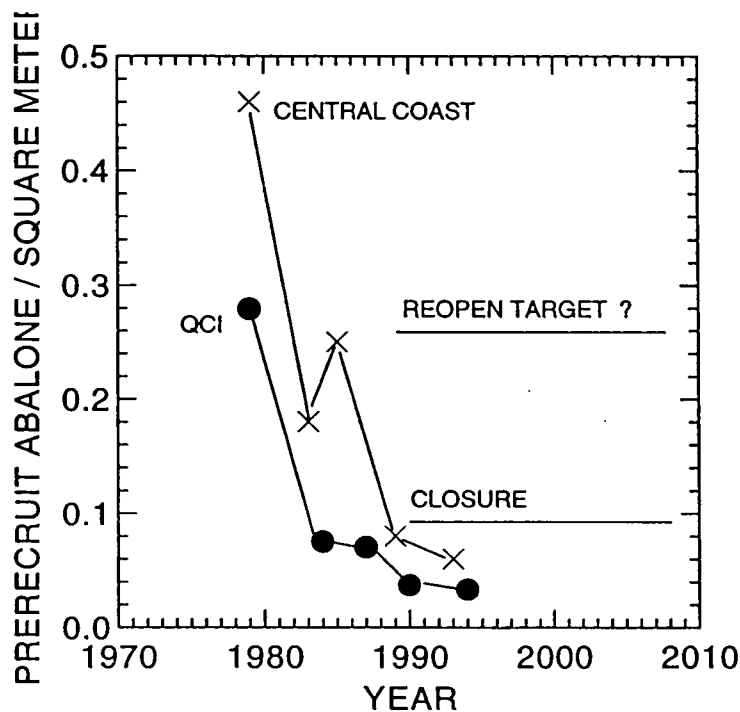


Fig. 4 Mean density of prerecruit northern abalone (92-99 mm SL) from surveys in the Queen Charlotte Islands (after Winther et al. 1995) and (B) Central Coast of B.C. (after Thomas and Campbell 1996). The reopen density target was arbitrarily set at slightly higher than 50% of peak densities during the 1970s.

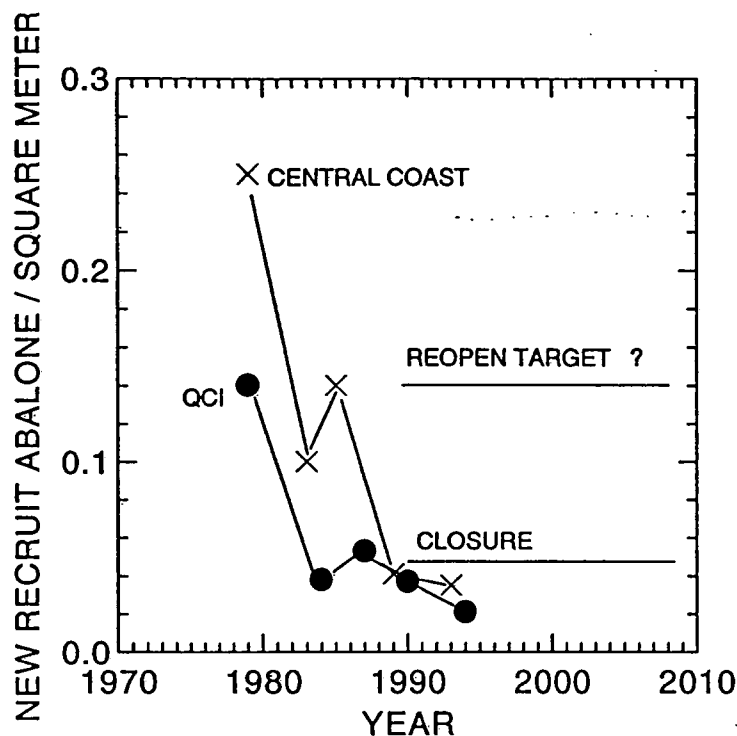


Fig.5 Mean density of new recruit northern abalone (100-106 mm SL) from surveys in the Queen Charlotte Islands (after Winther et al. 1995) and Central Coast of B.C. (after Thomas and Campbell 1996). The reopen density target was arbitrarily set at slightly higher than 50% of peak densities during the 1970s.

