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Management Framework for Strait of Georgia Lingcod

Cadre de gestion de la morue-lingue du détroit de Georgia

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ABSTRACT

Lingcod populations in the Strait of Georgia have been severely depressed for several decades and a commercial fishery closure was implemented in 1990 followed by a recreational fishery closure implemented in 2002. A Stock Assessment Framework for lingcod suggested that a management framework be developed in consultation with stakeholders that would identify benchmark abundance levels as reference points to measure recovery in abundance and identify management action associated with those benchmarks. In response to that recommendation, the Lingcod Mangement Framework Committee was formed in 2004 and included federal and provincial fisheries agencies' staff along with representatives of the recreational fishery sector, the commercial fishery sector and conservation groups. The committee identified criteria to be used as reference points in classifying the status of Strait of Georgia lingcod and to be used as decision rules for fishery management. Estimates of historic high levels of biomass are used in lieu of biomass estimates for the unfished Strait of Georgia lingcod population. Proportions of historic high biomass of 40% ($B_{40\%}$), 25% ($B_{25\%}$) and 10% ($B_{10\%}$) were selected as reference points for defining the status of lingcod populations and as decision rules for management actions. The $B_{40\%}$ level was identified as a desirable, long-term recovery target for Strait of Georgia lingcod abundance. Between $B_{25\%}$ and $B_{10\%}$, the population would be considered to be overfished. $B_{25\%}$ was identified as a desirable, short-term recovery target for Strait of Georgia lingcod if the current biomass levels fell below this reference point. The recommended timeframe for assessing forecasted biomass trajectories is 10 years. At $B_{25\%}$ the acceptable level of probability associated with identifying potential harvest levels should be at least 90%. At $B_{10\%}$ this probability level should be between 99-100%, and as such no harvest would be permitted for population estimates at or below $B_{10\%}$.

A Ricker stock-recruitment age structured model was selected by the committee to estimate historic and current biomass levels. The Strait of Georgia was modelled as a single unit (Statistical Areas 13-19; 28 and 29); as four geographic areas (Southeast: Statistical Areas 28 and 29, excluding 29-5; Northeast: Statistical Areas 15 and 16; Northwest: Statistical Areas 13 and 14; Southwest: Statistical Areas 17, 18, 19 and 29-5); and as a modified geographic area that excluded the Southeast area since catch and effort data for this area were unreliable and its current biomass estimates were less than 1% of historic biomass estimates. Current biomass estimates for the Northeast, Northwest and Southwest geographic areas were 12%, 7% and 20% respectively of historic biomass estimates.

The population model selected by the committee combined these three geographic areas and estimated the lowest level of depletion to have occurred in 1990 (2% of historic biomass) and the current biomass of lingcod is estimated to be 15% of historic biomass levels. Using the outlined management framework, this population is classified as overfished and any harvest level selected should be associated with a 95% probability of maintaining an increase in biomass for 10 years. The mean annual estimate of recreational landings prior to the closure in 2002 (1991-2001) was 4,880 pieces, ranging from 2,912 pieces in 1999 to 8,219 pieces in 2001. Based on these historic recreational fishery harvest levels, the committee recommended an annual harvest between 5,000 – 7,000 pieces. Stock projections for 5,000 and 7,000 pieces annually for the next 10 years suggests that there is a 50% probability that the stock will be at 44% and 43% respectively of historic biomass in the year 2013.

