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Review of the fishery and assessment of green sea urchin stocks in British Columbia, with quota recommendations for 1999/2000

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ABSTRACT

This paper (i) reviews the green sea urchin (*Strongylocentrotus droebachiensis*) fishery in British Columbia since its inception in 1987, with emphasis on recent years (post-1995); (ii) updates a biomass dynamic model to determine green urchin stock status in British Columbia; and (iii) presents initial results of fishery-independent surveys for green urchins. The green urchin fishery in B.C. developed rapidly from 1987 to 1991, and peaked in 1992 with landings of 1042 t. Declining landings and catch per unit of effort followed and management restrictions were implemented in 1992. In 1995, an individual quota system with dockside validation was implemented. In 1997/98, coastwide landings (all in the South Coast) were 160 t, approximately equal to the quota. The principal Pacific Fishery Management Areas for green sea urchins are 12, 13 (Queen Charlotte and Johnstone Straits) and 18, 19, 20 (Gulf Islands - Juan de Fuca Strait). Harvest logbook information is collected as a condition of licence, and verified against quota validation records. Median catch per unit of effort (CPUE) was calculated from the harvest logbook data to provide an index of changes in stock size. Analyses are conducted on a fishing season basis (1 October of year *i* to 31 March of year *i*+1). Biomass dynamic models were developed for the South Coast - inside waters northern region (PFMA 11,12,13) and South Coast - inside waters southern region (PFMA 17-20,28). Total allowable catches in the range of 25-50% * MSY are recommended to account for uncertainties in the input data and assumptions in the dynamic production models. Recommended yield options for the South Coast range from 144-289 t. A TAC calculated for PFMA 4 on the North Coast of B.C., based on a fishery-independent survey, is 6.1 t (calculated as a 10% exploitation rate applied to the surveyed biomass). Seven fishery-independent surveys were conducted in a core fishing area of PFMA 12 in eastern Queen Charlotte Strait. The lower 95% confidence bound of the mean annual legal-sized (≥55 mm test diameter) biomass for PFMA 11,12,13 from these surveys is similar to the biomass estimated by the dynamic production model. Information from the biomass dynamic model results, fishery-independent surveys, and reports from fishermen suggest that the stock in the South Coast - northern region is relatively abundant with recent good recruitment, whereas the status of the stock in the South Coast - southern region is more uncertain.

RÉSUMÉ

On trouve dans le document (i) un examen de la pêche de l'oursin vert (*Strongylocentrotus droebachiensis*) en Colombie-Britannique qui couvre toute la période de pêche, depuis ses débuts en 1987, mais qui met l'accent sur les dernières années (après 1995) ; (ii) des mises à jour d'un modèle dynamique de la biomasse visant à déterminer l'état du stock d'oursin vert en Colombie-Britannique et (iii) une présentation des résultats préliminaires de relevés effectués de façon indépendante des pêches. La pêche de l'oursin vert de la C.-B. a rapidement pris de l'ampleur de 1987 à 1991 pour atteindre un maximum en 1992, où les débarquements ont atteint 1 042 t. Les débarquements et les prises par unité d'effort ont ensuite diminué et des limites ont été imposées en 1992. Un régime de quotas individuels avec contrôle à quai a été instauré en 1995. En 1997-1998, les débarquements à l'échelle de toute la côte (provenant tous de la côte Sud) ont atteint 160 t, soit