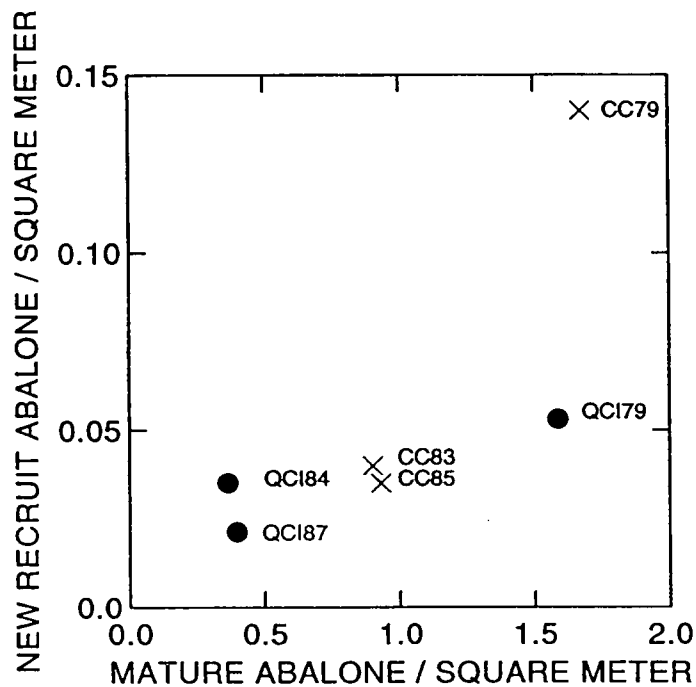


Fig. 6 Relationship between "mature" (≥ 70 mm SL) and estimated new recruit (100-106 mm SL, eight years later) northern abalone densities from surveys in the Queen Charlotte Islands (after Winter et al. 1995) and Central Coast of B.C. (after Thomas and Campbell 1996). The numbers associated with the survey location indicate the year of the survey for the "mature" northern abalone densities (e.g. QCI84=Queen Charlotte Islands 1984 survey) associated with new recruit northern abalone densities from the same area eight years later.