RÉSUMÉ

Les populations de morues-lingues du détroit de Georgia sont grandement réduites depuis plusieurs décennies; la pêche commerciale de cette espèce a été fermée en 1990, et sa pêche récréative, en 2002. Le cadre d'évaluation de stocks de morues-lingues recommande d'élaborer, en consultation avec les intervenants, un cadre de gestion qui établirait les valeurs d'abondance qui serviront de points de référence pour mesurer le rétablissement des populations et déterminer les mesures de gestion associées à ces points de référence. Pour donner suite à cette recommandation, on a créé en 2004 le Comité du cadre de gestion de la morue-lingue, formé de représentants des organismes fédéral et provincial de gestion des pêches, des secteurs de la pêche commerciale et de la pêche récréative ainsi que de groupes de conservation. Le Comité a déterminé les critères qui serviront de points de référence pour caractériser l'état de la morue-lingue du détroit de Georgia et des règles de décision pour en gérer la pêche. Des estimations de la biomasse historique maximale sont utilisées plutôt que des estimations de la biomasse de la population non pêchée du détroit de Georgia. Ainsi, les proportions de 40 % ($B_{40\%}$), de 25 % ($B_{25\%}$) et de 10 % ($B_{10\%}$) de la biomasse historique maximale de la morue-lingue du détroit de Georgia ont été choisies comme points de référence. La valeur $B_{40\%}$ constitue une cible de rétablissement à long terme. Entre $B_{25\%}$ et $B_{10\%}$, la population serait considérée comme surpêchée. La valeur $B_{25\%}$ constitue une cible de rétablissement à court terme si la biomasse actuelle était inférieure à ce point de référence. L'horizon temporel recommandé pour l'évaluation des trajectoires de biomasse prévues est de dix ans. Pour une biomasse de $B_{25\%}$, la probabilité liée aux taux d'exploitation possibles devrait être d'au moins 90 %. Pour une biomasse de $B_{10\%}$, cette probabilité devrait être de 99 à 100 %; la pêche ne serait pas permise si les estimations de la biomasse de la population ne dépassent pas $B_{10\%}$.

Le Comité a choisi un modèle stock-recrutement de Ricker structuré selon l'âge pour estimer les biomasses historiques et actuelles. Le détroit de Georgia a été modélisé comme une seule unité (zones statistiques 13 à 19, 28 et 29), comme quatre régions (sud-est : zones statistiques 28 et 29, excluant 29-5; nord-est : zones statistiques 15 et 16; nord-ouest : zones statistiques 13 et 14; sud-ouest : zones statistiques 17, 18, 19 et 29-5) et comme une région modifiée qui ne comprend pas la région sud-est puisque les données de capture et d'effort pour cette région ne sont pas fiables et que les estimations actuelles de la biomasse y sont inférieures à 1 % des estimations de la biomasse historique. Les estimations actuelles de la biomasse dans les régions nord-est, nord-ouest et sud-ouest correspondent respectivement à 12 %, à 7 % et à 20 % des estimations de la biomasse historique.

Selon le modèle de population choisi par le Comité, lequel regroupe ces trois régions, l'abondance de la morue-lingue a atteint un minimum en 1990 (2 % de la biomasse historique) et la biomasse actuelle représente 15 % de la biomasse historique. Selon le cadre de gestion, cette population est caractérisée comme surpêchée, et tout taux d'exploitation choisi devrait permettre donner une probabilité de 95 % que la biomasse augmente pendant dix ans.

Le nombre moyen de captures annuel de la pêche récréative avant la fermeture de cette pêche en 2002, soit de 1991 à 2001, a été estimé à 4 880; les prises ont varié de 2 912 en 1999 à 8 219 en 2001. En se fondant sur ces chiffres, le Comité a recommandé que de 5 000 à 7 000 morues-lingues soient capturées annuellement dans la pêche récréative. Les projections de l'effectif du

stock pour des captures annuelles de 5 000 et de 7 000 morues-lingues durant les dix prochaines années indiquent qu'il y a une probabilité de 50 % que la biomasse du stock atteigne respectivement 44 et 43 % de la biomasse historique en 2013.

1.0 OVERVIEW

Lingcod populations in the Strait of Georgia have been severely depressed for several decades (Richards and Hand 1989, King 2001). As such, the commercial fishery has been closed since 1990 and the recreational fishery has been subject to regulations. Prior to 2002, recreational fishery regulations to protect lingcod included an eight month winter non-retention period to protect nest guarding males, the non-retention of fish less than 65 cm, and reduced daily (1 per day) and annual catch limits (10 per year). In 2002, the recreational fishery was closed for the retention of lingcod as an additional measure to protect this stock (King 2001). In 2002, Fisheries and Oceans Canada implemented a Rockfish and Lingcod Sustainability Strategy since inshore rockfish (genus *Sebastes*), are also at historically low levels in British Columbia, including in the Strait of Georgia (Yamanaka and Lacko 2001). In 2003, a Stock Assessment Framework for Strait of Georgia lingcod recommended monitoring and assessment programs that would provide measures of the relative abundance and biological parameters for Strait of Georgia lingcod (King et al. 2003). The survey and research recommended by that framework has been implemented. The Stock Assessment Framework suggested that the next step in assessing and managing Strait of Georgia lingcod should be the development of a conservation-based management strategy conducted in consultation of stakeholders and with consideration of relevant legislation and regional policies (King et al. 2003). It was recommended that a management framework should identify benchmark abundance levels as reference points, either as targets for the recovery for the lingcod population, or as levels that triggered management responses (King et al. 2003). Developing a management framework with pre-agreed conservation and management actions that are triggered through decision rules are essential steps in the precautionary approach (Haigh and Sinclair 2000).

In response to that recommendation, the Lingcod Management Framework Committee was formed in 2004 and included federal and provincial fisheries agencies' staff along with representatives of the recreational fishery sector, the commercial fishery sector and conservation groups (Table B 1). The committee met eight times between April 2004 and April 2005 with the task to identify criteria to be used as reference points in classifying the status of Strait of Georgia lingcod and to be used as decision rules for fishery management. The committee also reviewed sources of commercial and recreational catch and catch per unit effort data to be used in estimating historic and current biomass levels of Strait of Georgia lingcod. An age-structured stock assessment model was used to estimate lingcod biomass, and the development of the model was directed by the committee. The committee provided input on the spatial-scale of the population model, the stock-recruitment relationship, biological parameters, and assumptions regarding recruitment variability. Decisions and recommendations made by the committee were based on consensus, and are contained in this report.

This report outlines the management framework suggested by the Lingcod Management Framework Committee. We provide background material reviewed by the committee in the selection of commercial and recreational catch and catch per unit effort data to be used in estimating historic and current biomass levels of Strait of Georgia lingcod. We document the population model endorsed by the committee and provide the estimates of historic and current biomass provided by the model. The population biomass trajectories for 10 years from 2003 onwards are used to outline projected recovery levels and associated probability of attaining future biomass levels under varying levels of harvest. Finally, we briefly review the fishery-independent measures of relative abundance that were recommended by the Stock Assessment Framework (King et al. 2003) and compare measured changes in relative abundance from surveys with the changes estimated by the population model.

2.0 MANAGEMENT FRAMEWORK FOR LINGCOD

The suggested criteria and recovery targets for Strait of Georgia lingcod are derived from standards for rebuilding plans adopted by the US Pacific Fishery Management Council for the US Pacific coast groundfish fisheries (PFMC 2003a; PFMC 2003b). We used estimates of historic high levels of biomass in lieu of biomass estimates for the unfished Strait of Georgia lingcod population. Proportions of historic high biomass of 40% ($B_{40\%}$), 25% ($B_{25\%}$) and 10% ($B_{10\%}$) were selected as reference points for defining the status of lingcod populations and as decision rules for management actions. The $B_{40\%}$ level was identified as a desirable, long-term (10 years) recovery target for Strait of Georgia lingcod abundance. Below $B_{25\%}$, the population would be considered to be overfished; therefore the $B_{25\%}$ level was identified as a desirable, short-term recovery target for Strait of Georgia lingcod.

The management framework and decision rules are specified in terms of an acceptable probability of being below the current stock size in ten years time (Figure 2.1). Thus, if the stock is estimated to be depleted to below 10% of the unexploited level ($B_{10\%}$), the probability of further decline has to be negligible; in effect, no catch would be permitted. For a stock at 25% ($B_{25\%}$) the allowable removals number is limited to be that which has a 10% probability of a