environ la valeur du quota. Les principales zones de gestion de la pêche de l'oursin vert du Pacifique sont les zones 12 et 13 (détroits de la Reine-Charlotte et Johnstone) et les zones 18, 19 et 20 (îles Gulf et détroit Juan de Fuca). Les renseignements des registres de pêche sont recueillis à titre d'une condition du permis et vérifiés à l'aide des registres de contrôle des quotas. La valeur médiane des prises par unité d'effort (PUE) a été calculée à partir des données des registres de pêche afin d'obtenir un indice de l'évolution de l'effectif du stock. Les analyses sont effectuées sur la base de la saison de pêche (1er octobre de l'année *i* au 31 mars de l'année *i* + 1). Des modèles de la dynamique de la biomasse ont été élaborés pour la partie nord (zones 11, 12 et 13) et la partie sud (zones 17 à 20 et 28) des eaux de l'intérieur de la côte Sud. Le total des prises admissibles correspondant à de 25 à 50 % du RMS est recommandé afin de tenir compte des incertitudes connexes aux données de base et aux hypothèses des modèles de production dynamiques. Les options de rendement recommandées pour la côte Sud vont de 144 à 289 t. Le TPA calculé pour la zone de gestion 4 de la côte Nord de la C.-B. à partir d'un relevé indépendant des pêches s'élève à 6,1 t (taux d'exploitation de 10 % de la biomasse déterminée par relevé). Sept relevés indépendants des pêches ont été réalisés dans une région de pêche principale de la zone de gestion 12, dans l'est du détroit de la Reine-Charlotte. La limite de confiance inférieure à 95% de la moyenne de la biomasse annuelle, fondée sur la taille légale (≥ 55 mm de diamètre) pour les zones de gestion 11, 12 et 13, obtenue des relevés est semblable à celle estimée à l'aide du modèle de production dynamique. Les résultats du modèle dynamique de la biomasse, les relevés indépendants des pêches et les rapports des pêcheurs portent à croire que le stock de la région nord de la côte Sud est relativement abondant et que son recrutement récent est assez bon. L'état du stock de la région sud de la côte Sud est cependant plus incertain.

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), and Perry and Waddell (1998). The objectives of the current assessment are:

1) to 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 October 1996 - March 1997 and November 1997 - March 1998 fishing seasons;

2) to update the biomass dynamic production model of Perry *et al*. (1998) and Perry and Waddell (1998) with data collected since the 1995-96 fishery, and to provide recommendations for harvest yields; and

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

BIOLOGY AND FISHERY BACKGROUND

Biology

The distribution and biology of green sea urchins in B.C. is summarised by Harbo and Hobbs (1996), but is generally poorly known. 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. They occur intertidally 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 from 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 unpredictable (in space and time) aggregations are common. 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 (Schiebling and Hennigar 1997). This amoeba has not been observed on the Pacific Coast of Canada to date.

Fisheries

Fisheries for green sea urchins occur on the Atlantic coast of Canada and in Maine, Alaska, and Washington states. In Alaska, green urchins are allowed to be harvested commercially only in the Central and Westward regions, with red urchins (*S. franciscanus*) the only urchin allowed to be harvested in the SE Region. In the Kodiak region in 1996, the green urchin fishery occurred during November and December, with 7 divers landing 16.4 t. In 1997 in this region, only 4 divers and 2 processors participated, and therefore the data remain confidential (PSFMC 1997). In Washington State in 1996, 200 t of green sea urchins were landed, which was higher than in 1995 primarily because of increased harvesting by natives. The 1997 harvest of green urchins (114 t) was lower than in 1996 due to quality problems (PSFMC 1997). The quota applied in Washington for green urchins is 204 t.

The fishery in B.C. developed rapidly, with landings reaching a peak of 1042 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 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 the assessments of Perry *et al*. (1998) and Perry and Waddell (1998), the data analyses were conducted on a "fishing season" basis, i.e. from the fall of one year to the spring of the following year. This lead to revision of the licence year so as to expire in summer (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). Fishers report that their fishing practices have changed as a result of quota restrictions and market demands for high quality roe, i.e. they now spend more time searching for high quality roe. However, some fishers on the South Coast indicate that despite the increased search time they continue to fish the same grounds with catches similar to previous years. The North Coast fishery suffered from poor roe yields and quality (Harbo and Hobbs 1996), and has been closed to fishing since 1997.

Perry *et al*. (1998) and Perry and Waddell (1998) recommended separating green sea urchin populations on the B.C. coast into four broad "stocks", rather than assuming they represent a single contiguous population. This present assessment follows this recommendation 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); and the west coast of Vancouver Island] (Fig. 1). 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 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.

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, i.e. year *i*, so that 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 Biological Data and Analysis Division (DFO, Vancouver). Detailed information on catch, effort, depth and locations fished for all fishing seasons (1987-1997) are provided in the fishers' harvest logbooks. Perry and Waddell (1998) used the median annual catch per unit of effort (U_{mi})

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

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 both catch and 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, with se_i the standard error of the annual mean catch per unit of effort as calculated from individual logbook records. 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 landings (L_i) divided by the catch per unit of effort (U_{Mi}) from the harvest logbook database

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

Changes in the range of depths fished may be useful as additional information on the status of the stocks (for example if fishers must consistently go deeper to find harvestable concentrations of urchins). We calculated mean maximum depths fished from the harvest logbook data, excluding zero values and excluding the average depth values occasionally provided by fishers.

Biomass Dynamic Model

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

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

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}), 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, 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 is represented as

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

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	$r/2q$

Since 1995-96 all fishing plans have restricted fishing in the South Coast to the traditional core fishing areas (PFMA 11,12,13; 17-20, 28). In the current assessment, the biomass dynamic production model was calculated using data for all years but only from these core fishing areas. Historically these core areas have contributed >90% to the coastwide landings of green sea urchins in B.C.

Biological Subsampling of Landings

Subsampling 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. The data are summarised as means and standard deviations by month and Statistical Area.

Fishery-independent Surveys

Scientific 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 area. These surveys have been conducted just prior to the opening, and just after the closing, of the fisheries in fishing seasons 1995, 1996, 1997, and 1998. Waddell *et al*. (1997) provide a detailed report of the methods and of the first set of surveys (October 1995 and March 1996, which sampled Stephenson Islets only); reports of the other surveys are in preparation.

The locations of these surveys were 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. Surveys have been conducted in October 1995, March 1996, November 1996, February 1997, November 1997, March 1998 and November 1998. The transect-quadrat technique was used, with quadrats (1 m^2) sampled along the transects 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)

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

with standard error

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

in which n = the number of transects sampled in a study site, U_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

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

On average, there have been 10 transects sampled in the Stephenson Islets area, 3-4 around Stubbs Island, and 4-6 transects in the Plumper Group. The same locations have been 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 the Stephenson Islets location was calculated by multiplying the density (D) by the area of Stephenson Islets between Chart Datum and 10 m below Chart Datum (485,200 m^2). This was converted to a biomass of legal-sized urchins using a factor of 93.8 g for the average weight of an individual urchin above legal size (see Waddell *et al*. 1997 for details). Removals by the fishery from Stephenson Islets were calculated for October 1995 to March 1996, November 1996 to March 1997, and from November 1997 to March 1998 using the data in the harvest logbook database (and cross-checking with the Individual Quota dockside validation program). Exploitation rates for Stephenson Islets were then calculated as removals/pre-fishery biomass.

A green sea urchin survey was also undertaken by the West Coast Green Urchin Association on the northern coast of B.C. in Area 4-5, at Hodgson Reefs and on the coastline directly east of Hodgson Reefs (Fig. 3). Twenty transect lines were randomly choosen in areas of known green urchin presence. The survey protocol was basically the same as that used in the Area 12 surveys (transect/quadrat method). Test diameters of all green urchins encountered in each quadrat were measured. Due to poor weather conditions, the survey was carried out during two time periods: May 21-23, and June 10-12, 1998. A DFO representative participated in the survey for one day in May, and a DFO-approved third-party observer was involved during the whole survey.

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 were submitted to conduct exploratory fishing in 1997-1998.

RESULTS

The Fishery

The history of this fishery has been one of a boom developmental period from 1988 to 1991, peak landings in 1992, followed by declining landings, declining catch per unit of effort (CPUE), and the imposition of management restrictions (Table 2, Fig. 4). Landings since the 1994 fishing season have been limited by quotas and have remained between 150-160 t (Table 2). Landings by Pacific Fishery Management Area by fishing season illustrate the significance of the core fishing areas PFMA 12, 13, 18, 19, and 20 before the closure of less productive areas in 1995 (Table 3a). Landings by statistical area by month for fishing season 1997 (Table 4) indicate steady harvests through December and into January 1998, but a dramatic decline in February 1998 (when spawning appears to have occurred and product quality declined). Historical landings on the North Coast are presented in Table 3b; no fishery has occurred in this region since 1995. Comparison of landings reported from sales slips versus harvest logbooks (Table 5) indicates that the logbooks recorded greater than 92% of the sales slip landings since 1991, and that sales slips have underestimated landings since 1995. Logbook records since 1995 have been verified against the dockside validation records from the individual quota system. 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 2.

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 may be real, considering the patchy distribution of green urchins and the varying skills of the fishers. However, some of these also 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 try and reduce these errors and the influence of these outliers, we calculated the median catch per unit of effort (U_{mi} , equation 2) and its standard error as a robust estimate. The median catch per unit of effort shows a declining trend 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 in recent years (Fig. 5). The standard errors about the medians are small.

The tendency towards increasing maximum depths fished that had occurred during the early 1990's appears to have stopped, so that recent maximum depths (as recorded on harvest logbooks) are similar to, or slightly shallower than, previous years (Fig. 6).

Mean test diameters sampled from commercial landings were well above the minimum legal size of 55 mm (Figs. 7, 8). Mean diameters in PFMA 13 tended to be smaller than those in Areas 11 and 12, and in the southern Strait of Georgia, mean diameters tended to be somewhat larger in Areas 19 and 20. No strong declines in size with month of harvest were noted, although data from Areas 19 and 20 in 1997/98 suggest such a trend.

Biomass Dynamic Model

Clark (1998) identifies four levels of fisheries assessments. These range from index assessments, in which an index derived from research surveys or fishery data is used to monitor stock status, to fully age or size structured analytical models such as virtual population analysis. Surplus production models occupy the second level of complexity, in which the relationships between yield and fishing effort can be evaluated with relatively little data. One of the requirements for surplus production modelling is that the data have sufficient contrast over the time series. For the B.C. green urchin fishery, the catch per unit of effort (U_i) versus total effort (E_{Ti}) on a fishing season basis declined with increasing effort through the early stages of the fishery, but when effort was reduced, CPUE remained lower than during the previous period of the developing fishery (Fig. 9). Only since 1995 has CPUE increased in each region with relatively small changes in effort. Therefore, biomass dynamic production models were calculated for the two geographic regions South Coast - inside waters northern region (PFMA 11,12,13), and South Coast - inside waters southern region (PFMA 17-20, 28). Calculation of the regression (equation 4) separately for these two regions using data from 1987 to 1997 fishing seasons produced meaningful parameter estimates in all cases (Table 6), consistent with the results of Perry and Waddell (1998). Probability values for the models ranged from 0.012 to 0.097, and explained from 49% to 72% of the variation. The MSY estimate is 480 t for PFMA 11, 12, 13 and 97 t for PFMA 17-20, 28 (Table 6). Plots of residuals for the two regression models are shown in Fig. 10, and indicate no strong patterns. Comparison plots (Fig. 11) of the fitted values and the residuals versus the response variable (log of the CPUE ratio - see

equation 4) indicate that the spread of the residuals along the response variable is greater than the spread of the fitted values for the regression calculated for Areas 17-20, 28. This indicates a poorer fit for this model, consistent with its lower R^2 value (Table 6). The estimated MSY for the South Coast - inside waters northern region is larger (211%) than that estimated for this region by Perry and Waddell (1998), and with 121% of the estimated effort at MSY. The traditional Schaefer model under equilibrium conditions for the two South Coast - inside regions using the calculated parameters and equation 5 are presented in Fig. 12.

Fishery-independent Surveys

Seven surveys have been conducted since October 1995 in the Stephenson Islets area of eastern Queen Charlotte Strait (PFMA 12). The mean densities calculated from these surveys (using equations 6 and 7) indicate trends towards declining densities of legal-sized green urchins during calendar year 1997, and then an increase in 1998 such that the highest mean density in Stephenson Islets was calculated from the November 1998 survey (Fig. 13). Mean densities at Stubbs Island showed high variability because only 3-4 transects were sampled each survey and it is an area with high local variabililty in the occurrence of urchins (i.e. a generally steep-sided island). The density of sub-legal sized urchins (Fig. 13) were higher than for legal-sized urchins, and were highest overall at the Stephenson Islets. The total abundances of legal and sub-legal urchins is much greater at Stephenson Islets than the other two survey locations because of its much larger area between Chart Datum and 10 m depth [this area is 25 times larger at Stephenson Islets (485,200 m^2) than at Stubbs Island (19,600 m^2)].

Estimated total legal-sized biomass, removals due to the fishery, and consequent exploitation rates for Stephenson Islets are presented in Table 7. Estimated removals by the fishery from Stephenson Islets doubled over the three fishing seasons since 1995. The fishery removals comprised 85 to 97% of the apparent change in biomass between the beginning and end of the 1995 and 1996 fishing seasons. However, the biomass of legal-sized urchins estimated at Stephenson Islets at the end of the fishery in March 1998 was greater than the biomass estimated in November 1997 at the beginning of the fishery. Obviously, there is either (or both) growth of sub-legals into the legal population or net immigration of legal-sized green urchins into the study area which needs to be considered in order to calculate more detailed statistics such as natural mortality rates. Exploitation rates calculated from the fishery removals and the Autumn survey biomass ranged from 11 to 29%, consistent with its status as a major fishing location.

Results from these surveys can be used to estimate a potential range for the total biomass of legal-sized green urchins in PFMA 11, 12, 13, for comparison with the biomass dynamics model results. The mean of the mean densities of legal-sized urchins sampled on each survey in each area (e.g. Fig. 13) was 1.05 m^{-2} for Stephenson Islets, 1.14 for Stubbs Island, and 0.54 for the Plumper Group. The mean of the survey-mean densities in the Plumper Group and its standard error (0.54 ± 0.12) was chosen to represent the potential mean density of a typical green urchin ground in PFMA 11, 12, 13 instead of Stephenson Islets, since the latter ground is recognised as being a prime area for

green urchins and therefore unrepresentative of typical densities. Assuming the area of green urchin fishing grounds in PFMA 11, 12, 13 to be $9*10^7$ m^2 as estimated from the harvest logbook records (Perry and Waddell 1998), and the mean weight for a typical green urchin above legal size in this area to be 93.8 g (Waddell *et al*. 1997), an estimate of the biomass of legal-sized green urchins is ($9*10^7$ m^2 * 0.54±0.12 m^{-2} * 93.8 g =) 4560 t ± 1000 t. Assuming further that 2 standard errors approximates the 95% confidence interval suggests a range of mean annual biomass from 2,560 to 6,560 t. The lower limit of this interval is close to the biomass estimated for this region from the biomass dynamic model (2,317 t; Table 6). Perry and Waddell (1998) estimated a total biomass of legal-sized urchins for this region of 2,234 t, which is similar to the biomass estimated from the dynamic model in the present analysis. However, they used a mean density of 0.20 urchins m^{-2} from red urchin surveys conducted in October 1995 (Waddell *et al*. 1997) and a slightly higher estimate of the weight of a typical urchin above legal size (122.5 g). The density estimate used in the present assessment is considered a better estimate as it includes information from the past 3 years, although from a smaller geographic location (the Plumper Group). Applying an exploitation rate of 10% (i.e. lower than that applied to the key fishing ground of Stephenson Islets - Table 7) to the lower bound of the 95% confidence interval suggests a TAC of 256 t for PFMA 11-13. This value is similar to the sum of the 0.5*MSY TAC levels (240 t) shown for these areas in Table 8.

Survey data from Stephenson Islets can also be used to derive the catchability coefficient, for comparison with the catchability estimated from the biomass dynamic model. Catchability (q) is determined as

(8) $$q = \frac{C}{E*N}$$

with C the catch, E the effort, and N the beginning stock size. Ignoring the time variability in q over the fishing season (i.e. assuming a constant N over the duration of fishing, as calculated from the Autumn surveys, Table 7) and using the total catch and total effort over the fishing season (Table 7) produces values of q for Stephenson Islets from 1995 to 1997 of 0.001 to 0.002 per diver hour. This estimate is about one order of magnitude larger than the value for catchability estimated by the dynamic model (Table 6). A higher catchability in a small area known as a "hot spot" is to be expected in comparison with the whole of Areas 11-13.

In the North Coast survey, the total area (between 0 and 10 m Chart Datum (CD)) was determined to be 5,378,400 m^2 for the coastline and 2,539,600 m^2 for Hodgson Reefs (calculated using COMPUGRID). Using the total survey area of 7,918,000 m^2, and the mean overall legal density of 0.082 m^{-2}, there were approximately 649,276 legal greens in the whole survey area. Assuming an average legal green urchin weight of 93.8 g, this represents a total legal biomass of 60.9 t. A Total Allowable Catch calculated as 10% (e.g. below that applied to the Stephenson Islets) of the estimated biomass equals 6.1 t.

It should be noted that for reasons unknown to us, many of the transects were surveyed in shallower waters, and do not fully represent the 0 to 10 m CD depth range (especially in the Hodgson Reefs). The transects should have been started at 10 m (32.5 ft) below CD and ended at 0 m CD. In other words, the survey densities are more representative of shallower waters,

whereas the total numbers and biomass have been calculated for the full 0 to 10 m CD depth range. The few quadrats that were surveyed in the deeper waters had very low legal densities, so our calculations may be biased on the high side. On the other hand, the surveys were performed in the summer, and may not represent typical green urchin fall distributions (when they are subject to commercial harvest, and when higher densities would be expected).

It should also be noted that the ratios of legal to sublegal green urchins vary between the different areas. The ratios are about 1:1 for the coastline, >2:1 for all areas combined, and 4:1 for the Hodgson Reefs. This may indicate that Hodgson Reefs has been fished heavily in the past and that recruitment has been poor in this area.

Yield Recommendations

The dynamic production model estimated the maximum sustainable yield (MSY) for South Coast - inside waters northern and southern regions (Table 6). These results are used to provide recommendations for yield options by Pacific Fishery Management Area (Table 8). MSY estimates are assigned to each management area on the basis of the proportion that area contributed to aggregate landings (on a fishing season basis) from 1988 to 1997 (Table 3). MSY estimates for the South Coast - inside waters northern region were used for PFMA 11, 12 and 13, and assigned on the basis of their proportional catch (Table 4) as 4:63:33%, respectively. MSY estimates for South Coast - inside waters southern region were used for PFMA 17-20, 28, and assigned on a percentage basis of 5.7:40.5:35.2:15.7:2.9%, respectively. Mace (1988) recommends allowable catches within a range of 0.6 - 0.9 of MSY as a cautionary reduction for deterministic production models, since the deterministic MSY is not usually sustainable in a stochastic environment. Garcia *et al*. (1989) recommend maximum target yields of 1/2 to 2/3 of the estimated MSY, to account for the broad assumptions of surplus production models. These assumptions include deterministic biological processes, the fishery acting on a single stock with stable size distribution, and that catchability is not density dependent; many of these are not likely to be true for green sea urchins in B.C. Two other problems with the use of catch per unit of effort as an abundance index, which argues for a cautious interpretation of the dynamic model results, are the likelihood that fishing pattern changed with the implementation of the IQ system (i.e., a greater focus was placed on harvesting urchins with likely high quality roe), and the small-scale spatial distributions of adult urchins. The latter in particular should be an important consideration, and analyses conducted at finer spatial scales (when data are available) are warranted. Considering these problems, we calculate total allowable catches that range between 25% and 50% of the MSY estimated from the dynamic model. These reductions are presented in Table 8 as 0.25*MSY, 0.35*MSY, and 0.5*MSY for each management area. The range in recommended total yield for PFMA 11, 12, 13, 17-20, 28 combined is 144 - 287 t.

Are these reductions from the estimated MSY "suitably precautionary"? No estimates of natural mortality of green sea urchins are available for the coast of B.C. Using an estimate of the maximum age (t_{max}) of green sea urchins in New Brunswick from Robinson and MacIntyre (1997) of 20 years in Hoenig's (1983) generalised mortality model

(9) $$ln\,(z) = 1.44 - 0.982 * ln\,(t_{max})$$

generates an estimate of total morality (z) of 0.22. Total mortality can be assumed to equal natural mortality (M) in the absence of fishing. Patterson (1992) and Walters (1998) suggest that fishing mortality (F) should be about 0.6*M. Woodby *et al*. (1993) used a ratio of F/Z = 0.2 to be precautionary in the harvest of sea cucumbers in Alaska, which is equivalent to F=0.25*M. Using the more conservative relationship between F and M of Woodby *et al.* (1993), and the value of M derived from life span, the estimate of F is 0.06. Assuming that the present biomass in Areas 11-13 is the minimum of those estimated in this paper (2317 t from the surplus production model), the yield from this biomass with F=0.06 would be 135 t, derived from the equation: yield = abundance * (1-exp(-F)). This yield is similar to the 0.25*MSY to 0.35*MSY range of TAC's for this area presented in Table 8 (120 - 168 t), suggesting that these TAC limits meet the precautionary criteria published in the literature for other species.

Following the same reasoning for Management Areas 17-20, 28, the only biomass estimate available is that from the surplus production model (virgin biomass = 871 t, Table 6); no information is available on the present biomass. Using a value of F=0.06 with this biomass indicates yields of 51 t, which is about the level of the 0.5*MSY reduction in Table 8. However, considering the lack of information on current abundance in this area, and reports of fewer urchins than in Areas 11-13, we recommend 0.35*MSY as the maximum TAC for these management areas; moving to the next lower level of 0.25*MSY should provide additional opportunities for rebuilding this population.

DISCUSSION

Problems expressed in previous assesments (Perry and Waddell 1998) regarding the quality of data in the harvest logbooks, have been reduced or eliminated with the implementation of the individual quota and dockside validation program. This program provides a verified data set against which to check the harvest logbook records. It does not, however, completely guard against misreporting of locations fished or effort expended; however, in general we feel that the quality of the data in this fishery is much improved.

The major change between the results of the analyses conducted in the present assessment with the results from the past assessment of Perry and Waddell (1998) is an increase (by 216%) in the virgin biomass (and therefore the MSY) calculated by the biomass dynamic model for the South Coast - northern region (PFMA 11-13). Some of this increase can be explained by the exclusion of PFMA 11 from the model analyses of Perry and Waddell (1998) and its inclusion in the present study. The

question is whether this increase represents improvements to the status of this stock? Fig. 8 indicates that CPUE has been increasing in both South Coast - northern and southern regions since 1995, with relatively little change in effort. This implies that it has been easier for divers to reach their quotas recently, suggesting improved abundances (or availability) of legal-sized green urchins. Independent calculations of legal-sized green urchins for PFMA 11-13, based on surveys conducted in Stephenson Islets and the Plumper Group, also support the conclusion of a relatively large biomass of green urchins. For example, estimates of biomass from the dynamic model (2,317 t), from the October 1995 survey in PFMA 12 (2,234 t) as described in Perry and Waddell (1998), and the mean (±1 standard error) annual biomass estimated from the mean density at the Plumper Group from 1995 to 1998 (4,560±1,000 t) all suggest a biomass on the order of 2,200 t or greater. Further, the most recent surveys conducted in the Stephenson Islets (November 1998) had the highest density of legal-sized green urchins of the survey series. This survey also had high densities of sub-legal sized animals, suggesting recent good recruitment. Reports from participants in the fishery also suggest good fishing yields recently (the 1997 and 1998 fishing seasons), and the presence of many new small urchins in Areas 12 and 13. Small green urchins were also collected in Departure Bay (Nanaimo) in 1998, suggesting that a large recruitment event probably occurred in 1998. Total allowable catches for these areas in the range of 0.35*MSY (Table 8) would seem to be adequately precautionary.

Less confidence in estimates of the stock status of green sea urchins can be expressed for the South Coast - southern region (PFMA 17-20,28), as no data independent of the fishery has been collected to compare with the dynamic model results. Model estimates from the present analysis indicate little change since the past assessment (Perry and Waddell 1998). Reports from participants in the fishery indicate difficulty completing individual quotas, and a general concern for the stock in this region. The TAC recommendations (Table 8) reflect these perceptions of different stock conditions between the South Coast - northern and southern regions by suggesting increased quotas in PFMA 11-13 and decreased quotas in PFMA 17-20,28. Total allowable catches for these southern areas should not exceed 0.35*MSY (Table 8) and could be lower (0.25*MSY) in order to reduce fishing pressure and assist with rebuilding this stock.

Industry has expressed considerable interest in expanding the fishery into the North Coast of B.C. (PFMA 3,4) and on the west coast of Vancouver Island. They recognise the need to “prove” that adequate resource exists in these areas. It appears that the industry favours organised surveys patterned on the Stephenson Islets surveys to determine the resources in these closed areas. The survey conducted in PFMA 4 Subarea 5 in May and June 1998 estimated 60.9 t of legal-sized green urchins in the area surveyed. Using an exploitation rate of 10%, which is lower than the rates applied to key fishing grounds in the South Coast - northern region (Table 7), provided an estimated TAC of 6.1 t. Similar approaches could be adopted for other closed areas.

RECOMMENDATIONS

1) Yield Options

Yield options for the 1999-2000 fishing season by management area should be conservative (considering the assumptions in the biomass production model and the uncertainties in the use of CPUE as an index of abundance for aggregated sedentary species) and maintained below the estimated MSY. However, the present analyses, and reports from surveys and participants in the fishery, suggest that increases in the abundance of green urchins have occurred in the South Coast - northern region (PFMA 11-13), such that this region is likely to withstand increased removals. Yield options for PFMA 11-13, calculated as 0.25*MSY to 0.50*MSY range from 120 to 240 t; an intermediate yield of 168 t is suggested to be precautionary. The present analyses and reports from the fishery suggest little change in green urchin stock abundance in the South Coast - southern region (PFMA 17-20,28), and consequently the yield options for these areas are recommended to be reduced. The range, expressed as 0.25*MSY to 0.35*MSY, for this southern region is 24.2 to 33.9 t. The value of opening areas with TAC's <3 t (<1 individual quota) should be reconsidered. A TAC calculated as 10% of the biomass estimated from surveys on the North Coast (PFMA 4) is 6.1 t. This could probably be increased to 2 individual quotas (7 t, an expoitation rate of 11%) without adversly affecting the stock status.

2) Fishery-independent surveys and biological information

Analyses of green sea urchin data collected during directed surveys produce useful biomass estimates for comparison with fishery data, and provide independent comparisons with results from the biomass dynamic model. They should continue and be expanded to locations in addition to local "hot spots". In particular, surveys in the South Coast - southern region (PFMA 18-20) are recommended to assess stock status and trends in those locations. Information on green urchin larval biology and recruitment is needed to identify recruitment pulses and changes in the size structure of the population. Rapid and broad-scale survey methods are needed to assess green urchin distributions and stocks in lightly or unexploited areas.

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Table 1. Summary of management actions in the green sea urchin fishery, 1987 to 1997/98.

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 were 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. South Coast: 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. North Coast: 7 days/wk, season reduced to Jan. 1 to Feb. 28 and Oct. 1 to Dec. 31.
1994	South Coast: 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. North Coast: 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. South Coast: 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. North Coast: 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. South Coast: 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 North Coast: North Coast closed, except under an exploratoy 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. South Coast: Areas 11, 12, 13, 17 to 20 and 28 open from Nov. 10, 1997 to Mar. 15, 1998. Area quotas, with total of 366,079 lb (166.1 t) (IQ 7,471 lb). North Coast: 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. South Coast: Areas 11, 12, 13, 17, 18, 19, 20, and 28 open from Nov. 10, 1998 to Mar. 15, 1999. Area quotas, with total of 366,079 lb (individual quotas 7,471 lb). North Coast: Total quota of ~13,000 lb allotted to Area 4 from Nov. 10, 1998 to Mar. 15, 1999.