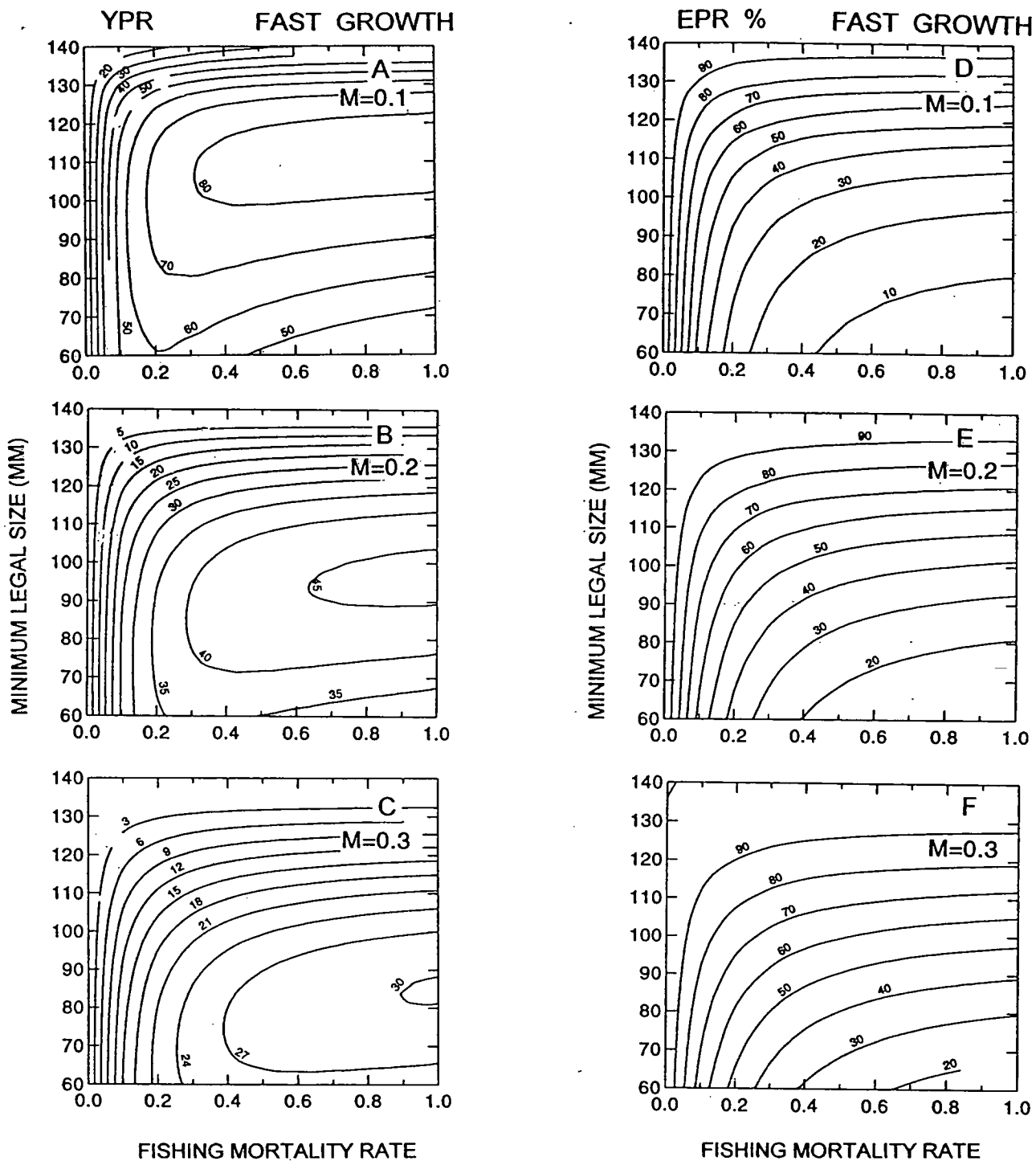


Fig. 7 Yield per recruit (g) and egg per recruit (percentage of total eggs produced by an unfished population) analyses for the northern abalone using fast growth parameters and different natural mortality rates (A and D) $M=0.1$, (B and E) $M=0.2$ and (C and F) $M=0.3$, respectively. See text, Appendix 1 and Table 7 for explanation and parameters used in the analyses.

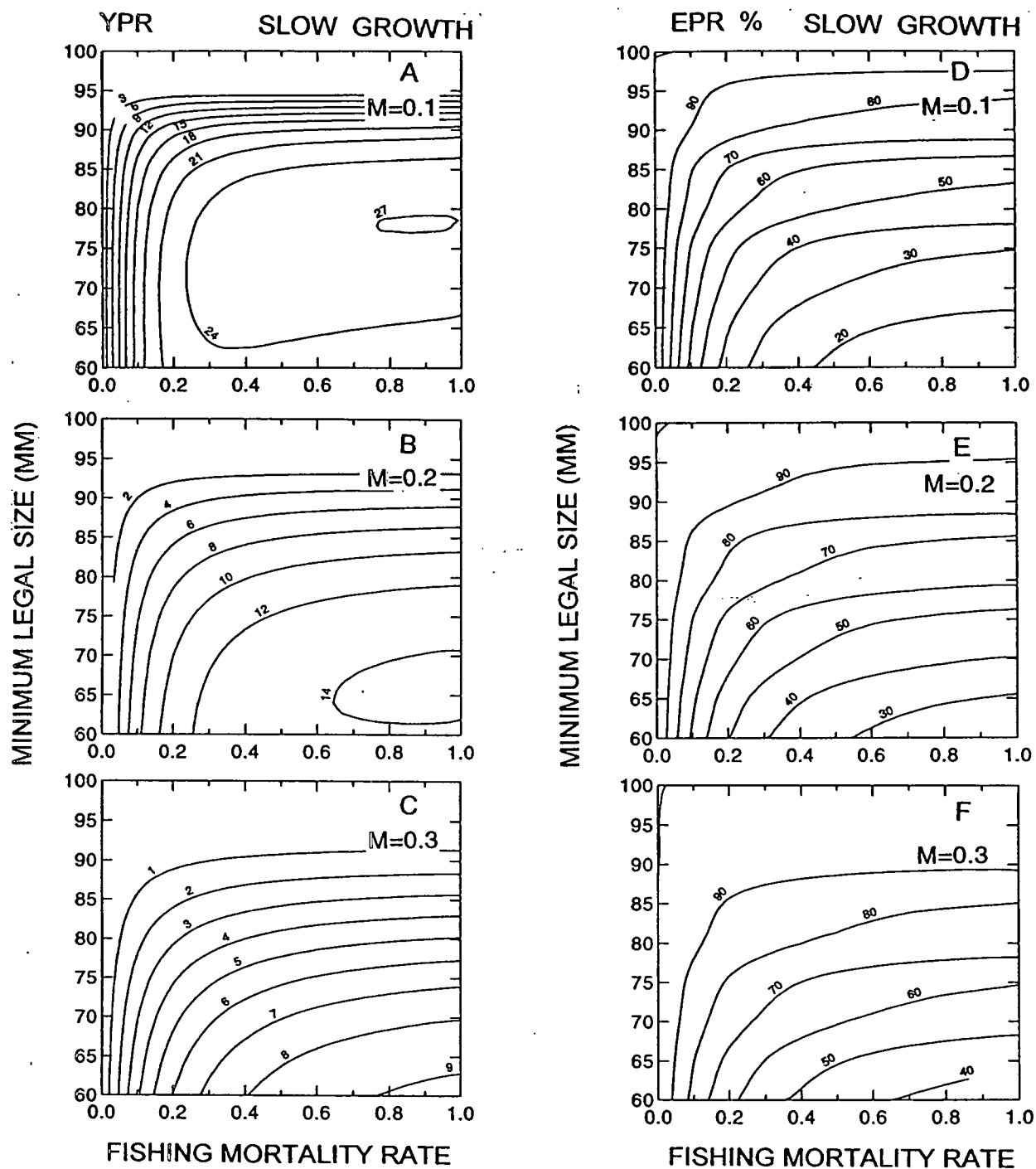


Fig. 8 Yield per recruit (g) and egg per recruit (percentage of total eggs produced by an unfished population) analyses for the northern abalone using slow growth parameters and different natural mortality rates (A and D) $M=0.1$, (B and E) $M=0.2$ and (C and F) $M=0.3$, respectively. See text, Appendix 1 and Table 7 for explanation and parameters used in the analyses.

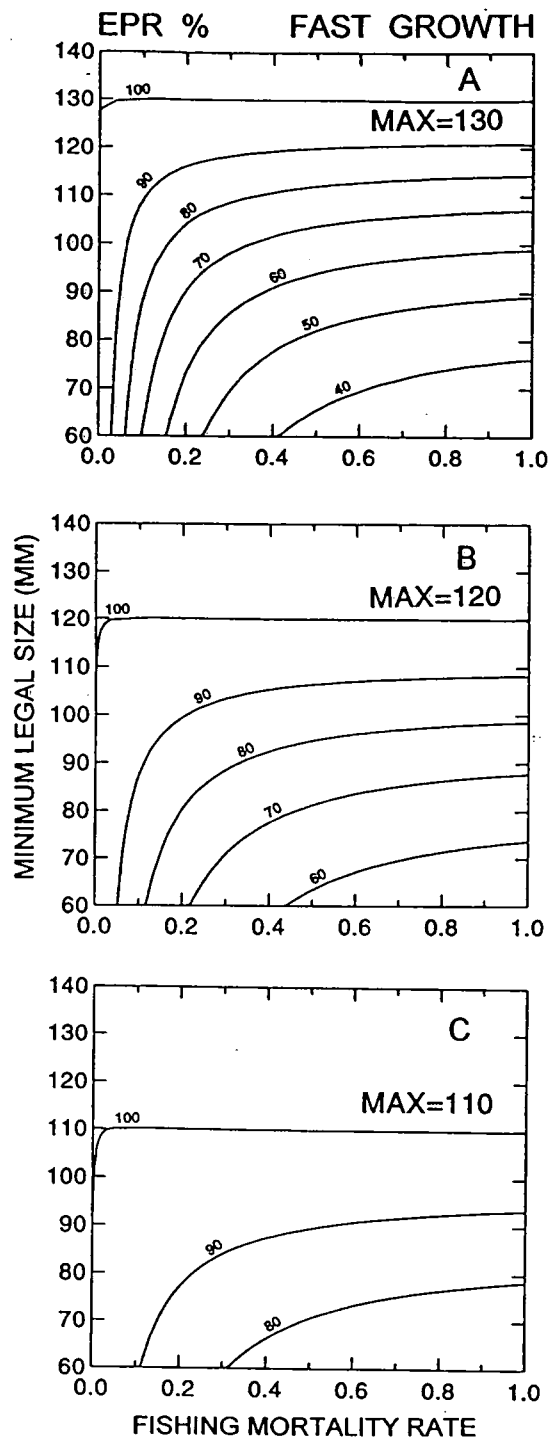


Fig. 9 Egg recruit (percentage of total eggs produced by an unfished population, i.e., 68.75×10^8 eggs, see Table 7) analyses for the northern abalone using fast growth parameters, $M=0.2$ and different maximum legal sizes (A) 130 mm SL, (B) 120 mm SL and (C) 110 mm SL. See text, Appendix 1 and Table 7 for explanation and parameters used in the analyses.

ERRATA

Campbell, A. 1997. Possible criteria for reopening the Northern abalone (*Haliotis kamtschatkana*) fishery in British Columbia. DFO Can. Stock Assess. Sec. Res. Doc. 97/64

Page 4: line 10, "1908" should read "1980".

Page 14 line 21, " $M = 0.02$ " should read " $M = 0.20$ ".