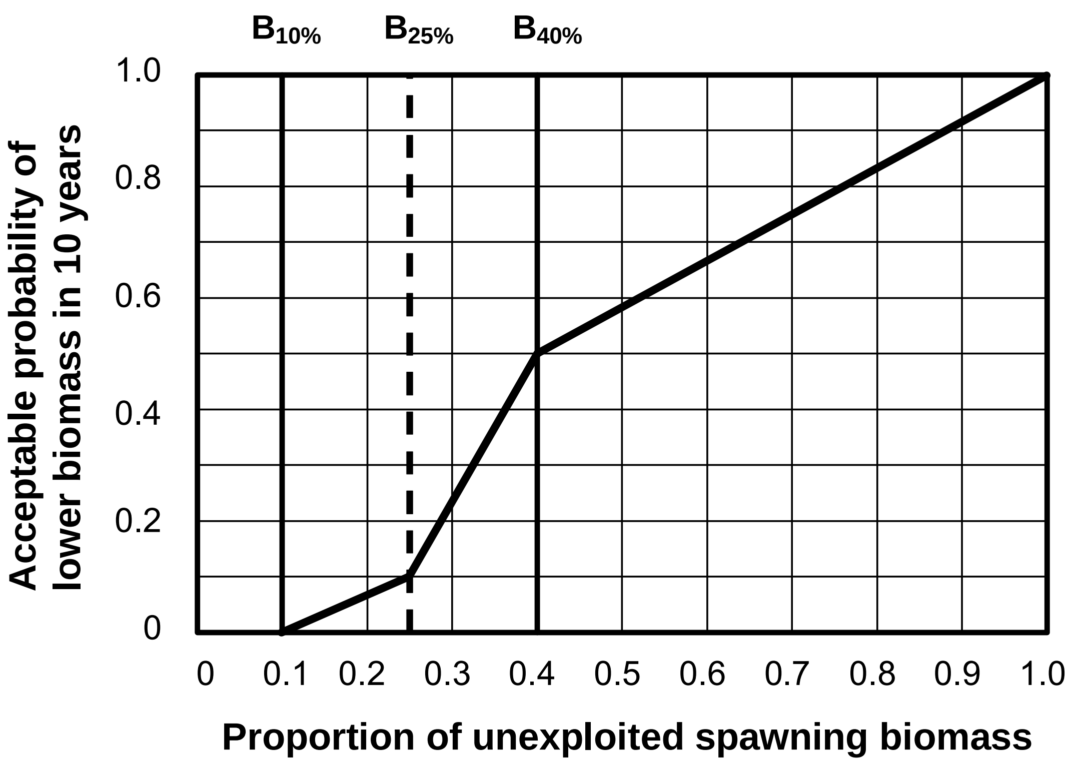


Figure 2.1. An illustration of the decision rule relating current state of the stock to the acceptable probability of obtaining a lower spawning stock size after ten years of constant removals.

lower stock size in ten years time. However, this is augmented by two constraints:

1. the allowable removals shall have a negligible probability of depleting the stock to below $B_{10\%}$ in any of the next ten years;

2. if the stock is above $B_{25\%}$, the removals shall have no more than a 10% probability of depleting the stock to below $B_{25\%}$ in any of the next 10 years.

3.0 AREA OF THE STRAIT OF GEORGIA CONSIDERED

Most fisheries in the Strait of Georgia are managed by minor Statistical Area (Figure 3.1). It should be noted that the groundfish stock assessments and management units typically assess and manage groundfish stocks for the Strait of Georgia as one large unit (i.e. Major Area 4B comprised of minor Statistical Areas 12-20; 28-29). However, from 1990-2002 the only fishery for lingcod in the Strait of Georgia has been a recreational fishery, which is managed by minor Statistical Areas, and sub-Areas. In 2002, the lingcod recreational fishery was closed for Statistical Areas 13-19; 28 and 29. This is the portion of the Strait of Georgia considered in this report. The committee identified that Statistical Area would be the smallest spatial unit that should be considered when investigating the potential for any limited fishery. For modelling purposes, data for Statistical Areas were aggregated for the whole Strait of Georgia and subsequently into four large geographic categories: southeast (Statistical Areas 28 and 29); northeast (Statistical Areas 15 and 16); northwest (Statistical Areas 13 and 14) and southwest (Statistical Areas 17-19).

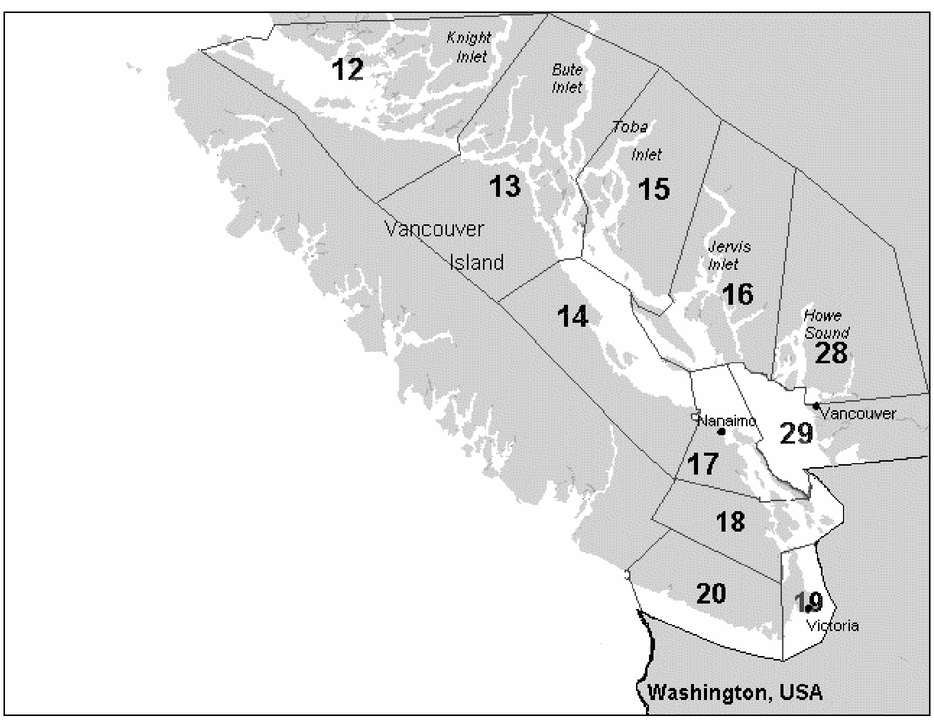


Figure 3.1. Minor Statistical Areas within the Major Area 4B, Strait of Georgia. This paper focuses only on Statistical Areas 13-19, 28 and 29.

4.0 FISHERY-DEPENDENT DATA ESTIMATES OF THE RELATIVE ABUNDANCE OF LINGCOD

The only sources of long-term, continuous data that can be used as estimates of relative abundance for lingcod in the Strait of Georgia are catch and catch per unit effort data available from the historical commercial lingcod fishery and from the Strait of Georgia creel survey program for recreational fisheries (Appendix C).

4.1 LINGCOD COMMERCIAL FISHERY

4.1.1 Historic Overview

Commercial fishing for lingcod in British Columbia began around 1860 (Cass et al. 1990). Between 1900 and the 1940s, lingcod was ranked fourth in commercial importance in British Columbia after salmon, herring and sardines, and was the main source of fresh fish throughout the year (Wilby 1926; Cass et al. 1990). Prior to 1927, lingcod landings were grouped with other groundfish species (sablefish, rockfish, Pacific cod, Pacific hake and tomcod) into a ‘cod’ category (Wilby 1937) though there is some suggestion that lingcod comprised almost all of the catch (Ketchen et al. 1983). Data considered in this report are from 1927 onwards.

Overall, the handline fishery accounted for over 80% of the lingcod commercial catch in the Strait of Georgia. During the 1920s, the commercial catch was almost exclusively taken by handline, but during the 1930s trawlers began to fish for lingcod, and use of this gear to catch lingcod in the Strait of Georgia increased during World War II (Chatwin 1958; Forrester and Ketchen 1963). Reliable trawl statistics for this period are not available, but Chatwin (1958) estimates that the proportion of lingcod caught in the Strait of Georgia by trawl never exceeded 20%. In 1947, traditional lingcod fishing grounds were closed to trawl gear and the proportion of the lingcod catch by trawl dropped to about 3% (Chatwin 1958; Forrester and Ketchen 1963). