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Assessment of Green Sea Urchin *(Strongylocentrotus droebachiensis)* Stocks in British Columbia, 2003.

Évaluation des stocks d'oursin vert (*Strongylocentrotus droebachiensis*) en Colombie-Britanique en 2003.

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ABSTRACT

This paper *(i)* provides an analysis of the green sea urchin fishery in British Columbia by updating information from the 2001 and 2002 fishing seasons; (*ii*) provides analyses and recommendations for limit and target reference points for the 2003-2004 and 2004-2005 fishing seasons; and (*iii*) presents results from fishery-independent surveys of green sea urchins conducted in B.C., Canada. Reference points are determined using biomass dynamic models applied to the core stocks in the B.C. south coast: Queen Charlotte Strait (Pacific Fisheries Management Areas 11-13) and the Gulf Islands (PFMA 17-20,28). Two methods are used to determine the parameters of these models: a linear approximation to the dynamic Schaefer model and a time series fitting method. For both core stocks, both models produce similar (i.e. overlapping 95% confidence intervals) estimates of the maximum sustainable yields (MSY). The time series fitting method produces a lower MSY with narrower confidence intervals for the smaller stock (Gulf Islands region), and it is recommended as the more conservative method for calculating reference points. The calculated MSYs are recommended as limit reference points. A Bayesian approach to a state-space model is developed to incorporate uncertainties in both the observations from the fishery and in the specification of the surplus production model, and to include information from the fishery-independent surveys. The result of this model is a probability distribution for MSY which can be used to assist with the choice of target reference points (TRPs) for this fishery. Target reference points for both core regions in the south coast combined are in the range of 101.5 to 203.1 t. Target reference points in this range have a low probability (1.4 – 12.7%) of including the actual MSY (the limit reference point), according to the Bayesian model developed here. Fishery-independent surveys have been conducted annually since 1995 at index sites in Area 12 (Queen Charlotte Strait) and indicate that the biomass of green urchins in this area in 2001 and 2002 was among the highest observed for legal-sized urchins.

RÉSUMÉ

Ce document présente *(i)* une analyse de la pêche de l'oursin vert en Colombie-Britannique fondée sur la mise à jour des données pour les saisons de pêche 2001 et 2002, (*ii*) des analyses et des recommandations en matière de points de référence limites et cibles pour les saisons de pêche 2003-2004 et 2004-2005 et (*iii*) les résultats de relevés de l'oursin vert indépendants des pêches effectués en C.-B. Les points de référence sont déterminés à l'aide de modèles de la dynamique de la biomasse appliqués aux principaux stocks de la côte sud de la C.-B. : celui du détroit de la Reine-Charlotte (secteurs d'exploitation des pêcheries du Pacifique 11 à 13) et celui des îles Gulf (secteurs d'exploitation des pêcheries du Pacifique 17 à 20 et 28). Les paramètres de ces modèles sont déterminés par deux méthodes : une approximation linéaire du modèle dynamique de Schaefer et une méthode d'ajustement de série chronologique. Les deux modèles donnent des estimations semblables (c.-à-d. que leurs intervalles de confiance à 95 % se chevauchent) du rendement équilibré maximal (REM) pour les deux stocks principaux. La méthode d'ajustement de série chronologique donne un REM moindre et un intervalle de confiance plus restreint pour le plus petit stock (région des îles Gulf), et elle est recommandée comme la méthode la plus conservatrice pour calculer les points de référence. L'établissement des REM calculés comme points de référence limites est conseillé. Une approche bayésienne est mise au point pour résoudre un modèle espace-état afin d'intégrer les incertitudes entourant les données de pêche et les caractéristiques du modèle de production excédentaire, ainsi que l'information tirée des relevés indépendants des pêches. Le résultat de ce modèle est une distribution de probabilité pour le REM

qui peut être utilisée pour faciliter le choix de points de référence cibles pour cette pêche. Les points de référence cibles pour les deux principales régions de la côte sud sont de l'ordre de 101,5 à 203,1 tonnes. D'après le modèle bayésien, le REM réel (point de référence limite) a peu de chance (de 1,4 à 12,7 %) de se retrouver dans cet intervalle. Selon les relevés indépendants des pêches effectués chaque année depuis 1995 à des sites indicateurs dans le secteur 12 (détroit de la Reine-Charlotte), la biomasse d'oursins verts de taille légale dans ce secteur en 2001 et en 2002 compte parmi les plus élevées jamais observées.

INTRODUCTION

Commercial harvesting for green sea urchins, *Strongylocentrotus droebachiensis*, in British Columbia began in 1987. The fishery was managed with few restrictions until 1991, when licence limitation was introduced to control record high effort and catches, followed by quota limitations in 1994 and an individual quota system with dockside validation in 1995. Previous stock assessments were conducted by Harbo and Hobbs (1996), Perry *et al*. (1998), Perry and Waddell (1998, 1999), Perry *et al*. (2001) and an overview paper was published in 2002 (Perry *et al*. 2002). The Request for Working Paper prepared by the Fishery Manager for this fishery is included as Appendix I. The objectives for this paper as outlined in the Request for Working Paper are: *i*) calculation of green sea urchin harvest quotas in all areas for which data are available; *ii*) incorporation of relevant information from recent green urchin surveys; and *iii*) presentation of biological data collected from commercial fishery sampling. Accordingly, the objectives of the current assessment are to:

1) provide an analysis of the green sea urchin fishery in British Columbia by updating the historical sales slip, harvest logbook, and port validation information with data from the November 2001 - March 2002 and November 2002 – March 2003 fishing seasons;

2) provide recommendations for harvest yields for the 2003-2004 and 2004-2005 fishing seasons; and

3) present results from fishery-independent surveys of green sea urchins.

Problems which have been identified in previous green urchin assessments for British Columbia include uncertainties with the catch per unit of effort (CPUE) data which are used as the major input data for the assessment, and uncertainties about the risks associated with selection of "arbitrary" reductions of MSY to identify Target Reference Points (i.e. are the proposed reductions from MSY to determine the target reference points "sufficiently precautionary"?). This present assessment attempts to improve on both of these issues by developing an assessment model which includes uncertainties in both the input observations and the model structure, and which uses fishery-independent survey data, to identify the probabilities that various values of target reference points might include the limit reference point.

BIOLOGY AND FISHERY BACKGROUND

Biology

Green sea urchins occur in cool temperate waters in both the Pacific and Atlantic Oceans. They are circumpolar in the Pacific, occurring from northern Washington State through the Aleutian Islands and west to Hokkaido and Korea. Recent analyses are indicating that green urchins (*S. droebachiensis*) from the North Pacific and North Atlantic are very similar genetically, and genetically very similar to the white urchin *S. pallidus* (Biermann 2003). Green urchins occur inter-tidally and to depths of >140 m, generally on rocky, gravel or shell substrates. Sexes are separate, with sizes at maturity of 25 mm in the Atlantic (Miller and Mann 1973) and 35-45 mm in Alaska

(Munk 1992). In B.C., the spawning period generally occurs during February and March. Larvae are pelagic for 9-10 weeks depending on temperature (Strathmann 1978) and in the Atlantic the upper temperature limit for larval development is 10°C. Green urchin growth rates vary considerably depending on food availability, with rates of 1 cm yr^{-1} recorded for the Strait of Georgia (Foreman and Lindstrom 1974) and slightly >1 cm yr^{-1} in Alaska (Munk 1992). On the Atlantic Coast, growth rates may be as low as 1-2 mm yr^{-1} under food-limited conditions (Himmelman 1986). It takes about 4 years (Munk 1992) for a green urchin to reach a test diameter of 55 mm (the minimum legal size in B.C.). Maximum test diameters can be >100 mm. Ageing of green sea urchins using rings on the coronal test plates and the rotules (components of Aristotle's lantern) has indicated that animals from the Bay of Fundy on the Atlantic Coast may be up to 20-25 years old (Robinson and MacIntyre 1997). Green sea urchins appear to be more mobile than red sea urchins, and with patchy distributions. They may undertake deep-shallow migrations. Occasional large-scale mortalities of green sea urchins along parts of the Atlantic Coast of Nova Scotia between 1992 and 1995 have been linked to a marine amoeba, *Paramoeba invadens*, whose prevalence appears to be enhanced by water temperatures >10°C (Scheibling and Hennigar 1997). This amoeba has not been observed on the Pacific Coast of Canada to date.

Fisheries

British Columbia

The fishery in B.C. developed rapidly, with landings reaching a peak of 978 t and a landed value of 4.4 million dollars in 1992, followed by a sharp decline. It is conducted by divers, and is principally a roe fishery whose product is landed and shipped live to the Japanese market. The fishery for green sea urchins is conducted during winter, with the highest market prices occurring around Christmas. It is managed with a 55 mm test diameter lower size limit, licence limitations and, beginning in 1995, with area quotas, individual quotas, and area closures. Management actions since the inception of the fishery are summarised in Table 1. Submission of sales slips and harvest logbooks are conditions of licence. In previous assessments (Perry *et al*. 1998; Perry and Waddell 1998, 1999; Perry *et al*. 2001), the analyses were conducted on a "fishing season" basis) (i.e. from the fall of one year to the spring of the following year). Accordingly, the licence year is defined as from 1 June to 31 May. The fishery is conducted by SCUBA divers using small vessels due to the patchy distribution of the resource. In the early 1990's, the fishery expanded to remote locations with the addition of packer vessels (Harbo and Hobbs 1996). However, this practice stopped when fishing was restricted to the two core areas (see below). Fishers report that their fishing practices changed as a result of quota restrictions in the mid-1990's and market demands for high quality roe (i.e. they now spend more time searching for high quality roe than was done at the start of the fishery). The North Coast fishery suffered from poor roe yields and quality (Harbo and Hobbs 1996); there has been very little fishing in the North since 1997.

Previous assessments (Perry *et al*. 1998, 2001; Perry and Waddell 1998, 1999) recommended separating green sea urchin populations on the B.C. coast into four broad "stocks", rather than assuming a single continuous population. The present assessment follows this recognition of four stocks [B.C. North Coast (Pacific Fishery Management Areas 1-10); South Coast - inside waters northern component (PFMA 11-16); South Coast - inside waters southern component (PFMA 17-20, 28, 29) (Fig. 1); and the west coast of Vancouver Island]. We justify this on the basis of the expected duration of the planktonic larval stages (1-2 months at prevailing winter-spring temperatures of 6-

10°C; e.g. Hart and Scheibling 1988) and the general circulation of B.C. inside waters. Thomson (1981) indicates that the northern Strait of Georgia has a weak circulation (except for the strong tidal currents near Seymour Narrows) with a possible counter-clockwise pattern; this should separate the two components of the South Coast - inside waters. Thomson (1994) cites the results of estimates of the winter flushing time for the Strait of Georgia as 3-6 months, sufficiently longer than the expected larval duration of green urchins. However, there may be greater exchange of larvae between the South Coast - inside waters southern component and the west coast of Vancouver Island.

Other jurisdictions
Fisheries for green sea urchins occur on the Atlantic coast of Canada and in Maine, Alaska, and Washington states. In addition, significant new fisheries have recently developed along the Pacific coast of Russia, whose large volume of sales to Japan have depressed prices for green urchins worldwide. In Alaska, green urchins are allowed to be harvested commercially only in the Central and Westward regions. The fishery in the Westward (e.g. Kodiak) region began in 1986 and peaked in 1988 with 87 t harvested. In recent years the Kodiak harvest has been small (11 t combined from 1997-2001) with very few divers participating (Ruccio and Jackson 2002). The Alaska Department of Fish and Game has established low Guideline Harvest Levels (GHLs) which allow for exploration and development of the green urchin fishery. The GHL for the Kodiak District in 2002/2003 was set at 30 t. Management regulations include hand-picking by divers as the only legal method of harvest, a season that lasts from 1 October to 31 January, and an "acceptable" minimum size limit of 53 mm. In Washington State, the green urchin fishery takes place in the Strait of Juan de Fuca, mostly in the San Juan Islands and Port Angeles areas. It peaked in 1993 at greater than 544 t, but then declined in 2000 to its lowest level (about 45 t) since the fishery began in 1986. Preliminary landings for the current season (up to 21 May 2003) are estimated at 80 t (http://www.wa.gov/wdfw/shelfish/divereg, accessed 30 May 2003). Fishing is permitted by dive gear only and may be harvested only from waters deeper than 3 m (10 feet) below mean lower low water. The non-Indian green urchin quota for the 2002-2003 fishing season was set at 113 t. In Maine, the green sea urchin fishery currently ranks fourth in the value to the state of fishery resources. Commercial landings peaked in the late 1980's at greater than 22,000 t, but declined to less than 5,000 t in 2001. The fishery is managed with limited entry, and minimum (52 mm) and maximum (76 mm) size limits. Chen and Hunter (2003) have conducted a stock assessment of this fishery using a length-based model, and determined that the current stock size is about 10% of the virgin stock, with an exploitation rate of close to 40%.

In Nova Scotia, landings of green sea urchins were on the order of 900 t in 2000. Management is with a minimum size limit of 50 mm, harvesting by divers only, and with two types of licenses: full-time, and exploratory. The primary regulatory tool is restriction of the number of fishing licenses per geographic area of coastline, so that the fishery is managed by "individual restricted zones", with one licensee per area (DFO, 2000a). Catch per unit of effort is not considered as a good index of stock size for this fishery because the restricted zones allow fishermen to plan for nearly uniform harvests (DFO, 2000a). Disease is believed to be the major threat to this fishery and has been estimated to have killed 10 to 100 times the weight of urchins harvested by the fishery (DFO, 2000a). In Quebec, the green sea urchin fishery has had modest landings (less than 20 t in each of 1998 and 1999; DFO, 2000b). It is managed by a 50 mm minimum size limit, prohibition of the use of towed gears, and limiting the number of fishing licenses per area. It is considered as a developing fishery (DFO, 2000b).

METHODS

All analyses in this current assessment are presented on a "fishing season" basis, defined as 1 June of year i to 31 May of year i+1; in practice for the recent years of the fishery this reduces to 1 October of year i to 31 March of year i+1. A "fishing season" is denoted by the year fishing started (e.g. the 1997 fishing season includes 1 October 1997 to 31 March 1998).

Basic information on landings (L) and landed values are derived from sales slip information as collected by the Catch and Effort Unit of the Regional Data Unit of the Information Management Division (DFO, Vancouver). Detailed information on catch, effort, depth and locations fished for all fishing seasons (1987-2002) are provided in the fishers' harvest logbooks, which are completed as a condition of licence. Since landings in the harvest logbooks for the fishing seasons from 1988 to 1990 represent <90% of the saleslip landings (see Results - The Fishery, below), total effort (E_{Ti}, in diver hours) in fishing season i (i = 1988, 1989, 1990) was estimated as saleslip landings (S_i) divided by the catch per unit of effort (U_{Mi}) from the harvest logbook database

(1)
$$E_{Ti} = \frac{S_i}{U_{Mi}}.$$

Previous assessments used the median annual catch per unit of effort (U_{mi}); justification for the use of the median CPUE is provided by the analysis of Perry and Waddell (1998). Values of catch per unit of effort calculated from individual harvest logbook records showed many high outliers in every fishing season. Some of these outliers undoubtedly result from errors in the harvest logbooks, for example, when the same number of hours fished is entered for every dive over several days of fishing. To reduce the influence of these outliers, the median catch per unit of effort (U_{Mi}) was calculated. In every fishing season, the median U_{Mi} provided the lowest estimate of catch per unit of effort compared with other methods of estimating CPUE (Perry and Waddell, 1998). The time trends were similar amongst all the three estimates examined. The median U_{Mi} and its standard error were chosen as a robust estimator of catch per unit of effort, and was calculated as

(2)
$$U_{Mi} = \text{median}_i\left(\frac{c_{ij}}{e_{ij}}\right).$$

with c_{ij} and e_{ij} representing the catch (c) and effort (e) for year i from harvest logbook records (j) with non-zero entries for effort, as a robust measure of CPUE. This practice is continued in the present assessment. The standard error of the median (se_{Mi}) was calculated as 1.2533*se_i (Sokal and Rohlf 1981, p. 139), with se_i the standard error of the annual mean catch per unit of effort as calculated from individual logbook records.

Area 13 was divided into two quota areas, 13A and 13B, at the start of fishing season 2001-2002. Quota area 13A is comprised of subareas 13-1 to 13-27, and quota area 13B is comprised of subareas 13-28 to 13-43. This split was made in an effort to spread the fishing effort out more evenly, as subareas near Campbell River (in particular 13-28 and 13-32) had been targeted heavily in past fishing seasons.

Biomass Dynamic Model

Schnute version

Development of a biomass dynamic production model followed the approaches outlined in Schnute (1977), Polovina (1989) and Hilborn and Walters (1992). Schnute (1977) developed a linear approximation to the dynamic Schaefer production model as:

(3) $$\ln\left(\frac{U_i}{U_{i-1}}\right) = r - q\left(E_{i-1} + E_i\right)/2 - \left(\frac{r}{qk}\right)\left(U_{i-1} + U_i\right)/2 \ .$$

with U_i the catch per unit of effort for year *i* (here using U_{Mi}), E_i the effort for year *i* (using E_{Ti} for 1988-1990), *r* the intrinsic rate of population increase of biomass, *q* the catchability coefficient, and *k* the unexploited biomass. This equation can be represented as a regression of the form:

(4) $$Y_i = \alpha + \beta X_i + \gamma Z_i + \varepsilon_i$$

with

$$Y_i = \ln\left(U_i/U_{i-1}\right)$$
$$X_i = \left(E_{i-1} + E_i\right)/2$$
$$Z_i = \left(U_{i-1} + U_i\right)/2$$

and ε_i a lognormal error term. The parameters α, β, and γ are then equal to *r*, *-q*, and *-r/(qk),* respectively. Solutions to this regression equation were calculated using S-Plus.

Once *r, q*, and *k* are known, the traditional Schaefer model under equilibrium conditions with C_i the expected catch, is represented as:

(5) $$C_i = qkE_i\ (1 - (q/r)E_i\ ) \ .$$

Hilborn and Walters (1992) provide the following summary of management parameters once the parameters of the Schaefer model have been determined:

Maximum surplus yield (MSY)	$rk/4$
Stock size for MSY	$k/2$
Rate of exploitation at MSY	$r/2$
Effort required to achieve MSY	$r/2q$

Approximate 95% confidence intervals about MSY were calculated as described by Schnute (1977, 1989).

Since 1995-96, all fishing plans have restricted fishing in the South Coast to the core fishing areas (PFMA 11,12,13; 17-20, 28). Since the 1999 fishing season, these core areas have been reduced further to PFMA 11-13 and PFMA 18-20. Since 2001, Area 20 has been opened to fishing only upon completion of a pre-fishery survey, which did not occur in 2001. Therefore, this area was closed in 2001 and 2002. However, to be consistent with the analyses of previous assessments, the current assessment uses data from PFMA 11-13 and 17-20,28 for all years for the biomass dynamic production model. Historically, these core areas have contributed >90% to the coastwide landings of green sea urchins in B.C.

Time-series fitting version

A time series version of the biomass dynamic model has been developed (Pella and Tomlinson 1969) and has been recommended by Hilborn and Walters (1992) as providing a better fit to data than other methods. Hilborn and Walters (1992) also recommended evaluation of different formulations of biomass dynamic models as a check on the performance (and assumptions) of these models. The basic equations for fitting the time series version of the surplus production model are:

$$\hat{B}_{i+1} = \hat{B}_i + r\hat{B}_i(1 - \frac{\hat{B}_i}{k}) - C_i \tag{6}$$

$$\hat{U}m_i = q\hat{B}_i \tag{7}$$

with C_i the observed catch, $\hat{U}m_i$ and $\hat{B}_i$ the predicted median catch per unit effort and biomass at year i, and q, r, and k the parameters of the surplus production model, as described above. We also assume that the error for the observed median CPUE (Um_i) is multiplicative and log-normal with a constant coefficient of variation:

$$Um_i = \hat{U}m_i e^{\varepsilon} = q\hat{B}_i e^{\varepsilon}, \qquad \varepsilon \sim N(0;\sigma^2) \tag{8}$$

and that the biomass at the first year of the fishery is equal to the unexploited biomass. The estimates of the model parameters (*q, r, k),* biomass *(*B_i), and CPUE ($\hat{U}m_i$) are obtained by adjusting various combinations of *q, r, and k* until the following likelihood function is maximized:

$$L = \prod \frac{1}{\sqrt{2\pi}\hat{\sigma}} \exp\left(\frac{-\left(\ln(Um_i) - \ln(\hat{U}m_i)\right)^2}{2\hat{\sigma}^2} \right) \tag{9}$$

where $\hat{\sigma}$ is the estimated standard deviation of the errors for the observed CPUE data

$\hat{\sigma}^2 = \sum \frac{(\ln(Um_i) - \ln(\hat{U}m_i))^2}{n}$ (n is the number of years for which CPUE data are available). Parameter values causing the population to go extinct before 2002 were not considered.

After obtaining the model parameters, 1000 sets of simulation data were generated using the Monte Carlo simulation technique. CPUE was reproduced for each set of the simulations according to a probability distribution (log-normal), the standard deviation of which was estimated based on the original data (see Equation 9). Each set of simulated data was used to produce estimates of the model parameters. Thus, there were 1000 estimates of the model parameters, which provided a probability distribution for each parameter and for MSY.

Bayesian model
New in this assessment this year is an attempt to incorporate the uncertainties associated with the use of CPUE as the main input data to these models and an attempt to identify the probability that any selected target reference point may in fact include the limit reference point. In this terminology, MSY is defined to be the limit reference point, with the target reference point being, for example, a recommended quota option.

A Bayesian model was constructed which included uncertainties in both the observations ("observation error") and in the model structure ("process error"). This improves upon the two models discussed above because the Schnute version includes only process uncertainties, whereas the time-series method includes only observation uncertainties. This new model also incorporate the observations from fishery-independent surveys conducted collaboratively by DFO and industry in the Queen Charlotte Strait region (PFMA 11-13) to help "tune" or constrain the model. In this sense, the results of these surveys, in particular their interannual variability, are considered to be representative of the variability throughout the entire management areas of which the survey locations are a part. Data from the fisheries-independent surveys conducted in the Gulf Islands (PFMA 17-20,28) were not used for the Gulf Islands Bayesian model as these data had insufficient coverage (numbers of transects) to be representative of that entire region. Catch and effort data from the early years of the fishery (1987 – 1995) are very uncertain, because of the boom nature of the fishery (Fig. 4), variable recording diligence, and different strategies of fishing. These uncertainties were also incorporated into the Bayesian analysis. A Bayesian model allows for the use of prior knowledge to help define "reasonable" distributions for the range of values for each parameter. For example, if a particular value between *x* and *y* is most likely (e.g. the mean), then the prior distribution could be represented by a normal curve centred on this mean value. Bayes theorem provides an approach by which prior probability distributions are updated to posterior probability distributions using observed data. The posterior probability distribution reflects the likelihood of various possible values for an estimated parameter such as MSY. The details of the Bayesian analysis used in this assessment are provided in Appendix 2; an example of a general application of Bayesian decision analysis to developing fisheries is provided by Mcallister and Kirkwood (1998).

Biological Subsampling of Landings

Dockside sub-sampling of the landings of green sea urchins was begun in 1996/97 in order to determine the sizes of animals landed and their variation among fishing areas. Dockside validators measured the test diameters of 25 green urchins from every landing. The harvest date and location were also recorded for each measurement.

Fishery-independent Surveys

Fishery-independent surveys have been conducted to obtain biological and population information on green sea urchins in B.C. independent of the commercial fishery. These are small localised surveys designed to develop working relationships with industry and native fishery interests and to provide biological information from a part of the core fishing areas. In the present assessment, they are also used to help "tune" the Bayesian analysis. In the Queen Charlotte Strait region, surveys have been conducted annually (or more frequently) since 1995. Waddell *et al*. (1997, 2002, 2003) provide detailed reports of the methods and results for the first three sets of surveys (October 1995 and March 1996; November 1996 and February 1997; and November 1997 and March 1998). Reports of the other surveys are in preparation.

These surveys are located in PFMA 12, at the intersection of subareas 5,6, and 18 in eastern Queen Charlotte Strait. Specific locations are the Stephenson Islets (50°34.5′ N, 126°49.5′ W), Stubbs Island, and the NW sector of the Plumper Group (Fig. 2). Stephenson Islets was identified by the fishing industry as a key, first-choice location for harvesting of green urchins. Fishery-independent surveys have been conducted less regularly in the Gulf Islands region, starting in 1997 in Active Pass but expanding to six additional locations in 1999 and 2000 (Fig. 3), although only two locations were surveyed in 2001 and one in 2002. In the Gulf Islands region, East Point on Saturna Island was considered to be the major fishing ground for green urchins.

On each survey, the transect-quadrat technique was used, with quadrats (1 m^2) sampled along each transect by divers working from deep to shallow. Green urchins were counted and test diameters measured on all surveys. Subsamples were collected for measurements of weight and gonad condition. The mean densities of legal (≥55 mm test diameter) and sub-legal (<55 mm) green urchins were calculated for each study site using the procedures of Jamieson and Schwarz (1998)

(10)
$$\overline{D}=\frac{\sum_{i=1}^{n} N_i}{\sum_{i=1}^{n} L_i}$$

with standard error

(11)
$$SE(\overline{D})=\sqrt{\frac{1}{\overline{L}^2}\frac{1}{n}\frac{\sum (N_i-L_i(\overline{D}))^2}{n-1}}$$

in which n = the number of transects sampled in a study site, N_i = the total number of green urchins found in transect i, i = 1,2,...n, L_i = the total number of quadrats in transect i, and the average area of the transects is represented as

(12)
$$\overline{L}=\frac{1}{n}\sum_{i=1}^{n} L_i$$

On average during each survey, there have been 10 transects sampled in the Stephenson Islets area, 3-4 around Stubbs Island, and 4-6 transects in the Plumper Group. Only 2-4 transects were generally sampled at each Gulf Islands location due to time and tide constraints. For repeat surveys, the same locations were sampled on each survey, but not the exact same transects as the divers' path underwater varied somewhat each time. The total number of urchins in each location was calculated by multiplying the density (D) by the area of the location, with this latter being defined by fishing logbook records (and calculated from chart datum to 10 m below chart datum using ArcView software). This density was converted to a biomass of legal and sub-legal sized urchins using test diameter – weight relationships determined from laboratory analyses of subsamples of urchins collected on each survey (e.g. see Waddell *et al*. 1997, 2002, 2003).

Exploratory Fishing Protocol

An exploratory fishing protocol was developed in collaboration with the fishing industry to begin to provide information on green sea urchin aggregations and abundances in areas outside of the normal core fishing locations. Briefly, exploratory fishing was to be conducted by licensed industry vessels, which were allowed to sell their catch in the normal manner. For the South Coast, the catches were considered to be additional to the established quota since the protocol was not available for areas open to fishing in the 1995-1996 fishing season. Each vessel was required to have a DFO authorised observer on-board at all times while fishing, to make detailed observations of the fishery and to ensure that the exploratory protocol was followed. This protocol required prior identification by the fisher of the proposed fishing "sites", defined to have an area of 1 nmi^2. For any site, the maximum time for divers to be in the water was 16 diver hrs. Once this limit was reached, fishing in the current site was to cease. The intent of this regulation was to broadly limit effort on any particular aggregation of urchins, while still allowing for information on catch per unit of effort. No proposals to conduct exploratory fishing have been submitted since 1998.

RESULTS

The Fishery

The history of this fishery has been one of boom, bust, and recovery. Perry *et al.* (2002) identify three stages (Fig. 4; Table 2): a developing period (1986-1990) with increasing effort, landings, and value but declining CPUE; a crisis period (1991-1993) with peak effort and landings which then declined sharply, and a minimum in CPUE; and a rebuilding-to-sustainable period (1994-present) characterised by active management measures, stable effort and landings, and increasing CPUE. Landings since the 1994 fishing season have been limited by quotas. In fishing season 2001, total landings (123 t; Table 2) were only 68% of the total allowable catch (Table 1) as a result of low prices and market over-supply from Russia. In fishing season 2002, total landings (144 t) were 80% of the total allowable catch, for the same reasons. These do not appear to signal an inability to achieve quotas due to a lack of product. Landings by Pacific Fishery Management Area by fishing season reflect the areas open to fishing in seasons 2001 and 2002 (PFMA 12, 13, 18, and 19; Table 3a). Landings by statistical area by month for fishing seasons 2001 and 2002 (Table 4) indicate harvests occurred mostly in December in the Gulf Islands and January in Queen Charlotte Strait, apparently because of the depressed prices in other months and the rise in prices around Christmas and New Year's Day. Historical landings on the North Coast are presented in Table 3b; only one minor commercial fishing event has occurred in this region since 1995. Comparison of landings reported from sales slips versus harvest logbooks (Table 5) indicate that the logbooks recorded greater than 96% of the sales slip landings since 1991, that sales slips have substantially underestimated landings since 1995, and that in recent years saleslips have recorded less than 50% of the validated landings from harvest logbooks. Since 1995, the dockside validation records from the individual quota system have been used as the logbook records. Original logbooks underestimated landings from 1988 to 1990, therefore, the total effort for these years (as input into the biomass dynamic model) has been adjusted using equation 1. Currently, sales slip data are sufficiently unrepresentative of fishing activities as to be useless to this assessment.

The median catch per unit of effort by major fishing region shows declining trends with fishing season until 1992 in the South Coast - inside waters southern region (PFMA 17-20, 28) and 1993 in the South Coast - inside waters northern region (PFMA 11, 12, 13), and an increase since 1994 (Fig. 5). This increase has been sustained in both regions into the most recent fishing seasons. The standard errors about the medians are small.

Test diameters from commercial landings sampled in fishing seasons 2001 and 2002 were well above the minimum legal size of 55 mm, consistent with results from previous years (Fig. 6). Median diameters in PFMA 13 tended to be slightly smaller than those in Areas 11 and 12, and in the southern Strait of Georgia, median diameters tended to be larger in Area 19.

Biomass Dynamic Model

Schnute version

The pattern of median CPUE versus effort over time (Fig. 7) for the green sea urchin fishery in both core regions had sufficient contrasts to enable the use of surplus production modelling to define biological reference points for management actions. These results also suggest that catch per unit of effort now is as good as (PFMA 11-13; Fig. 7A), or better than (PFMA 17-20,28; Fig. 7B), CPUE at the start of the fishery in 1987. The predicted catches from the Schnute version of the surplus production model are shown in Fig. 8. The maximum sustainable yield (MSY ± 95% confidence interval) for the Queen Charlotte Strait region (PFMA 11-13) was 274 ± 40 t, with a model R^2 of 0.60 and a P-value of 0.004 (Table 6). The MSY calculated for the Gulf Islands region (PFMA 17-20,28) was 135 ± 55 t with a model R^2 of 0.39 and a P-value of 0.05 (Table 6).

Time Series Fitting version

The time series fitting method produced maximum likelihood estimates of MSY of 321 t with two standard deviations (approximating the 95% confidence interval) of 42 t for the Queen Charlotte Strait region and an estimate of 86 ± 10 t for the Gulf Islands region (Figs. 9B, 10B). Both approaches (Schnute's and the time series fitting method) to calculating the surplus production model for green sea urchins in these regions produced comparable results, since their 95% confidence intervals about MSY overlapped. The time series fitting procedure produced a lower MSY and smaller confidence interval for the southern region (the region with the smaller biomass, and therefore potentially more vulnerable to overfishing). Therefore, this method was selected as generating a more conservative result.

Bayesian model

Results from the Bayesian model (Figs. 9A, 10A) show a greater range (i.e. greater uncertainty) of possible MSY values than is produced by the time series fitting model. The most likely (i.e. the mean) estimate of MSY is similar for both types of analyses for PFMA 11-13, however 2 standard deviation ranges are much larger for the Bayesian analysis (Bayesian estimate of 335 ± 210 t; time series estimate of 320 ± 42 t). The "true" MSY for PFMA 11-13 has a 50% probability of being between 279 and 376 t (i.e. between the first and third quartiles) in the Bayesian analysis compared with 305 to 333 t in the time series analysis. In addition, the minimum estimate of MSY is 22 t in the Bayesian analysis, whereas it is 251 t in the time series fitting method (Fig. 9). These differences are to be expected considering the Bayesian model includes uncertainties in both observations and model structure. Note that one aspect of observation uncertainties included in the Bayesian model is that resulting from poor CPUE data from the early years of the fishery (see Appendix 2).

A similar comparison between the Bayesian analysis and the time series fitting method for the Gulf Islands (Fig. 10) provides the following results: the mean estimate of MSY ± 2 standard deviations is 101 ± 116 t for the Bayesian analysis, and 86 ± 10 t for the time series method. The inter-quartile range (50% of the values occur between the 1st and 3rd quartiles) is 62 – 125 t for the Bayesian analysis and 82 – 90 t for the time series method.

Values of other parameters estimated by the time-series fitting and Bayesian models are also similar, when considering the larger uncertainties of the Bayesian analysis:

	Time-series model		Bayesian model	
	Mean	95% Confidence Interval	Mean	95% Confidence Interval
Queen Charlotte Strait				
q	$6.6*10^{-5}$	$5.1*10^{-5} – 8.4*10^{-5}$	$6.3*10^{-5}$	$0.5*10^{-5} – 11.3*10^{-5}$
r	0.66	0.49 – 0.87	0.53	0.03 – 0.98
K	1987.5	1544.8 – 2525.0	3652.1	1229.6 – 20711.6
Gulf Islands				
q	$2.2*10^{-4}$	$1.7*10^{-4} – 2.9*10^{-4}$	$1.2*10^{-4}$	$0.08*10^{-4} – 3.4*10^{-4}$
r	0.53	0.39 – 0.71	0.29	0.01 – 0.80
K	669.2	502.5 – 862.5	3412.7	451.4 – 11783.1

Fishery-independent Surveys

Eight surveys have been conducted during the fall (just prior to the opening of each season's fishery) since October/November 1995 in the Stephenson Islets area of eastern Queen Charlotte Strait (PFMA 12). The mean densities calculated from these surveys indicate local minima in the biomass of legal sized green urchins during autumns of 1997 and 2000, and then an increase such that the highest biomass of legal-sized urchins in Stephenson Islets was observed during the October 2002 survey (Fig. 11). Sub-legal biomass has continued to increase. Mean legal biomass at Stubbs Island has also increased since 1998, such that the highest biomass of the series was observed in 2001 and 2002. Although the sub-legal biomass has declined at Stubbs Island since 2000, the difference may not be significant (note the overlapping error bars). Mean legal and sub-legal biomass at the Plumper Islands were maximum in 2001 and declined slightly (although perhaps not significantly) in 2002.

In the Gulf Islands region (Fig. 3), only one additional survey was successfully completed since the previous assessment (Table 7). This was in the fall of 2001, at East Point. Two transects were completed with high variability of mean legal-sized density between the two transects. Since all surveys to date at East Point have completed only one or two transects, the apparent increase in mean density of legal-sized urchins may not be representative of actual time trends. More observations in a convenient working location are required.

Yield Recommendations

MSY estimates from the time series fitting method are assigned to each management area on the basis of the proportion that area contributed to aggregate landings (on a fishing season basis) from 1995 to 2002 (Table 3a, and summarized in Table 8). Traditionally, MSY values have been considered as targets which management actions should try to achieve. However, many of the assumptions of surplus production models, such as no change in gear efficiency, constant catchability (in time, space, and across ages), a linear relationship between CPUE and effort, and equal availability of the fish to the fishery (Perry et al., 1999) are not likely to be true during the development of a fishery such as for green sea urchins, particularly regarding the discovery of new patches of urchins as the fishery expanded. Therefore, the MSY values calculated in this assessment are defined as limit reference points which management actions should ensure are not exceeded. The target reference points, to which management actions should aim, should be set sufficiently far from the limit reference point to ensure that the limit point is not exceeded.

Previous green urchin assessments in B.C. (Perry *et al*. 1998, 2001; Perry and Waddell 1998, 2001) recommended arbitrary reductions of 0.25*MSY to 0.5*MSY as target reference points, based on arguments by Garcia *et al* (1989) and Mace (2001). However, these previous assessments were unable to determine if these reductions were “suitably precautionary”, i.e. whether these target reference points had a low probability of including the true limit reference point (MSY) value. The Bayesian model results of Figs. 9 and 10 now permit this analysis. Table 9 presents estimates of the risk that any particular target reference point less than the limit reference point (MSY) will include the “true” MSY value.

Quota options

Since the Bayesian analysis is new for this assessment, we have chosen to use it to estimate the risks that various reductions from MSY might include the “true” MSY value. For this assessment, we retain the previous practice of using the time series fitting method to calculate the limit reference points (MSY) and the potential target reference points. Therefore, using these (50%, 35%, and 25%) reductions from MSY as target reference points, the specific recommendations for each PFMA in both South Coast – inside waters northern and southern regions are indicated in Table 8. Quotas are allocated to each PFMA based on the proportion of landings each PFMA comprised of the total landings over the baseline period 1995-2002. This period has been changed from that used in previous assessments (previously they included 1988 to current) to reflect the restricted nature of the fishery (restricted both in areas open to fishing and in total allowable catch). The range in recommended total yield for PFMA 11-13 and 17-20,28 combined is 101.5 to 203.1 t, based on 0.25*MSY and 0.50*MSY reductions. Other reductions from MSY, the probability that these might include the “true” MSY (Table 9), and the quota allocations by PFMA, can be easily calculated.

DISCUSSION

The three models used in this assessment are all based on a similar approach: the surplus production model. However, each model makes different assumptions about the major source of uncertainty. In the Schnute model, uncertainties are assumed to occur in the model structure; in the time-series fitting method, they occur in the observations; and the Bayesian state-space model includes uncertainties in both observations and model structure. Hilborn and Walters (1992) recommend trying different model formulations. The general similarity of predicted MSY from all of these models in this assessment provides a certain degree of comfort that this level of MSY is relatively robust to the particular source of uncertainties.

The Bayesian analysis suggests that the reduction from the estimated MSY (25-50% of MSY) applied in previous assessments has been sufficiently precautionary, with the probability that these target reference points might include the limit reference point being less than 3%. Figure 12 indicates that the probability of including the limit reference point rises quickly when the target reference point is 75% of the limit point for PFMA 11-13, and 50% of the limit reference point for PFMA 17-20,28. Note the much shorter lag of low probabilities in the Gulf Islands analysis compared to that in Queen Charlotte Strait (Fig. 12).

The MSY estimated from the Schnute model for the Gulf Islands region (PFMA 17-20,28) in this assessment is higher than that from previous assessments (135 t in the present assessment compared with 85 t in Perry *et al.* 2001). This higher estimate for MSY might be a result of very high recent CPUE values in this region for fishing seasons 2001 and 2002 (Figures 5 and 7). Note that this model assumes uncertainties in the model structure only and not in the observations. However, in 2001 there were only two vessels fishing in the Gulf Islands, and six vessels in 2002. If these were the "better" fishermen, perhaps concentrating on the more productive green urchin beds, it is possible that they could produce a higher-than-usual CPUE. The MSY estimate from the time series model, which assumes uncertainties in the observations, is similar to the result in Perry *et al*. (2001).

The green sea urchin stocks that are surveyed in the Queen Charlotte Strait region of Area 12 (Stephenson Islets, Stubbs Island, and Plumper Island) continue to remain strong, with high biomass of both legal-sized and sub-legal sized urchins at all three locations in the most recent survey (October 2002). Surveys in the Gulf Islands region, however, have been more difficult to conduct. The low number of transects conducted in 2001 and the unsuccessful survey in 2002 do not permit a biomass trend to be identified for this region. Selection of a more convenient survey location is probably needed.

Additional studies of green sea urchin biology, in particular as it relates to potential growth rates, age validation (rather than the use of size frequency analyses to infer age classes), and cannibalism are in progress and are expected to help to increase knowledge of this species in B.C. waters and provide confidence to assessing future changes in these populations.

SUMMARY OF RECOMMENDATIONS

1) Yield Options

Yield options for the 2003-2004 and 2004-2005 fishing seasons by management area should consider the estimated MSY's as limit reference points. Target yield options are suggested in the range of 0.25 to 0.50 of MSY (101.5 to 203.1 t for all areas combined).

2) Fishery-independent surveys and biological information

Fishery-independent surveys should continue in Area 12 and a suitable working site should be selected to continue annual surveys in the Gulf Islands (Area 18 or 19). Experimental studies on growth rates and age determination should continue.

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REFERENCES

Biermann, C. 2003. http://faculty.washington.edu/biermann/research.htm. Accessed 30 May 2003.

Chen, Y. and M. Hunter. 2003. Assessing the green sea urchin (*Strongylocentrotus drobachiensis*) stock in Maine, USA. Fish. Re. 60:527-537.

DFO, 2000a. Nova Scotia green sea urchin. DFO Science Stock Status Report C3-48 (2000).

DFO, 2000b. Green sea urchin of the inshore waters of Quebec. DFO Science Stock Status Report C4-13 (2000).

Foreman, R.E. and S.C. Lindstrom. 1974. Urchin survey report. Rep. Fish. Res. Bd., Pacific Biol. Stn. 1973: 1-59.

Garcia, S., P. Sparre, and J. Csirke. 1989. Estimating surplus production and maximum sustainable yield from biomass data when catch and effort time series are not available. Fisheries Res. 8: 13-23.

Harbo, R. and K. Hobbs. 1996. Precautionary quotas in the 1994 and 1995 green sea urchin fisheries in British Columbia, p. 207-230. In: C.M. Hand and B.J. Waddell (eds). Invertebrate working papers reviewed by the Pacific Stock Assessment Review Committee (PSARC) in 1993 and 1994. Can. Tech. Rep. Fish. Aquat. Sci. 2089.

Hart, M.W. and R.E. Scheibling. 1988. Heat waves, baby booms and the destruction of kelp beds by sea urchins. Mar. Biol. 99: 167-176.

Hilborn R, and C.J. Walters. 1992. Quantitative Fisheries Stock Assessment. Chapman and Hall. New York.

Himmelman, J.H. 1986. Population ecology of green sea urchins on rocky barrens. Mar. Ecol. Progr. Ser. 33: 295-306.

Jamieson, G.S. and C.J. Schwarz. 1998. Survey protocol considerations for 1995 red sea urchin surveys, p. 69-82. In: B.J. Waddell, G.E. Gillespie and L.C. Walthers (eds). Invertebrate working papers reviewed by the Pacific Stock Assessment Review Committee (PSARC) in 1995. II. Echinoderms. Can. Tech. Rep. Fish. Aquat. Sci. 2215.

Mace, P. 2001. A new role for MSY in single-species and ecosystem approaches to fisheries stock assessment and management. Fish and Fisheries 2:2-32.

Mcallister, M.K. and G.P. Kirkwood. 1998. Using Bayesian decision analysis to help achieve a precautionary approach for managing developing fisheries. Can. J. Fish, Aquat. Sci. 55: 2642-2661.

Miller, R.J. and K.H. Mann. 1973. Ecological energetics of the seaweed zone in a marine bay on the Atlantic Coast of Canada. III. Energy transformations by sea urchins. Mar. Biol. 18: 99-114.

Munk, J.E. 1992. Reproduction and growth of green urchins *Strongylocentrotus droebachiensis* (Muller) near Kodiak, Alaska. J. Shellfish Res. 11: 245-254.

Pella, J.J. and P.K. Tomlinson. 1969. A generalised stock production model. Bull. Inter-Am. Trop. Tuna Comm. 13: 421-458.

Perry, R.I. and B.J. Waddell. 1998. Stock assessment and quota recommendations for 1996/97 for the green sea urchin fishery in British Columbia, p. 261-308. In: G.E. Gillespie and L.C. Walthers (eds). Invertebrate working papers reviewed by the Pacific Stock Assessment Review Committee (PSARC) in 1996. Can. Tech. Rep. Fish. Aquat. Sci. 2221.

Perry, R.I. and B.J. Waddell. 1999. Review of the fishery and assessment of green sea urchin stocks in British Columbia, with quota recommendations for 1999/2000. Canadian Stock Assessment Secretariat, Research Document 99/113, 43pp.

Perry, R.I., B.J. Waddell, A. Campbell and K. Hobbs. 1998. Review of fishery-dependent data and quota recommendations for 1995/96 for the green sea urchins fishery in British Columbia, p. 111-146. In: B.J. Waddell, G.E. Gillespie and L.C. Walthers (eds). Invertebrate working papers reviewed by the Pacific Stock Assessment Review Committee (PSARC) in 1995. II. Echinoderms. Can. Tech. Rep. Fish. Aquat. Sci. 2215: 69-82.

Perry, R.I., B. Waddell and Z. Zhang. 2001. Assessment of green sea urchin (S*trongylocentrotus droebachiensis*) stocks in British Columbia, 2001. Canadian Stock Assessment Secretariat Res. Doc. 2001/137. 42pp.

Perry, R.I., C.J. Walters, and J.A. Boutillier. 1999. A framework for providing scientific advice for the management of new and developing invertebrate fisheries. Reviews in Fish Biology and Fisheries 9: 125-150.

Perry, R.I., Z. Zhang and R. Harbo. 2002. Development of the green sea urchin (*Strongylocentrotus droebachiensis*) fishery in British Columbia, Canada – back from the brink using a precautionary framework. Fishery Research 55: 253-266.

Polovina, J.J. 1989. A system of simultaneous dynamic production and forecast models for multispecies or multiarea applications. Can. J. Fish. Aquat. Sci. 46: 961-963.

Robinson, S.M.C. and A.D. MacIntyre. 1997. Aging and growth of the green sea urchin. Bull. Aquacul. Assoc. Canada 97-1: 56-60.

Ruccio, M.P. and D.R. Jackson. 2002. Red sea cucumber and green sea urchin commercial fisheries management plans for the Registration Area J (Westward Region), 2002/03. Regional Information Report No. 4K02-44, Alaska Dept. of Fish and Game, Kodiak, Alaska.

Scheibling, R.E. and A.W. Hennigar. 1997. Recurrent outbreaks of disease in sea urchins St*rongylocentrotus droebachiensis* in Nova Scotia: evidence for a link with large-scale meteorological and oceanographic events. Mar. Ecol. Prog. Ser. 152: 155-165.

Schnute, J. 1977. Improved estimates from the Schaefer production model: theoretical considerations. J. Fish. Res. Bd. Canada 34: 583-603.

Schnute, J. 1989. The influence of statistical error on stock assessment: illustrations from Schaefer's model. In: Beamish, R.J. and McFarlane, G.A. (eds.) Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models.. Can. Spec. Publ. Fish. Aquat. Sci. 108: 101-109.

Sokal, R.R. and J.F. Rohlf. 1981. Biometry, 2nd Edition. W.H. Freeman and Co. New York.

Strathmann, R. 1978. Length of pelagic period in echinoderms with feeding larvae from the northeast Pacific. J. Exp. Mar. Biol. Ecol. 34: 23-27.

Thomson, R.E. 1981. Oceanography of the British Columbia Coast. Can. Spec. Publ. Fish. Aquat. Sci. 56. 291p.

Thomson, R.E. 1994. Physical oceanography of the Strait of Georgia - Puget Sound - Juan de Fuca Strait system, p. 36-98. In: R.C.H. Wilson, R.J. Beamish, F. Aitkens and J. Bell (eds). Review of the Marine Environment and Biota of the Strait of Georgia, Puget Sound and Juan de Fuca Strait. Can. Tech. Rep. Fish. Aquat. Sci. 1948.

Waddell, B.J., R.I. Perry, G. Scharf and G. Ross. 1997. Surveys on green sea urchin (*Stongylocentrotus droebachiensis*) populations in Queen Charlotte Strait, British Columbia, October 1995 and March 1996. Tech. Rep. Fish. Aquat. Sci. 2143: 36 p.

Waddell, B.J., C.M. Crossley, D.P. Tzotzos, R.I. Perry and D. Kensall. 2002. Survey results of green sea urchin (*Strongylocentrotus droebachiensis*) populations in Queen Charlotte Strait, British Columbia, November, 1996 and February, 1997. Can. Tech. Rep. Fish. Aquat. Sci. 2419. 65pp.

Waddell, B.J., R.I. Perry and D. Kensall. 2003. Survey results of green sea urchin (*Strongylocentrotus droebachiensis*) populations in Queen Charlotte Strait, British Columbia, November 1997 and March 1998. Can. Tech. Rep. Fish. Aquat. Sci. 2476. 68 pp.

Table 1. Summary of management actions in the green sea urchin fishery, 1987 to 2002/2003.

Year	Management Actions
1987	Scientific permits were issued, July 22 to December 31, to fishing vessels for harvest by diving. Logbooks were issued with permits to collect data on stock abundance and distribution. Permits were limited to the inside waters of Vancouver Island, Areas 12 to 19, 28 and 29. Some minor area closures for parks or study areas were in effect as for most dive fisheries. A precautionary minimum size limit of 40 mm was set as a condition of the permit. Sales slip data did not have a separate species code, so green and red sea urchin landings are mixed. As a result, landings have been estimated from logbook returns and hails from processors. Effort was restricted by limiting the season to the months of traditional peak market demand for sea urchins, Oct.-Dec. and Jan.-Feb. Nineteen vessels reported landings.
1988	Permits were issued for the period Jan. 16 to Feb. 28. Sales data for green sea urchins was recorded with a separate species code. A conservative closure was set, Jan. 16 to Feb. 28 in subareas 13-1 to 13-3 due to the intensive fishery in a small area. A Z category (Z-A) licence for green sea urchins was introduced for the fall fishery which opened Oct. 1. The minimum size limit was increased to 55 mm test diameter and set as a condition of licence. The season was limited again, Jan. 1-Feb. 28 and Oct. 1-Dec. 31. Sixty-eight vessels reported landings.
1989	The Z-licence, minimum size limit and seasonal restrictions continued. A conservation closure was set for subareas 12-1 and 13-29 to 13-40, north of Campbell River, Jan. 31-Feb. 28/89 due to heavy fishing pressure and a high incidence of undersized urchins landed. One hundred thirteen vessels reported landings.
1990	The Z-licence, minimum size limit and seasonal restrictions continued. There were 91 vessels reporting landings. Licence limitation for 1991 was announced with the eligibility criteria of landings of 9,072 kg (20,000 lb.) over the two year period 1988 and 1989. At least 33 vessels were expected to qualify before appeals were held.
1991	Licence limitation – 47 vessels qualified and 47 vessels reported landings.
1992	A conservation closure was set in the Kelsey Bay area, subareas 12-1, 13-32, 13-33 and 13-35, Feb. 25-Feb. 28. These subareas did not reopen for fall fishing until Dec. 7.
1993	Licences increased to 49. Notification of fishing required. No suction devices. Additional permanently closed areas for parks and reserves, IFF. <u>South Coast</u>: Reduced fishing times; Inside waters: season Jan. 4 to Jan. 28, 7 days/wk; Feb. 1 to Feb. 25, 4 days/wk, Mon.-Thurs. Fall fishery Nov. 1 to Dec. 16, 4 days/wk, Mon.-Thurs.; Dec. 6 to Dec. 30, 7 days/wk. Kelsey Bay limited to 7 days, Jan. 4 to 10. W.C.V.I.: season reduced to Oct. 4 to 28, 1992, 7 days/wk. <u>North Coast</u>: 7 days/wk, season reduced to Jan. 1 to Feb. 28 and Oct. 1 to Dec. 31.
1994	<u>South Coast</u>: A ceiling catch of 990,000 lb (449 t) was set along with area quotas. Fishers requested to harvest 25% in Jan.-Feb. and the balance in Nov.-Dec. The days fishing were limited to 4 days/week (M-R) for some periods and others at 7 days/week. <u>North Coast</u>: No quota set; season reduced to periods Jan. 1 to Feb. 28 and Nov. 1 to Dec. 31. Consideration will be given for spring/summer fisheries depending on roe quality and landings.
1995/96	Fishing licences changed to expire on May 31, 1996. No fishing occurred prior to Nov. this year. <u>South Coast</u>: Pilot individual licence quota (IQ) system implemented with port validation. Area quotas also established, with total of 382,276 lb (173.4 t). Only Areas 12, 13, 17 to 20, and 28 open; other areas available under an exploratory protocol. Fishing season was Nov. 20, 1995 to May 31, 1996. <u>North Coast</u>: No individual quotas. Areas 3 and 4 only open from Nov. 20, 1995 to Jan. 31, 1996, with quota of 200,00 lb (90.72 t). Other areas open to fishing only under an exploratory protocol.
1996/97	Harvest logs and validation forms combined onto one sheet. Biosamples (sample test measurements) were collected by validators. <u>South Coast:</u> IQ system still in effect (quota divided between 49 licence holders), with port validation. Area quotas established, with a total of 359,435 lb (163.0 t). Only Areas 12, 13, 17 to 20 and 28 open; other areas available under an exploratory protocol. Fishing season was Nov. 12, 1996 to Jan. 31, 1997, with an extension to Feb. 15, 1997. <u>North Coast</u>: North Coast closed, except under an exploratory protocol.
1997/98	Two year Management Plan (October 15, 1997 to May 31, 1999). Second season of the extended pilot program (validation process). Biological sampling of commercial catch <u>South Coast</u>: Areas 11, 12, 13, 17 to 20 and 28 open from Nov. 10, 1997 to Mar. 15, 1998; other areas available under an exploratory protocol. Area quotas, with total of 366,079 lb (166.1 t) (IQ 7,471 lb or 3,389 kg). <u>North Coast</u>: North Coast closed, except under an exploratory protocol. Survey undertaken in Area 4.
1998/99	Third season of the extended pilot program (validation process). Biological sampling of commercial catch. <u>South Coast</u>: Areas 11, 12, 13, 17, 18, 19, 20, and 28 open from Nov. 10, 1998 to Mar. 15, 1999; other areas available under an exploratory protocol. Area quotas, with total of 366,079lb (166.1 t) (individual quotas 7,471 lb or 3,389 kg). <u>North Coast</u>: Total quota of ~12,725 lb (~5,772 kg) allotted to Area 4 from Feb. 12 to Mar. 15, 1999.
1999/2000	Validation program continued. Biological sampling of commercial catch. <u>South Coast</u>: Areas 11, 12, 13, 18, 19, and 20 open from Nov. 10, 1999 to Mar. 15, 2000; other areas available under an exploratory protocol. Note Areas 17 and 28 are closed due to conservation concerns. Area quotas, with total of 414,393 lb (188.0 t) (individual quotas 8,457 lb or 3,836 kg). <u>North Coast</u>: Total quota of 13,000 lb (5,897 kg) allotted to Area 4. Season open from Jan. 21 to Mar. 15, 2000.

2000/2001	Validation program continued. Biological sampling of commercial catch. South Coast: Areas 11, 12, 13, 18, 19, and 20 open from Nov. 10, 2000 to Mar. 15, 2001; other areas available under an exploratory protocol. Conditional surveys for Areas 18 and 20 were performed which allowed those areas to stay open with the same quotas as the previous year. Area quotas, with total of 414,393 lb (188.0 t) (individual quotas 8.457 lb or 3,836 kg)). North Coast: Total quota of 13,000 lb (5,897 kg) allotted to Area 4. Season open from Nov. 10, 2000 to Mar. 15, 2001. First Nations had conservation concerns about the resource. Commercial fishers agreed not to fish the area this season.
2001/2002	Validation program continued. Biological sampling of commercial catch. A two-year Management Plan was established for the 2001/02 and 2002/03 fishing seasons. South Coast: Quota Area 13 was split into two: 13A (subareas 1 to 27) and 13B (subareas 28 to 43). Areas 11, 12, 13A, 13B, 18, 19, and 20 open from Nov. 20, 2001 to Mar. 15, 2002, with an extension of the opening to Apr. 19, 2002; other areas available under an exploratory protocol. Area 20 required a survey prior to fishing, which was not undertaken, so it was not fished. Area quotas, with total of 394,646 lb (179.0 t) (individual quotas 8.054 lb or 3,653 kg). Only 68% of allowable catch landed due to oversupply of product by other countries, mainly Russia. North Coast: Only Area 4 was considered for opening, but it required a survey prior to quota allocation. However, the survey was not undertaken. First Nations had conservation concerns about the resource. Commercial fishers agreed not to fish the area this season.
2002/2003	Validation program continued. Biological sampling of commercial catch. Continuation of the two-year Management Plan established the previous year. South Coast: Areas 11, 13A, 13B, 18, 19 and 20 open from Oct. 15, 2002 to Mar. 15, 2003; Area 12 was open from Nov. 4, 2002 to Mar. 15, 2002; other areas available under an exploratory protocol. Area 20 required a survey prior to fishing, which was not undertaken, so it was not fished. Area quotas, with total of 394,646 lb (179.0 t) (individual quotas 8.054 lb or 3,653 kg). Strong competition from Russia kept the price down again, and resulted in only 80% of the TAC being landed. North Coast: Only Area 4 was considered for opening, but it required a survey prior to quota allocation. However, the survey was not undertaken. First Nations had conservation concerns about the resource. Commercial fishers agreed not to fish the area this season.

Table 2. Green sea urchin landings (tonnes) and effort for British Columbia by fishing season (Oct./Nov. to Mar./Apr.), 1986/1987 to 2002/2003, as reported on sales slips, harvest logbooks, and validation logs. Bold print is the most reliable value when a choice of sources of data is shown.

Season	Licence Type	Number of Active Licences	Vessels with Landings	Fishing Days	Average Fishing Days/ Vessel	Total Landings (t)	Total Landed Value (million $)[9]	Average Landed Value ($/t)	Mean Overall CPUE (t/vessel day)	Mean Overall CPUE (kg/ Diver hr)[5]	Total Diver Hours	Average Hr/Diver Day[5,7]	Total Number of Divers	Average Hr/Vessel Day[5]
1986/87[1]	Permit[4]					n/a	n/a	n/a						
1986/87[2]			2	4	2.0	2			0.50	175	14[6]	n/a	1[+]	3.38
1987/88[1]	Z					n/a	n/a	n/a						
1987/88[2]			29	290	10.0	207			0.71	171	1,216[6]	2.96	48[+]	4.57
1988/89[1]	Z		**77**			**480**	0.669	1395						
1988/89[2]			63	688	10.9	378			0.55	156	2,418[6]	2.84	118[++]	4.67
1989/90[1]	Z		**115**			**642**	1.104	1719						
1989/90[2]*			93	1,095	11.8	484			0.44	131	3,691[6]	2.47	169[++]	3.79
1990/91[1]	Z		**71**			**455**	0.981	2155						
1990/91[2]*			51	923	18.1	353			0.38	107	3,310[6]	2.70	106[+]	4.25
1991/92[1]	Z		**49**			**783**	2.534	3235						
1991/92[2]*			44	1,510	34.3	753			0.50	100	7,523[6]	2.88	152[+]	5.72
1992/93[1]	Z		**56**			**978**	4.530	4632						
1992/93[2]*			53	1,987	37.5	954			0.48	81	11,835[6]	3.10	199[++]	6.77
1993/94[1]	Z		**53**			**577**	3.145	5453						
1993/94[2]*			52	1,267	24.4	533			0.42	69	7,667[6]	2.94	183[++]	7.39
1994/95[1]	Z		**43**			**223**	**1.614**	7251						
1994/95[2]			42	673	16.0	221	1.604		0.33	70	3,161[6]	2.73	101[++]	5.23
1995/96[1]*	Z		36[8]			135[8]	0.931[8]	6896						
1995/96[2]			**39**	500	12.8	**157**	**1.085**		0.31	71	2,201[6]	2.84	85[++]	4.75
1996/97[1]*	Z	48	31[8]			132[8]	0.828[8]	6290						
1996/97[3]			**32**	458	14.3	**150**	**0.943**		0.33	65	2,300[6]	2.62	72[+]	5.03
1997/98[1]*	Z	49	27			156[8]	0.983[8]	6303						
1997/98[3]			**27**	423	15.7	**160**	**1.008**		0.38	82	1,958	2.57	59	4.63
1998/99[1]*	Z	48	27			154	0.971	6269						
1998/99[3]			**26**	376	14.5	**156**	**0.982**		0.41	84	1,861[6]	2.71	60[+]	4.98
1999/00[1]*	Z	49	25[8]			147[8]	0.912[8]	6215						
1999/00[3]			**27**	357	13.2	**187**	**1.160**		0.52	103	1,810	2.82	65	5.07
2000/01[1]*	Z	48	30			165[8]	0.887[8]	5368						
2000/01[3]			**28**	315	11.3	**181**	**0.973**		0.58	107	1,701	3.05	56	5.40

Table 2. Continued.

Season	Licence Type	Number Of Active Vessels	Vessels with Landings	Fishing Days	Average Fishing Days/ Vessel	Total Landings (t)	Total Landed Value (million $)[9]	Average Landed Value ($/t)	Mean Overall CPUE (t/vessel day)	Mean Overall CPUE (kg/ Diver hr)[5]	Total Diver Hours	Average Hr/Diver Day[5,7]	Total Number of Divers	Average Hr/Vessel Day[5]
2001/02[1]*	Z		14[8]			104[8]	0.475[8]	4574						
2001/02[3]		38	**15**	185	12.3	**123**	**0.561**		0.66	126	974	3.16	32	5.27
2002/03[1]*	Z		14[8]			85[8]	0.350[8]	4109						
2002/03[3]		42	**17**	206	12.1	**144**	**0.591**		0.70	143	970	2.96	30	4.71

Footnotes:

[*] incomplete data (missing landing or effort data in the harvest logbooks).
[1] from sales slip data
[2] from harvest logbooks
[3] from combined harvest/validation logbooks
[4] scientific permits were issued to 38 vessels for fall 1987 to spring 1988 fishery. 1987 landings and fishing days are from harvest logs as green sea urchins were not separated from reds on sales slips until mid-1998. Note a vessel can hold more than one licence.
[5] excludes records with missing fishing hours (effort)
[6] incomplete records of fishing hours (effort)
[7] excludes records with missing diver identification
[8] preliminary values likely lower than actual
[9] Landed values for sales slip data calculated as the summation of landed weight, multiplied by the unit price for every landing. Landed values for harvest log data calculated as the average landed value ($/t) from sales slip data, multiplied by total landings (t) from harvest logbook data.
[+] possibly one or two more (due to sales slips with no CFV #, or missing diver codes)
[++] probably several more (due to missing diver codes)

Table 3a. Summary of green sea urchin landings (tonnes) by management area for the South Coast by fishing season (Oct. to Mar.), 1988/89 to 2002/03, as reported on sales slips (SS), harvest logs (HL) and validation logs (VL). ("-" = area closed; * = preliminary data). Totals were calculated using sales slips from 1988/89 to 1994/95 and harvest logs from 1995/96 to 2002/03.

	PACIFIC FISHERY MANAGEMENT AREA																		
	East Coast Vancouver Island											West Coast Vancouver Island							
Season	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**28**	**29**	**20**	**21**	**23**	**24**	**25**	**26**	**27**	**Annual Landings**
SS 1988/89	2.8	93.0	171.8	17.0	7.4	0.3	15.4	53.8	74.5	15.0	9.8	1.5		2.5	9.5				474.3
SS 1989/90		327.9	129.8	5.6			36.1	87.6	23.8	1.8	0.5	2.1		0.4	1.8			12.6	630.0
SS 1990/91	0.9	105.4	153.4			0.1		121.9	51.1	4.0		15.7							452.5
SS 1991/92	1.0	388.4	203.5	3.1	1.3	4.1	1.1	42.6	50.5	4.3	18.6	61.4	0.3		0.4			2.0	782.6
HL 1991/92	0	353.7	206.1	1.4			0.1	23.1	66.3	0	25.4	76.1			0.1				752.4
SS 1992/93	43.4	645.4	189.6			1.9		18.9	36.2	1.7	2.6	36.2							975.9
HL 1992/93	70.8	631.4	154.1			1.3	0.5	26.0	38.6	1.7	2.8	26.7							954.0
SS 1993/94*	1.5	250.9	102.1	0.9	1.0		0.8	28.3	60.7	0.4	0.8	16.2	3.8		0.4	0.4			468.2
HL 1993/94	27.6	214.1	92.6			0.7	1.7	39.9	46.3	0.5	0	16.9							440.6
SS 1994/95*	2.3	93.8	56.5	1.1	0	0.3	0	15.5	16.4	0	0.1	9.4	-	0	0	0	0	0	195.4
HL 1994/95	6.9	92.6	53.5	0	0	0	0.2	15.1	16.0	0	-	10.8	-	0	0	0	0	0	195.1
SS 1995/96*	-	46.3	49.8	-	-	-	0.4	10.6	18.0	0		6.0	-	-	-	-	-	-	131.1
HL 1995/96	0.7	60.5	54.8	-	-	-	0.4	12.2	18.3	0	0.1	6.1	-	-	-	-	-	-	153.1
VL 1995/96	-	61.9	53.8	-	-	-	0.4	13.0	18.0	0		5.7	-	-	0.2	-	-	-	153.0
SS 1996/97*	1.8	70.3	21.7	-	-	1.5	0	23.3	7.8	0	-	7.1	-	-	-	-	-	-	133.4
HL 1996/97*	2.8	77.0	27.0	-	-	-	0	18.1	17.4	0	- (0.4)	7.1	-	-	-	-	-	-	149.8
VL 1996/97	2.8	76.9	27.2	-	-	-	0	18.5	17.4	0	-	7.1	-	-	-	-	-	-	149.9
HL 1997/98*	2.4	76.5	39.9	-	-	-	0.7	16.3	17.4	0	-	6.8	-	-	-	-	-	-	160.0
VL 1997/98	2.4	76.5	39.9	-	-	-	0.7	17.0	16.7	0	-	6.8	-	-	-	-	-	-	160.0
HL 1998/99	0.7	76.6	39.8	-	-	-	0.3	14.9	16.7	0	-	6.6	-	-	-	-	-	-	155.6
HL 1999/00	3.0	105.5	56.3	-	-	-	-	8.8	9.0	-	-	3.7	-	-	-	-	-	-	186.3
HL 2000/01	0	104.4	56.3	-	-	-	-	9.2	9.1	-	-	2.3	-	-	-	-	-	-	181.3
HL 2001/02	0	62.0	41.8	-	-	-	-	9.0	9.8	-	-	-	-	-	-	-	-	-	122.6
HL 2002/03	1.0	78.4	44.0	-	-	-	-	10.7	9.8	-	-	-	-	-	-	-	-	-	143.9
Total 1988/89 to 2002/03	62.5	2545.7	1366.6	27.7	9.7	6.7	54.8	467.8	420.7	27.2	32.1	175.1	4.1	2.9	12.1	0.4	0	14.6	5231.5
% of Total	1.2	48.7	26.1	0.5	0.2	0.1	1.0	8.9	8.0	0.5	0.6	3.3	0.1	0.1	0.2	0.0	0.0	0.3	

Table 3b. Summary of green sea urchin landings (tonnes) by management area for the North Coast by fishing season (Oct./Nov. to Mar.) 1988/89 to 2002/03, as reported on sales slips (SS) and harvest logs (HL). The fishery was closed in the North Coast during the 1996/97 and 1997/98 fishing seasons. Totals were calculated using sales slips from 1988/89 to 1994/95 and harvest logbooks from 1995/96 to 2002/03.

	PACIFIC FISHERY MANAGEMENT AREA										
Season	**1**	**2E**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Annual Landings**
SS 1988/89		0.4				0.7					1.1
SS 1989/90	12.3										12.3
SS 1990/91						2.6					2.6
SS 1991/92	0.4										0.4
SS 1992/93									1.7		1.7
SS 1993/94*				93.5	1.0	3.8	0.2	0.2	8.5	0.1	107.3
SS 1994/95*				27.3					0.9		28.2
SS 1995/96*				4.0							4.0
HL 1995/96				4.3							4.3
Closed 1996/97	-	-	-	-	-	-	-	-	-	-	-
Closed 1997/98	-	-	-	-	-	-	-	-	-	-	-
HL 1998/99	-	-	-	0.2	-	-	-	-	-	-	0.2
HL 1999/00	-	-	-	0.3	-	-	-	-	-	-	0.3
HL 2000/01	-	-	-		-	-	-	-	-	-	
HL 2001/02	-	-	-		-	-	-	-	-	-	
HL 2002/03	-	-	-		-	-	-	-	-	-	
Total of 1988/89 to 2002/03	12.7	0.4	0	125.6	1.0	7.1	0.2	0.2	11.1	0.1	158.4
% of Total	8.0	0.3	0.0	79.3	0.6	4.5	0.1	0.1	7.0	0.1	

Table 4. Summary of green sea urchin landings (tonnes) by South Coast management area and month for fishing seasons 1998/99 to 2002/03 as reported on harvest logs. Only areas open to fishing, and months with catch, are reported. ("-" = closed to fishing). Note Quota Area 13 changed to 13A and 13B in fishing season 2001/02.

	South Coast Management Areas								Total
Month	**11**	**12**	**13**	**17**	**18**	**19**	**20**	**28**	**(tonnes)**
1998 Nov.	0.0	10.4	3.8	0.0	1.0	0.7	0.0	0.0	15.9
Dec.	0.0	49.3	36.0	0.0	4.5	5.8	1.0	0.0	96.6
1999 Jan.	0.7	16.8	-	0.3	8.9	10.1	4.6	0.0	41.4
Feb.	0.0	-.	-	0.0	0.6	-	1.1	0.0	1.7
Area Totals	0.7	76.5	39.8	0.3	15.0	16.6	6.7	0.0	155.6
1999 Nov.	0.0	9.2	7.0	-	2.3	0.2	0.0	-	18.7
Dec.	0.0	57.5	47.7	-	6.2	8.8	3.7	-	123.9
2000 Jan.	2.6	38.7	1.6	-	0.3	-	-	-	43.2
Feb.	0.4	-	-	-	0.0	-	-	-	0.4
Area Totals	3.0	105.4	56.3	-	8.8	9.0	3.7	-	186.2
2000 Nov.	0.0	0.9	2.8	-	0.0	0.0	0.0	-	3.7
Dec.	0.0	29.2	50.1	-	9.2	9.1	0.0	-	97.6
2001 Jan.	0.0	71.7	3.3	-	-	-	2.3	-	77.3
Feb.	0.0	2.6	-	-	-	-	0.0	-	2.6
Area Totals	0.0	104.4	56.2	-	9.2	9.1	2.3	-	181.2
New Areas→	**11**	**12**	**13A**	**13B**	**18**	**19**	**20**		Total
2001 Nov.	0.0	1.9	0.0	0.0	0.0	2.1	0.0		4.0
Dec.	0.0	11.2	11.1	19.2	6.2	7.7	0.0		55.4
2002 Jan.	0.0	46.6	5.2	6.2	2.8	-	0.0		60.8
Feb.	0.0	2.3	0.0	0.0	0.0	-	0.0		2.3
Area Totals	0.0	62.0	16.3	25.4	9.0	9.8	0.0		122.6
2002 Nov.	0.0	0.4	0.7	1.1	0.0	2.9	0.0		5.0
Dec.	0.0	11.8	5.0	14.5	10.3	7.3	0.0		48.9
2003 Jan.	1.0	51.4	7.9	13.4	0.0	-	0.0		73.8
Feb.	0.0	14.8	1.4	-	0.0	-	0.0		16.2
Area Totals	1.0	78.4	14.9	29.1	10.3	10.2	0.0		143.9

Table 5. Green sea urchin landings reported on sales slips compared to harvest logbook or validation records by fishing season (Oct./Nov. to Mar.), 1986/1987 to 2002/2003.

Season	Sales Slips (t)	Sales Slips (lb)	Harvest Logbooks (lb)	% of Logbook Returns
1986/87	n/a	n/a	5,220	n/a
1987/88	n/a	n/a	456,952	n/a
1988/89	480	1,055,758	832,625	79.4%
1989/90	642	1,416,184	1,067,996	75.4%
1990/91	455	1,003,315	778,926	77.6%
1991/92	783	1,726,341	1,660,117	96.2%
1992/93	978	2,156,128	2,103,210	97.5%
1993/94	577	1,271,440	1,174,527	92.6%
1994/95	223	490,886	487,590	98.8%
1995/96*	135	297,742	346,874	116.5%
1996/97*	132	290,165	330,526	113.9%
1997/98*	156	343,951	352,560	102.5%
1998/99*	154	339,667	343,579	101.2%
1999/00*	147	323,679	411,398	127.1%
2000/01*	165	364,349	399,665	109.7%
2001/02*	104	228,736	270,260	118.2%
2002/03*	85	187,732	317,274	169.0%

* Preliminary Data

Note: The above data assumes that all sales slips have been submitted annually, which may not always be the case. Sales slips landings for 1987 and 1988 are actually logs combined with a best guess from sales slips, as there was not a separate species code assigned to green sea urchins until the fall fishery in 1988.

Licence limitation was announced in 1989 for the 1991 fishery. Licence eligibility was based on landings from two of the three years 1987, 1998, and 1989. Fishers who knew they would not meet the landing criteria to get a limited licence were not inclined to submit harvest logbooks at the end of 1989 or in 1990, as they knew they could not renew their licence.

Table 6. Dynamic production model estimates for the parameters α, β, γ and their standard errors (in brackets) for the regression of equation 4. Regression coefficients (r^2), probability levels (p-values), and calculation from these parameters of the values of r, q, and k are as described in the text. Limit reference points MSY (maximum sustainable yield) and effort at MSY are calculated as described in the text.

	Regression Parameters				Management Parameters				
	α	β	γ	Model (r^2)	r $(yr)^{-1}$	q $(diver\ hr)^{-1}$	k (t)	MSY (t)	effort at MSY (diver hr)
South -inside Northern region (PFMA 11,12,13)	0.710 (0.203)	-0.0001 (0.00002)	-0.0053 (0.0018)	0.60	0.710	0.0001	1544	274	4126
p-level	0.004	0.001	0.013	0.004					
South - inside Southern region (PFMA 17-20,28)	0.356 (0.233)	-0.0003 (0.0001)	-0.0009 (0.0022)	0.39	0.356	0.0002	1520	135	707
p-level	0.15	0.02	0.68	0.05					

Table 7. Results and biomass estimates from fishery-independent surveys conducted in the Gulf Islands region.

LOCATION	PFMA	Number Of Transects	DATE	MEAN DENSITY ($\#/m^2$)		MEAN BIOMASS (g/m^2)		AREA (m^2)	TOTAL BIOMASS (t)	
				Sublegal	Legal	Sublegal	Legal		Sublegal	Legal
Collinson Point	18-02	1	Nov. 1999	21.23	0.46	470.75	38.56	458,717	215.9	17.7
(Active Pass)	18-02	1	Oct. 2000	26.05	1.80	580.73	99.38		266.4	45.6
Helen Point	18-02	6	Nov. 1997	0.04	0.04	1.63	5.08	197,778	0.3	1.0
(Active Pass)	18-02	1	Nov. 1999	2.03	0.93	44.54	62.55		8.8	12.4
Enterprise Reef (Active Pass)	18-02	2	Nov. 1997	0.08	0.22	2.08	39.83	182,425	0.4	7.3
East Point	18-11	1	Nov. 1999	21.30	2.13	362.93	130.38	993,734	360.7	129.6
(Saturna	18-11	2	Oct. 2000	27.50	1.31	501.52	76.64		498.4	76.2
Island)	18-11	2	Oct. 2001	26.80	8.46	752.33	669.91		747.6	665.7
Arachne Reef	18-04/06 & 19-05	2	Mar. 2000	2.39	0.51	51.12	33.94	71,041	3.6	2.4
Cooper Reef	19-05	2	Mar. 2000	0.79	0.21	13.12	15.30	332,298	4.4	5.1
Sooke Bluffs	20-05/06	5	Jan. 2000	0.10	0.19	3.47	15.81	1,411,799	4.9	22.3
	20-05/06		Jan. 2001	0.00	0.00	0.00	0.00		0.0	0.0

Table 8. Calculations of limit and target reference points for green sea urchins in South Coast management areas, derived from the time series fitting surplus production method. The ranges of quota options recommended for the 2001-2002 and 2002-2003 fishing seasons are in boldface. Estimates of risk for the target reference points are calculated using the Bayesian model.

	Pacific Fishery Management Area – South Coast – inside waters												
	11	12	13	Totals for Areas 11-13	Estimated risk *	17	18	19	20	28	Totals for Areas 17-20,28	Estimated risk *	Total
Proportion caught (1995-2002) of the total for each Region	.010	.636	.353			.01	.415	.447	.134	0			
Limit Reference Point (MSY ; t)	3.2	203.5	113.0	319.7		0.9	35.7	38.4	11.5	0	86.5		406.2
Target Reference Point 1 0.5 * MSY (t)	**1.6**	**101.8**	**56.5**	**159.9**	3.8%	**0.4**	**17.9**	**19.2**	**5.7**	**0**	**43.2**	12.7%	**203.1**
Target Reference Point 2 0.35*MSY (t)	**1.1**	**71.2**	**39.5**	**111.8**	2.2%	**0.3**	**12.5**	**13.4**	**4.0**	**0**	**30.2**	6.2%	**142.0**
Target Reference Point 3 0.25*MSY (t)	**0.8**	**50.9**	**28.2**	**79.9**	1.4%	**0.2**	**8.9**	**9.6**	**2.9**	**0**	**21.6**	3.0%	**101.5**

* Estimated risk that the proposed target reference point would include the limit reference point (MSY)

Table 9. Table of risk (probability) that a given target reference point might include the "true" limit reference point, derived from the Bayesian model.

	Management Areas 11-13	Management Areas 17-20,28
Limit reference point (MSY; t)	319.7	86.5
0.9 * MSY	43.2%	38.9%
0.8 * MSY	19.3%	29.8%
0.7 * MSY	7.8%	22.2%
0.6 * MSY	5.1%	17.3%
0.5 * MSY	3.8%	12.7%
0.4 * MSY	2.7%	8.4%
0.3 * MSY	1.8%	4.6%
0.2 * MSY	0.8%	1.8%
0.1 * MSY	0.2%	0.2%
0.01 * MSY	0%	0%

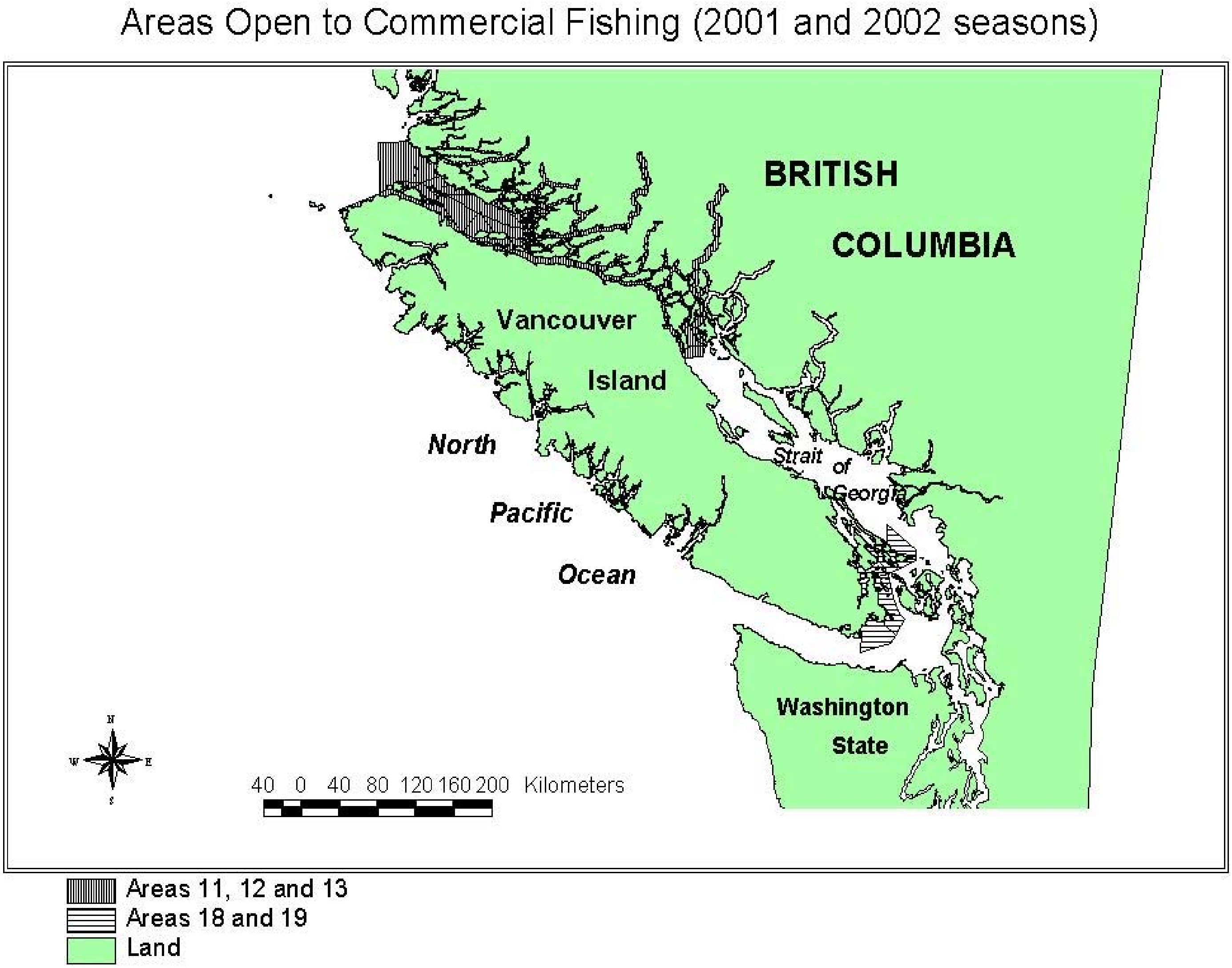


Fig. 1. Pacific Fishery Management Areas open to fishing for green sea urchins during the 2001 and 2002 fishing seasons.

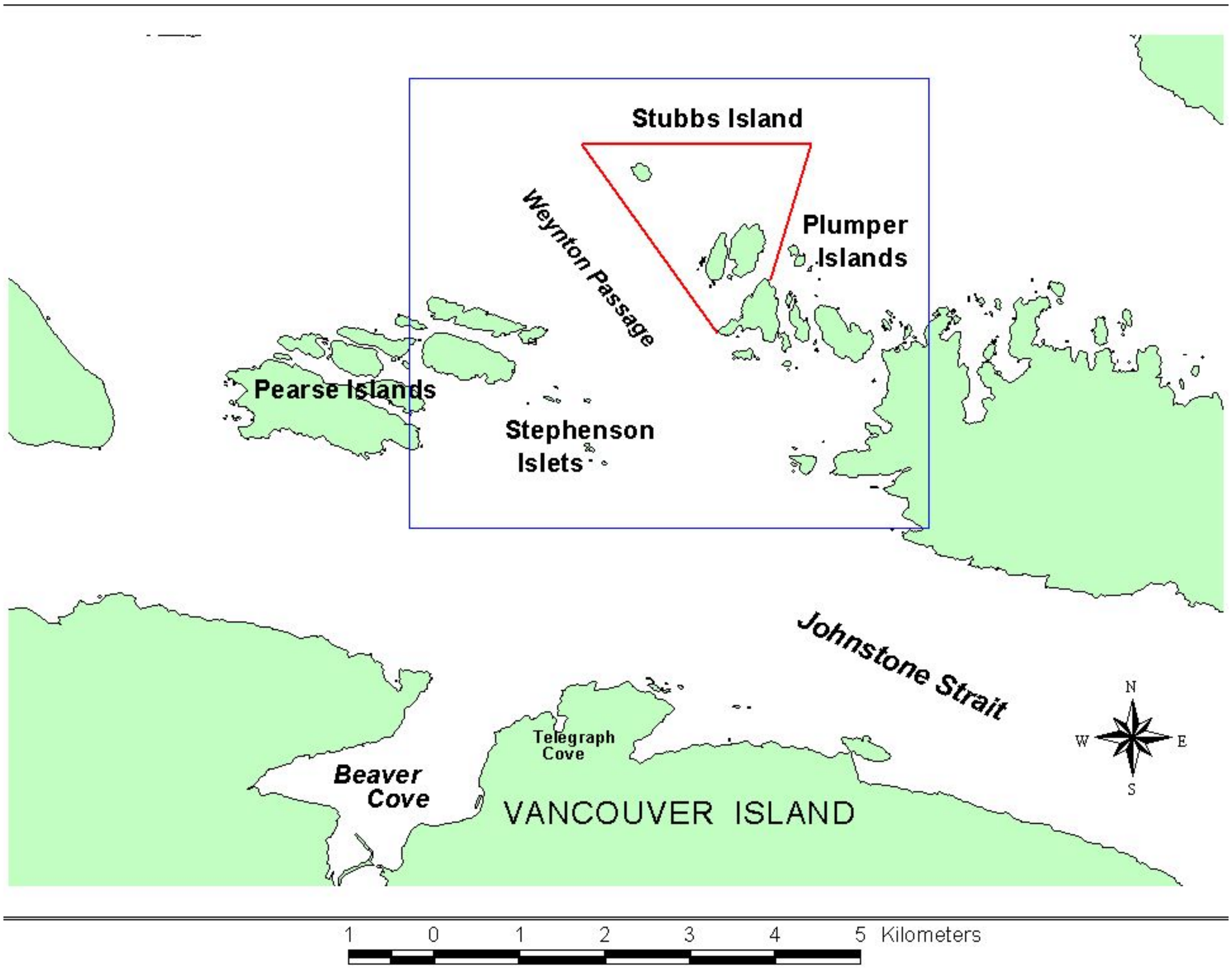


Fig. 2. Stephenson Islets location of the fishery-independent surveys conducted at the beginning of each fishing season from October 1995 to November 2002, eastern Queen Charlotte Strait, B.C. The red lines indicate the boundaries of the area closed to commercial fishing.

Fig. 3. Survey locations in the Gulf Islands region, 1997 to 2002.

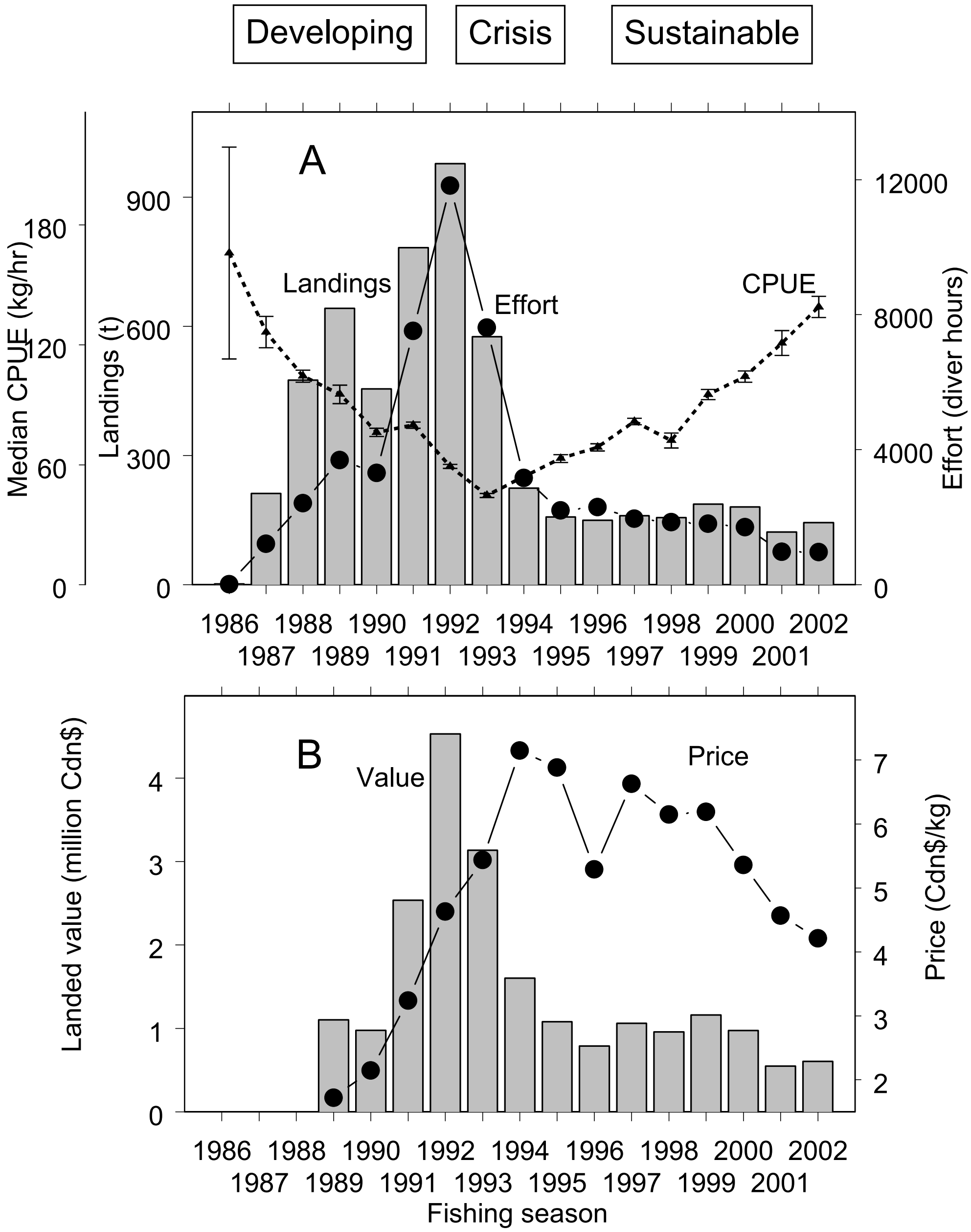


Fig. 4. (A) Landings (from sales slip data up to 1995, then from harvest and validation logs), effort, and CPUE; and (B) landed value for the green sea urchin fishery in B.C. and unit price. Data are presented on the basis of a fishing season (October of year *i* to March of year *i*+1).

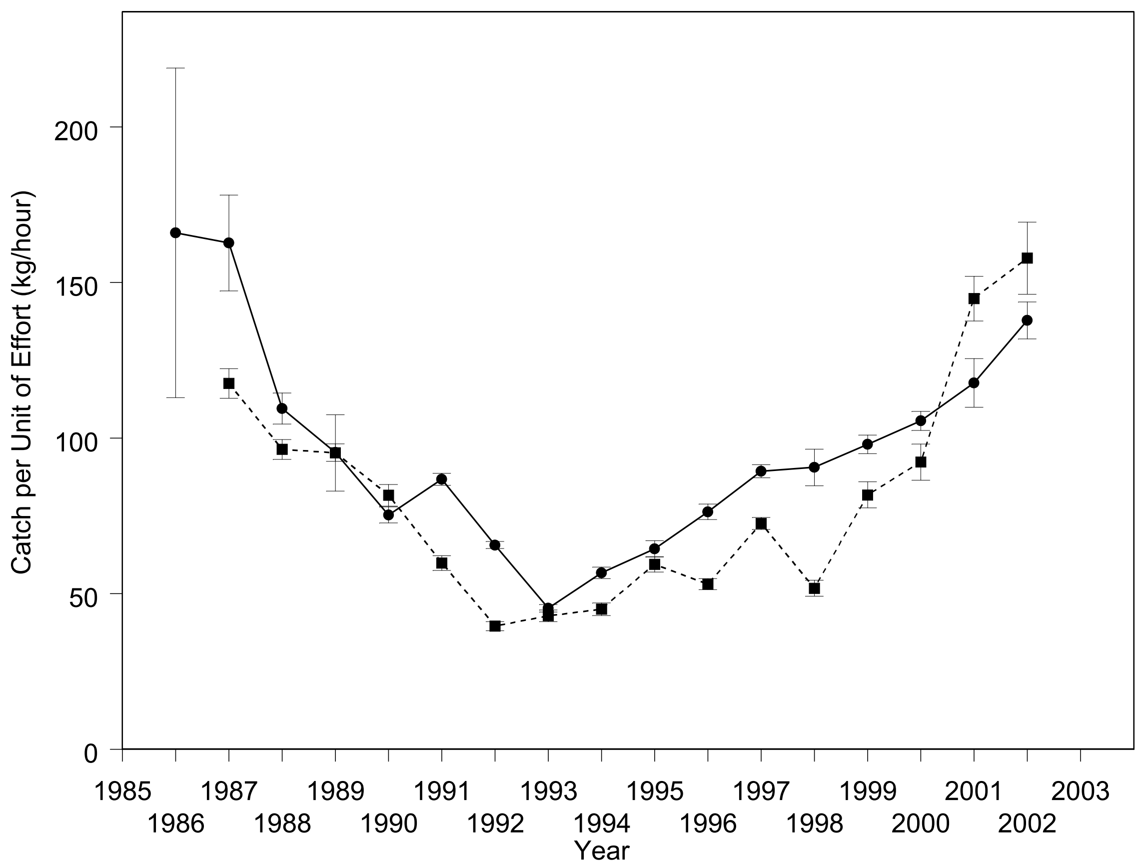


Fig. 5. Median catch per unit of effort ± 1 standard error (kg/diver hour) on a fishing season basis for the green urchin fishery in B.C.. Solid line: South Coast - inside waters northern component (PFMA 11, 12, 13); dashed line: South Coast - inside waters southern component (PFMA 17-20,28).

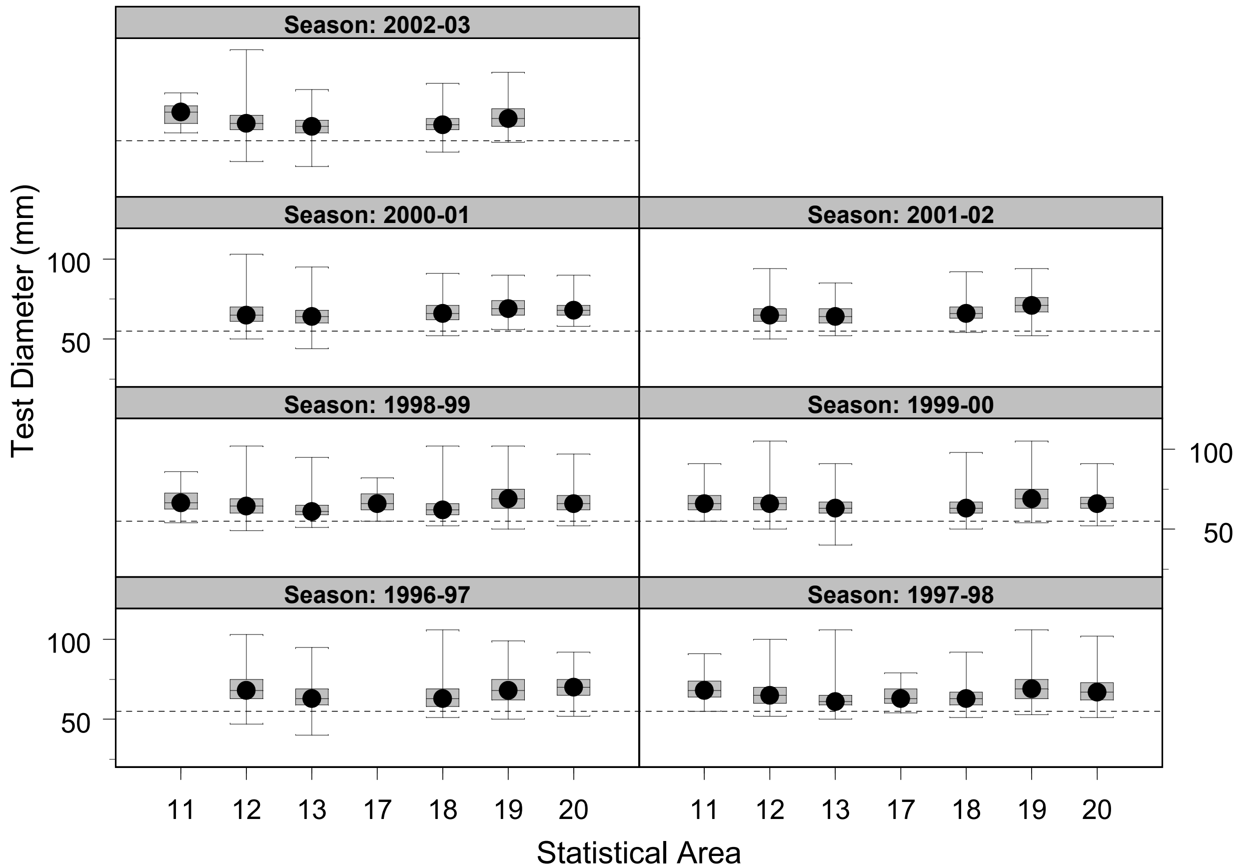


Fig. 6. Box and whisker plots of test diameters of green urchins sampled by port validators from each statistical area in each fishing season. Dot within box is the median, the upper and lower box edges define the 75th and 25th percentiles (interquartile distance), and the whiskers represent values that fall within 1.5 times the interquartile distance. Horizontal dashed line represents the legal size limit of 55 mm.

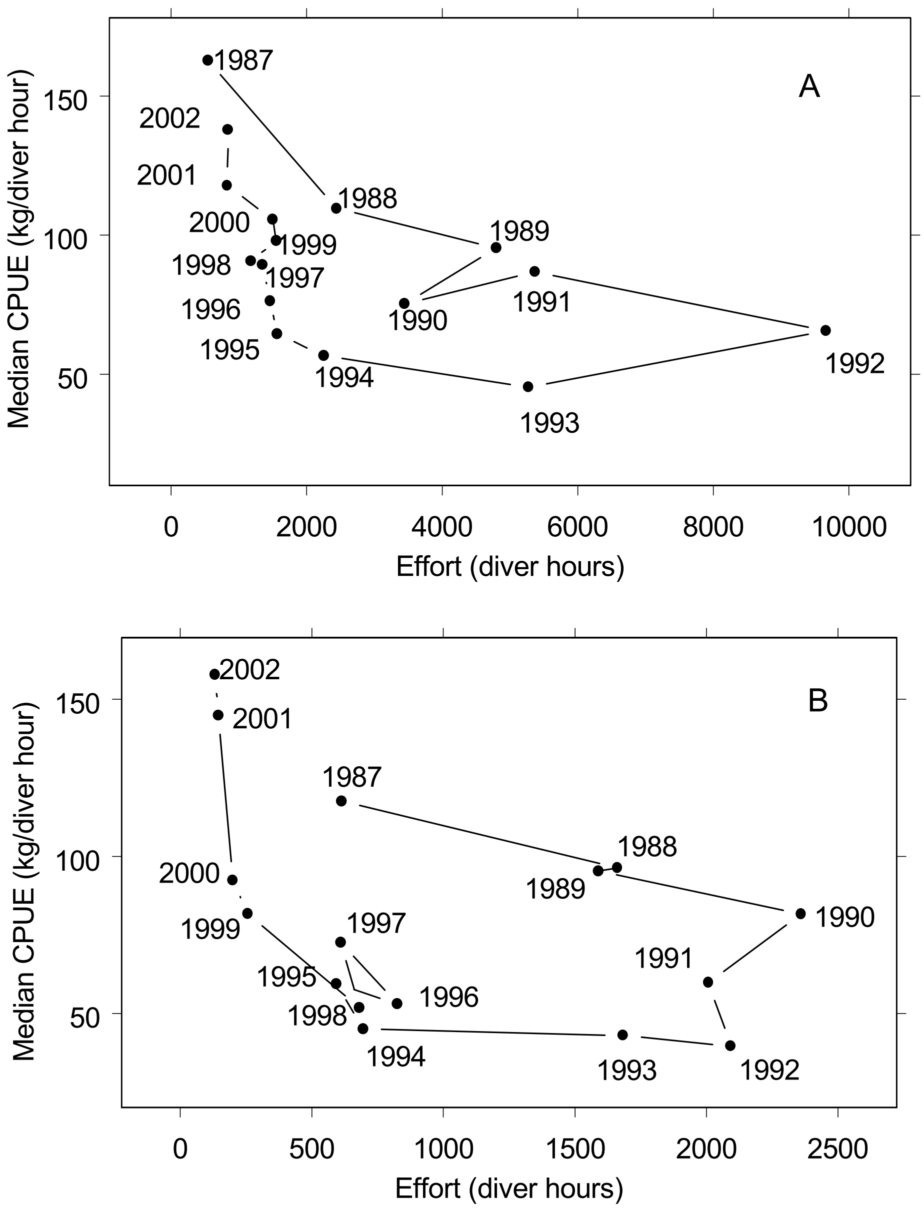


Fig. 7. Trajectories of median catch per unit of effort *versus* effort for the South Coast - northern (PFMA 11-13; A) and southern (PFMA 17-20,28: B) regions. Fishing seasons are indicated.

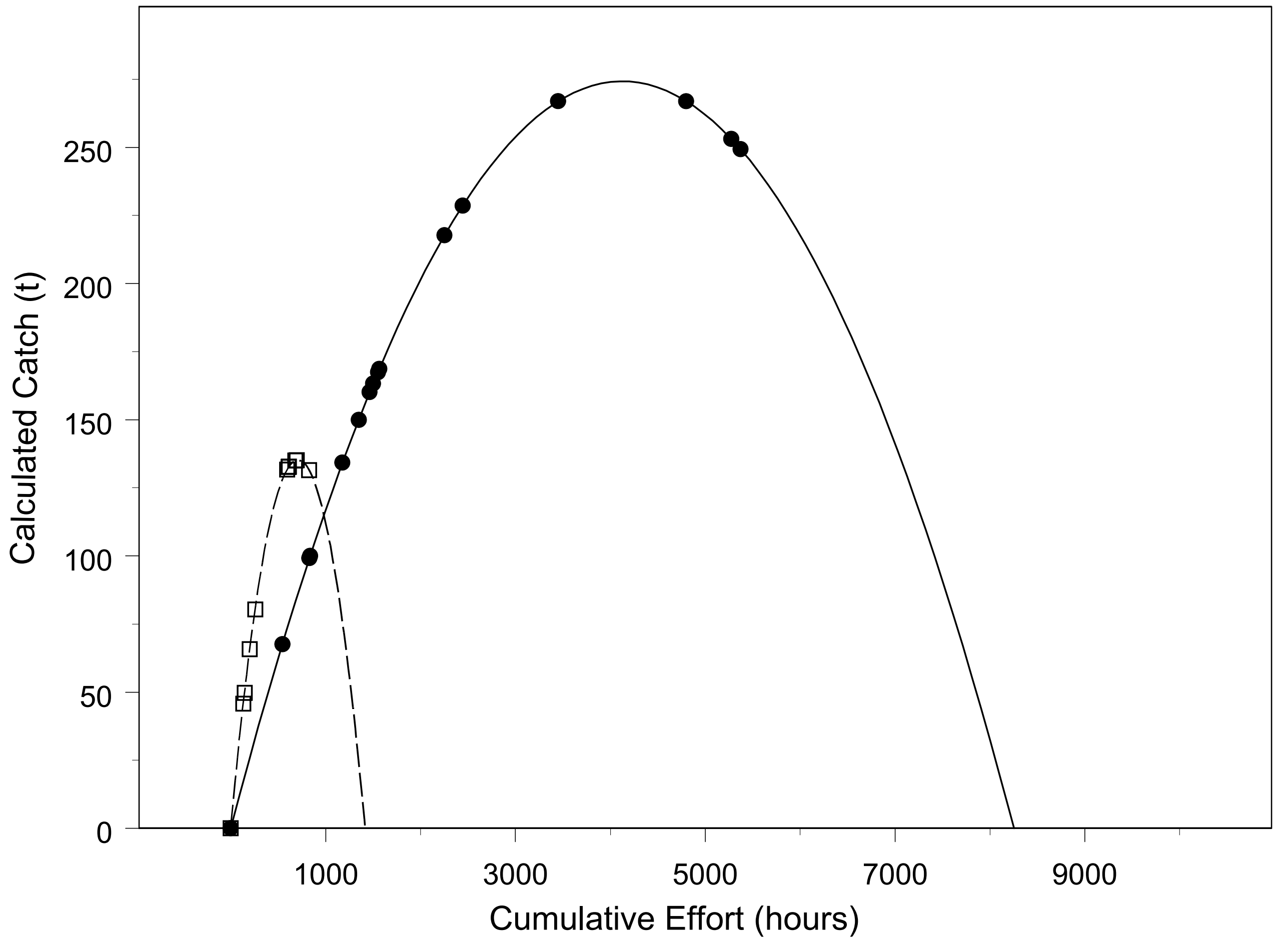


Fig. 8. Predicted Schaeffer model (Schnute version; text equation 5) for the biomass dynamic production model for the South Coast - inside waters northern region (PFMA 11-13; solid circles) and southern region (PFMA 17-20, 28**;** open squares). Peak of the dome for each model represents the estimated MSY and effort at MSY as estimated by the Schnute formulation.

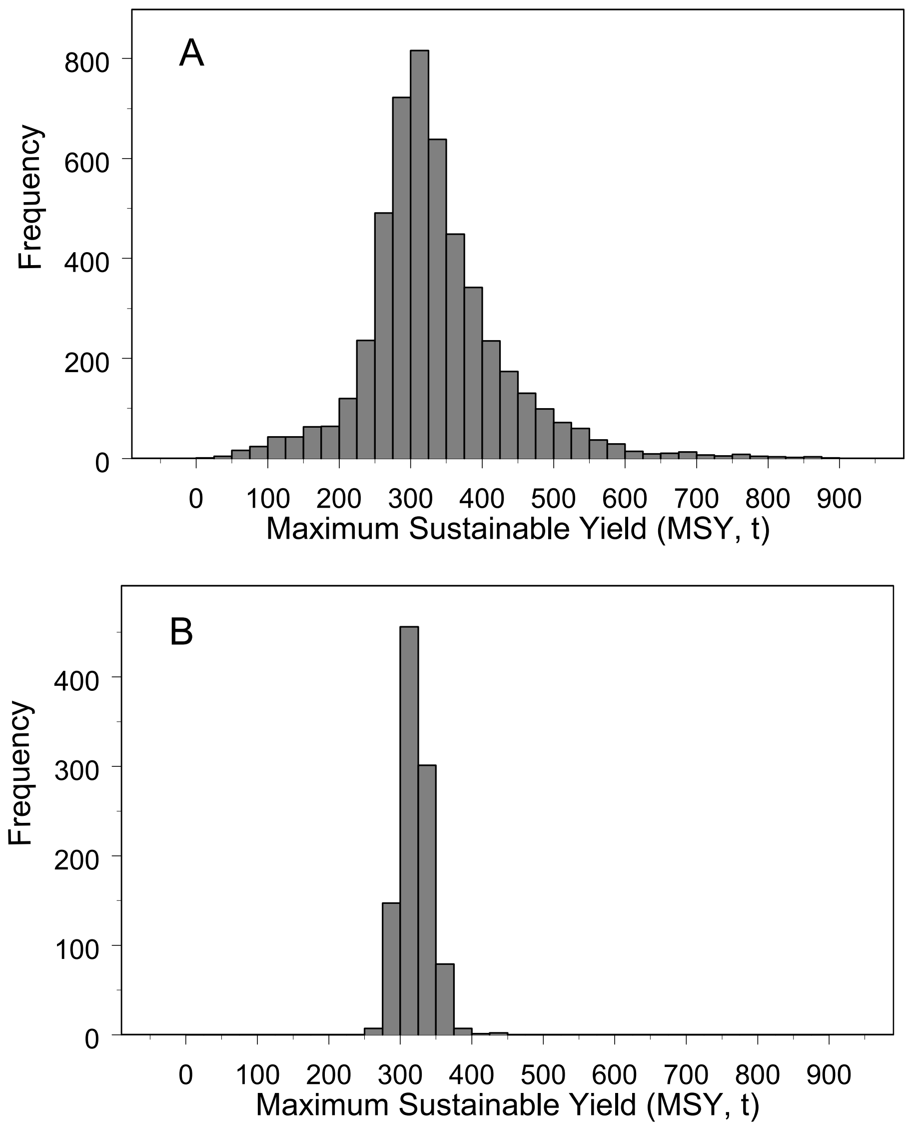
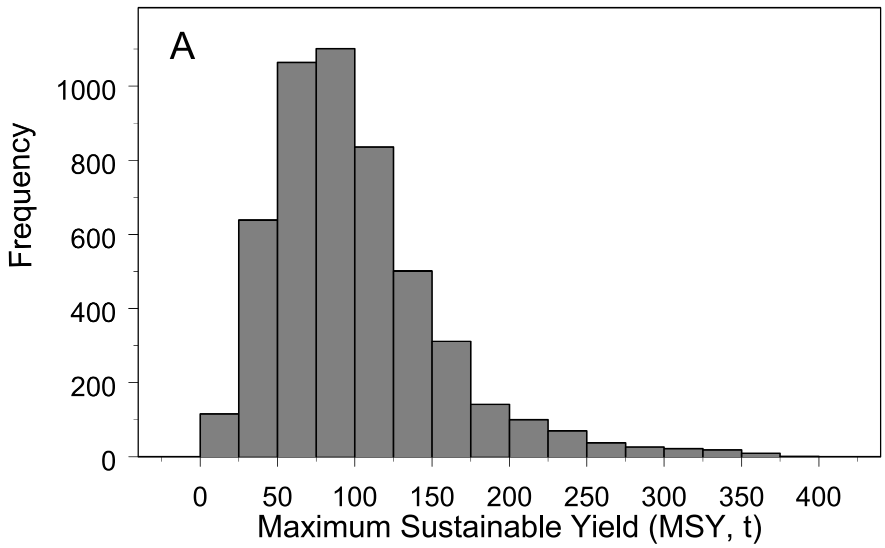


Fig. 9. Probability distribution for maximum sustainable yield (MSY) as estimated from (A) the Bayesian analysis; and (B) the time series fitting method for the biomass dynamic model for the Queen Charlotte Strait region (PFMA 11-13). Probability distributions are based on 5000 randomisations for the Bayesian analysis, and 1000 randomisations for the time series fitting method.



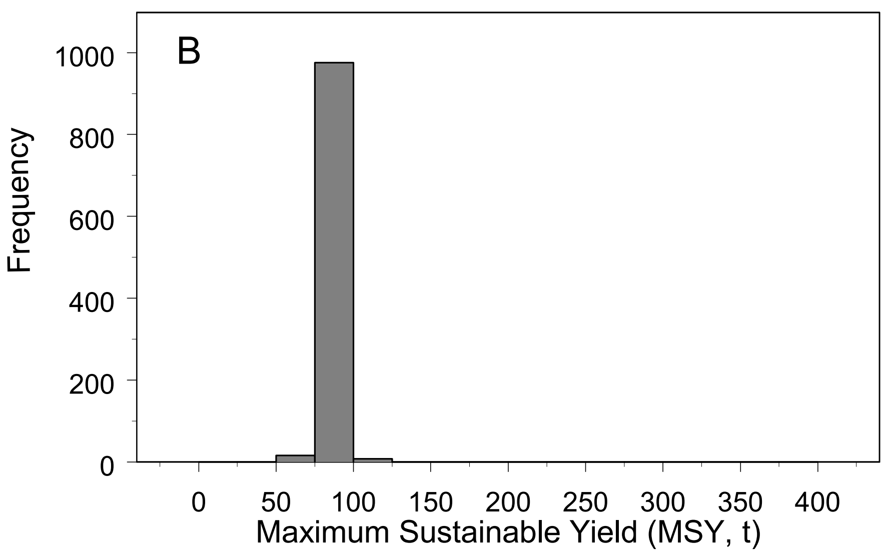


Fig. 10. Probability distribution for maximum sustainable yield (MSY) as estimated from (A) the Bayesian analysis; and (B) the time series fitting method for the biomass dynamic model for the Gulf Islands (PFMA 17-20,28). Probability distributions are based on 5000 randomisations for the Bayesian analysis, and 1000 randomisations for the time series fitting method.

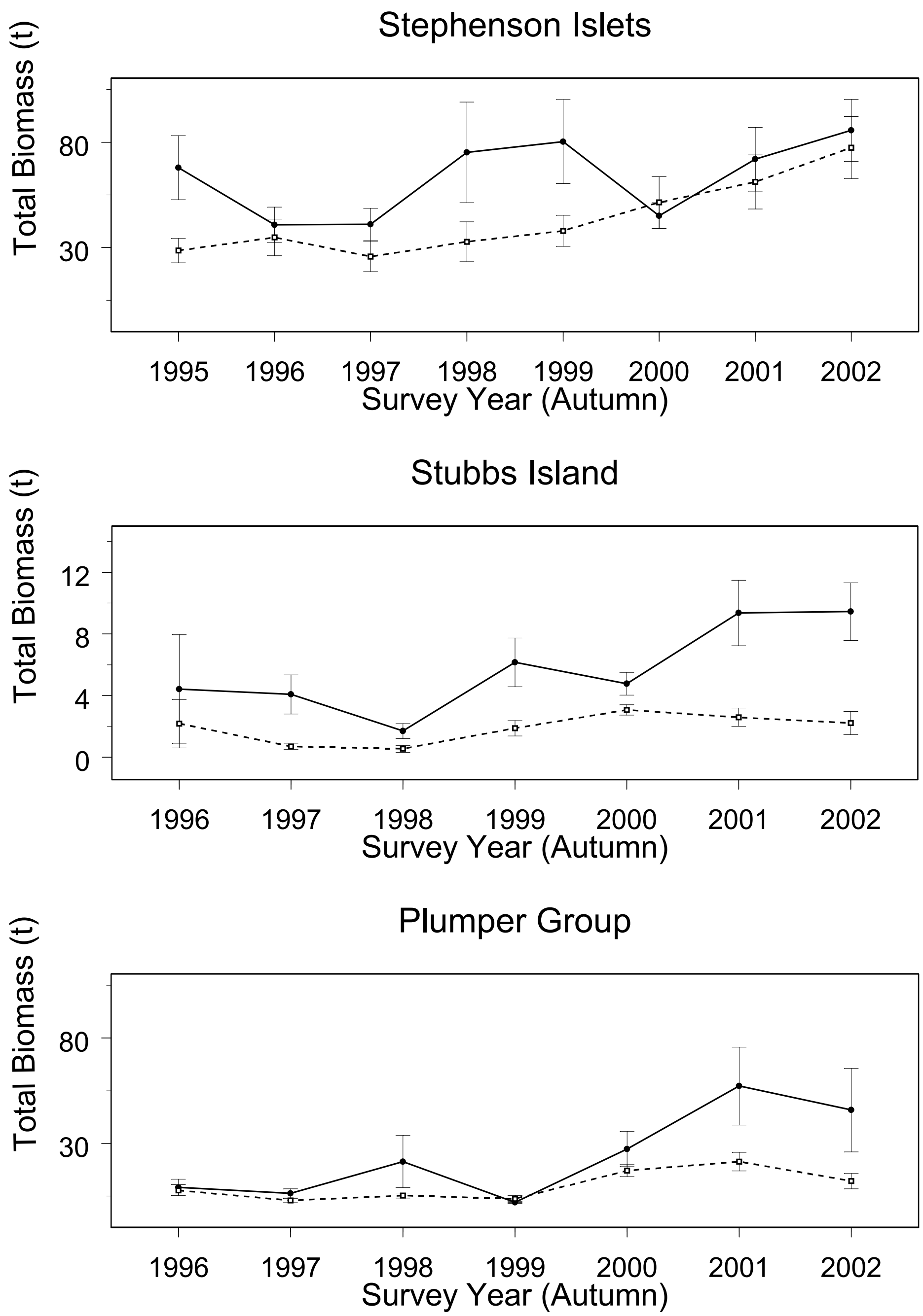


Fig. 11. Biomass estimated from fishery-independent surveys conducted annually in the autumn (October or November) in Area 12. Solid line: legal-sized biomass; dashed line: sub-legal sized biomass. Error bars represent standard errors about the mean.

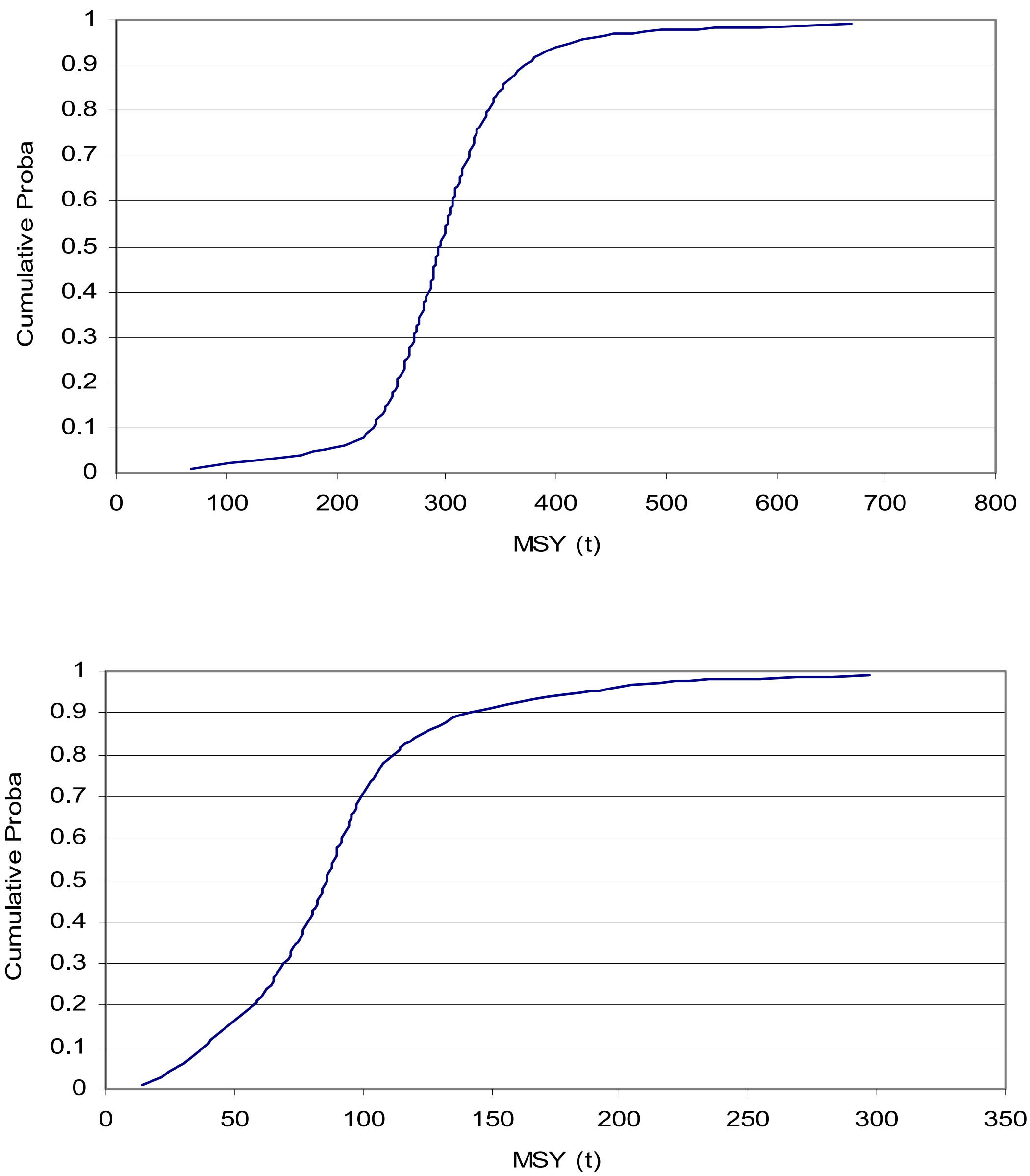


Fig. 12. Cumulative probability curves for estimates of Maximum Sustainable Yield (MSY, t) calculated from the Bayesian analysis for Queen Charlotte Strait (PFMA 11-13; top panel) and the Gulf Islands (PFMA 17-20,28: bottom panel). These curves indicate the probability that the "true" value of MSY (as calculated by the model) is less than or equal to any particular value of MSY. For example, for PFMA 11-13 (top panel), the probability that the "true" MSY is less than or equal to 250 t is about 0.1 (or 10%).

Appendix 1. PSARC INVERTEBRATE SUBCOMMITTEE

Request for Working Paper

Date Submitted: January 21, 2003

Individual or group requesting advice: Guy Parker - Fish Management
(Fisheries Manager/Biologist, Science, SWG, PSARC, Industry, Other stakeholder etc.)

Proposed PSARC Presentation Date: June 2003

Subject of Paper (title if developed): Quota recommendations for the Green Sea Urchin Fishery (and other nautical tales from the sea)

Stock Assessment Lead Author: Ian Perry (or to be determined by Stad)

Fisheries Management Author/Reviewer: Guy Parker/Erin Wylie

Rational for request: To provide an updated analysis of fisheries dependent and stock assessment survey data and develop quota options for the 2003-2005 fishing plan.

Objective of Working Paper: Calculation of green sea urchin harvest quota options in all areas of the coast for which data is available or areas in which fishing currently is conducted. Incorporation of relevant information from recent green urchin surveys conducted by the department and other groups on the coast (first nations, industry). Presentation of biological data collected from commercial fishery sampling (D&D) and from the independent surveys conducted by stock assessment.

Question(s) to be addressed in the Working Paper: What are the quota options available in this fishery and the risks associated with applying each one? From the analysis of the data collected in this fishery to date, are there any recommendations on improved methods or alternatives for conducting future stock assessment monitoring of stocks and fisheries impacts? What are the present short falls in the green urchin stock assessment programs? What future or additional data needs to be collected to refine future quota and biomass estimates?

Appendix 2. Bayesian analysis

1. *Commercial catch data*

There are 16 years of commercial catch and effort data (1987-2002). In the model, the years are sequentially named from year 1 for 1987 to year 16 for 2002.

2. *Uncertainties about true catches and fishing effort in the early years (years 1-9)*

Catch and effort data from the early years of the fishery (1987 – 1995) are very uncertain, because of the boom nature of the fishery (e.g. Fig. 4), variable recording diligence, and different strategies of fishing. Therefore, the true catch in each of the early years is modeled using a normal distribution with the reported catch as the mean and a large (30%) coefficient of variation. Thus, the likelihood of the true catch in year y (1<=y<=9), LC_y, is:

$$LC_y = \frac{1}{\sqrt{2\pi}\, sdc_y} \exp\left(-\frac{\left(C_y - \hat{C}_y\right)^2}{2sdc_y^{\,2}} \right)$$

where C_y and $\hat{C}_y$ are the true and reported catches in year y, and sdc_y ($= 30\%\hat{C}_y$) is the standard deviation for the true catch in year y.

Similarly, the true fishing effort in each of the early years is modeled using a normal distribution with the reported effort as the mean and a 30% coefficient of variation. The likelihood of the true effort in year y (1<=y<=9), LE_y, is:

$$LE_y = \frac{1}{\sqrt{2\pi}\, sde_y} \exp\left(-\frac{\left(E_y - \hat{E}_y\right)^2}{2sde_y^{\,2}} \right)$$

where E_y and $\hat{E}_y$ are the true and reported fishing effort in year y, and sde_y ($= 30\%\hat{E}_y$) is the standard deviation for the true effort in year y.

In later years (years 10-16; 1996-2002) the reported catch and effort are assumed to represent the true catch and effort, because of careful monitoring and dockside validation.

3. *Fisheries independent surveys*

Surveys were conducted in Stephenson Islet, Stubbs Island, and Plumper Islands in the fall of years 10-16. The estimated abundance of green sea urchins in the surveyed area serves as an index for the abundance of green sea urchin in the entire region (e.g. Queen Charlotte Strait-Johnstone Strait). We assume that the biomass in the surveyed area is proportional to the biomass in the entire region:

$$SB_y = \rho \times B_y$$

where SB_y is the biomass in the surveyed area in year y, B_y is the true biomass in the entire region in year y, and ρ is an unknown proportional coefficient. The likelihood for SB_y for PFMA 11-13 (10<=y<=16) is:

$$LSB_y = \frac{1}{\sqrt{2\pi}\, sds_y} \exp\left(-\frac{\left(\rho \times B_y - S\hat{B}_y\right)^2}{2 sds_y{}^2} \right)$$

where $S\hat{B}_y$ and sds_y are the estimated biomass and the associated standard deviation based on the survey data in year y.

Surveys were also conducted in the Gulf Islands region. The most intensively surveyed spot is Boiling Reef, which was surveyed from 1999 to 2001. However, it may not be appropriate to use the biomass estimated from these surveys as an index for the entire Gulf Islands region, as each of the three surveys only comprised one or two survey transects. Thus, survey data were not used in the modeling for green urchin population in the Gulf Islands region.

4. Biomass Dynamic Model

The expected animal biomass in year y, $\hat{B}_y$, is related to the biomass in the previous year, B_{y-1}:

$$\hat{B}_y = B_y + r \times B_{y-1}\left(1 - \frac{B_{y-1}}{K}\right) - C_y$$

where *r* is an intrinsic rate of population growth, *K* is the average maximum biomass the system can support (carrying capacity), and C_y is the commercial catch in year y. The expected catch per unit effort in year y, $\hat{U}_y$, is assumed to be proportional to the biomas in year y:

$$\hat{U}_y = q \times B_y$$

where *q* is known as the catchability coefficient.

Previously, we used both the process error approach (Schnute model) and the observation error approach (time-series) to estimate the model parameters, *r*, *K*, and *q* and the standard deviation for the observation error (Perry et al. 2001, 2002).

5. *State-Space Model*

State-space modeling allows us to incorporate both observation and process errors into the model fitting. Both errors are assumed to follow the log-normal distribution. The stochastic forms of the process and observation equations are:

$$\log(B_y) = \log(\hat{B}) + \mu_y$$

$$\log(U_y) = \log(\hat{U}_y) + \nu_y$$

where the u_y and v_y are independent random variables from N(0, σ^2) and N(0, τ^2) respectively. Re-parametization was carried out to increase the Markov chain mixing speed and to reduce parameter correlations (Miller and Meyer, 2000).

$$\begin{cases} R = r \times K \\ Q = q \times K \\ P_y = B_y / K \end{cases}$$

The stochastic forms of the equation then become:

$$\log(P_y) = \log(\hat{P}_y) + \mu_y$$

$$\log(U_y) = \log(\hat{U}_y) + \nu_y$$

where the expected $\hat{P}_y$ is calculated as:

$$\begin{cases} \hat{P}_y = 1 & (if \quad y = 1) \\ \hat{P}_y = P_{y-1} + \dfrac{R}{K} \times P_{y-1} \times (1 - P_{y-1}) - \dfrac{C_y}{K} & (if \quad y > 1) \end{cases}$$

and the expected $\hat{U}_y$ is calculated as:

$$\hat{U}_y = Q \times P_y$$

Given $\hat{P}_y$, the likelihood for P_y is:

$$LP_y = \frac{1}{\sqrt{2\pi}\sigma P_y} \exp\left(-\frac{\left(\log(P_y) - \log(\hat{P}_y)\right)^2}{2\sigma^2} \right)$$

The likelihood for U_y is:

$$LU_y = \frac{1}{\sqrt{2\pi}\tau U_y} \exp\left(-\frac{\left(\log(U_y) - \log(\hat{U}_y)\right)^2}{2\tau^2} \right)$$

6. *Prior Probability Distribution*

There are altogether 40 parameters in the model for the green sea urchin in the Queen Charlotte region: standard deviation for process error (σ); standard deviation for observation error (τ); Q, R, K, ρ; 9 true catches in the first 9 years ($C_y \quad (1 <= y <= 9)$); 9 true fishing effort in the first 9 years ($E_y \quad (1 <= y <= 9)$); 16 ratios of biomass to the carrying capacity ($P_y \quad (1 <= y <= 16)$). There are 39 parameters in the model for the green sea urchin in the Gulf region (without ρ).

An inverse gamma distribution was specified for both σ and τ:

$$\pi(\sigma) = \frac{\exp\left(-\frac{1}{\beta\sigma}\right)}{\Gamma(\alpha) \times \beta^{\alpha} \times \sigma^{\alpha+1}} \qquad (\sigma > 0, \quad \alpha > 0 \quad \beta > 0)$$

$$\pi(\tau) = \frac{\exp\left(-\frac{1}{B\tau}\right)}{\Gamma(a) \times B^{a} \times \tau^{a+1}} \qquad (\tau > 0, \quad a > 0 \quad B > 0)$$

The expected σ and the standard deviation of the inverse gamma distribution were both set to be the maximum likelihood estimate of the standard deviation for the observation error ($\hat{\tau}$) using the time-series method. This results in a reasonably vague specification with $\alpha = 3$ and $\beta = \frac{1}{2 \times \hat{\tau}}$ (Carlin and Louis, 1998). Similarly, the expected τ and the corresponding standard deviation were also set to be the same as $\hat{\tau}$, resulting in $a = 3$ and $B = \frac{1}{2 \times \hat{\tau}}$. R follows the log normal distribution:

$$\pi(R) = \frac{1}{\sqrt{2\pi}\,\delta R} \exp\left(-\frac{\left(\log(R) - \overline{R}\right)^2}{2\delta^2} \right)$$

where $\overline{R}$ is the expected R on the log scale, and δ is the standard deviation. An interval around the maximum likelihood estimate is taken to express an area of high prior probability for R. The points of 50% and 150% of the maximum likelihood estimate of R were taken, respectively, to be the 30th and 70th percentile points of the lognormal distribution for the Queen Charlotte region, to be 25th and 75th percentile points for the Gulf region. Mean and standard deviation for the lognormal distribution were calculated using the method of Abramowitz and Stegun (1970). The prior distributions for the remaining parameters were taken to be uninformative. The catchability coefficient, q, has an uniform distribution on the log-scale, ρ has a standard uniform distribution between 0 and 1, and K, $C_1 - C_9$, $E_1 - E_9$, and $P_1 - P_{16}$ have positive uniform distributions.

7. *Bayesian Theorem*

Based on the Bayesian theorem, the posterior probability for a vector of parameters θ is:

$$p(\theta \mid x) = \frac{L(x \mid \theta) \times \pi(\theta)}{\int L(x \mid \vartheta) \times \pi(\vartheta) d\vartheta}$$

where $L(x \mid \theta)$ is the likelihood of the data given the parameter value, θ, $\pi(\theta)$ is the prior probability, and $\int L(x \mid \vartheta) \times \pi(\vartheta) d\vartheta$ is a normalizing constant to make sure the probability for any particular value of θ within the set range is between 0 and 1 and the accumulated probability sums to unity. In most cases, the normalizing constant does not have a closed form and is very hard, if possible at all, to be calculated. Markov Chain Monte Carlo (MCMC) simulations enable us to formulate the marginal probability distributions by sampling from the posterior distribution, which is proportional to the product of likelihood of the data and prior distributions, with no need of knowing the normalizing constant. The method involves selecting a starting parameter vector and generating a sequence of parameter vectors (like chains), which converge to the posterior distribution. The posterior distributions in our study can be expressed as follows:

for the Queen Charlotte Strait region:

$$p(\sigma, \tau, Q, R, K, \rho, C_1 ... C_9, E_1 ... E_9, P_1 ... P_{16}) \propto (\sigma)\pi(\tau)\pi(q)\pi(R) \times \\ \times \prod_{y=1}^{16} LP_y \times LU_y \prod_{y=1}^{9} LC_y \times LE_y \prod_{10}^{16} LSB_y$$

for the Gulf Islands region:

$$p(\sigma, \tau, Q, R, K, C_1 ... C_9, E_1 ... E_9, P_1 ... P_{16}) \propto (\sigma)\pi(\tau)\pi(q)\pi(R) \times \\ \times \prod_{y=1}^{16} LP_y \times LU_y \prod_{y=1}^{9} LC_y \times LE_y$$

8. *Full Conditional Distribution*

The full conditional distribution for parameter θ_i is the distribution of θ_i conditioned on all the remaining parameters. To express the full conditional distribution for a parameter, all other parameters are treated as known and their current values are used. To construct the full conditional distribution for θ_i, $f(\theta_i)$, we need only to pick the terms in the posterior distribution which involve θ_i (Gilks et al. 1996). Thus, the full conditional distribution is proportional to the posterior probability. The full conditional distribution for each of the parameters in our study is as follows:

σ :

$$f(\sigma) = \pi(\sigma)\prod_{y=1}^{16} LP_y$$

τ :

$$f(\tau) = \pi(\tau)\prod_{y=1}^{16} LU_y$$

Q:

$$f(Q) = \pi(Q)\prod_{y=1}^{16} LU_y$$

R:

$$f(R) = \pi(R)\prod_{y=1}^{16} LP_y$$

K:

$$f(K) = \prod_{y=1}^{16} LP_y \prod_{y=10}^{16} LBS_y$$ (for the Queen Charlotte Strait region)

$$f(K) = \prod_{y=1}^{16} LP_y$$ (for the Gulf Islands region)

ρ :

$$f(\rho) = \prod_{y=10}^{16} LBS_y$$ (for the Queen Charlotte Strait region)

C_y (1<=y<=9):

$$f(C_y) = LC_y \times LU_y \times LP_{y+1}$$

E_y (1<=y<=9):

$$f(E_y) = LE_y \times LU_y$$

P_y:

$$\begin{cases} f(P_y) = LP_y \times LP_{y+1} \times LU_y & (if \quad 1 <= y <= 9) \\ f(P_y) = LP_y \times LP_{y+1} \times LU_y \times LSB_Y & (if \quad 10 <= y <= 15) \\ f(P_y) = LP_y \times LU_y \times LSB_Y & (if \quad y = 16) \end{cases} \qquad \text{(for Queen Charlotte region)}$$

$$\begin{cases} f(P_y) = LP_y \times LP_{y+1} \times LU_y & (if \quad 1 <= y <= 15) \\ f(P_y) = LP_y \times LU_y & (if \quad y = 16) \end{cases} \qquad \text{(for Gulf Islands region)}$$

9. *Metropolis algorithm*

The commonly used MCMC technique, the Metropolis algorithm, was applied in the study. A general version of the Metropolis algorithm for sampling from the posterior distribution $p(.|x)$ is that, at each iteration *t*, the next state θ_{t+1} is chosen by first sampling a candidate point ϑ_t from a proposal distribution $q(.|\theta_t)$. The candidate point ϑ_t is then accepted with the following probability:

$$p = \min\left(1, \frac{p(\vartheta_t) \times q(\theta_t | \vartheta_t)}{p(\theta_t) \times q(\vartheta_t | \theta_t)}\right)$$

If the candidate point is accepted, the next state becomes $\theta_{t+1} = \vartheta_t$, otherwise the chain does not move, i.e. $\theta_{t+1} = \theta_t$. Remarkably, the proposal distribution can have any form (Gilks et al. 1996). In our study, we used a uniform distribution as the proposal distribution for each parameter.

The Metropolis algorithm may be applied simultaneously to all elements of the parameter vector. In this case, a multivariate probability kernel which converges to the joint probability distribution needs to be established, so that random samples can be drawn from it. The algorithm can also be applied in one block-at-a-time or one variable-at-a-time (Hasting 1970, Chib and Greenberg 1995). In this case, only full conditional density functions that converge to their respective conditional distributions are needed for random sampling. It is usually far easier to establish full conditional density functions than to find one function that converges to the joint probability distribution (Chib and Greenberg, 1995). We used the second approach, the procedure of which generally follows the description by Clifford (1994), Gilks et al. (1996), and Quinn and Deriso (1999):

Step 0: Choose an arbitrary starting point for each element of θ_i (the vector θ is of length m; m=40 for Queen Charlotte region and m=39 for Gulf region), and then set $t = 1$ (1st iteration) and $i = 1$ (1st parameter);

Step 1: Calculate the likelihood for parameter θ_i at iteration *t*, $y_{t,i}$, from the corresponding full conditional distribution $y_{t,i} = f(\theta_{t,i})$;

Step 2: Generate a proposal value, $\vartheta_{t,i}$, for parameter θ_i at iteration *t*, from an uniform distribution $[\theta_{t,i} - \Delta_{t,i}, \theta_{t,i} + \Delta_{t,i}]$;

Step 3: Calculate the likelihood, $y'_{t,i}$, for the proposal $\vartheta_{t,i}$ from the full conditional distribution $y'_{t,i} = f(\vartheta_{t,i})$;

Step 4. Generate a random number, *r*, from the standard uniform distribution (0, 1);

Step 5. Let $\theta_{t+1,i} = \vartheta_{t,i}$, if $r < y'_{t,i} / y_{t,i}$; otherwise let $\theta_{t+1,i} = \theta_{t,i}$;

Step 6. Increment *i* by one, if $i < m$; set $i = 1$ and increment *t* by one, if $i = m$;

Step 7. Go back to Step 1, if $i < m$ or $t < n$ (the predetermined number of iterations); the whole process is finished, if $i = m$ and $t = n$.

Clifford (1994) recommended dynamic adjustment of Δ so that candidate samples are accepted about 50% of the time. In our study, Δ was dynamically adjusted by increasing or decreasing by 5% if the proposal samples for the previous five cycles had been accepted more or less than 50% of the time. Initial values were set to be the maximum likelihood estimates based on the time series approach. The results of the first 100,000 cycles were ignored as a "burn-in" period for the algorithm to set itself up. All together, 2,600,000 cycles were conducted. After the initial results from 100,000 cycles were discarded, every 500th sample was saved to reduce autocorrelation. Convergence of the simulations were tested using the Heidelberger and Welch test and Geweke tests from the program CODA (Convergence Diagnosis and Output Analysis Software for Gibbs sampling output version 0.40) (Best et. al. 1997). The tests did not show evidence against convergence.

References

Abramowitz, M., and Stegun, I. 1970. Handbook of mathematical functions. Dover, New York.

Best, N.G., Cowles, M.K., and Vines, S.K. 1997. CODA Manual version 0.40. MRC Biostatistics Unit, Cambridge, U.K.

Carlin, B.P., and T.A. Louis. 1996. Bayes and empirical bayes methods for data analysis. Chapman and Hall, London, U.K.

Chib, S., and Greenberg, E. 1995. Understanding the Metropolis-Hastings algorithm. Am. Stat. 49: 327-335.

Clifford, P. 1994. Discussion of the paper by Newton and Raftery. J. R. Statist. Soc. B 56: 34-35.

Gilks, W.R., Richardson, S., and Spiegelhalter, D.J. 1996. Markov chain Monte Carlo in practice. Chapman and Hall, London. UK.

Hastings, W.K. 1970. Monte Carlo sampling methods using Markov chains and their applications. Biometrika. 57:97-109.

Miller, R.B., and Meyer, R. 2000. Non-linear state space modelling of fisheries biomass dynamics using Metropolis-Hastings within-Gibbs sampling. Appl. Statist. 49: 327-342.

Perry, R.I., B. Waddell and Z. Zhang. 2001. Assessment of green sea urchin (S*trongylocentrotus droebachiensis*) stocks in British Columbia, 2001. Canadian Stock Assessment Secretariat Res. Doc. 2001/137. 42pp.

Perry, R.I., Zhang, Z., and Harbo, R. 2002. Development of the green sea urchin (*Strongylocentrotus droebachiensis*) fishery in British Columbia, Canada - back from the brink using a precautionary framework. Fish. Res. 55: 253-266.

Quinn, T.J., and Deriso, R.B. 1999. Quantitative fish dynamics. Oxford University Press, New York.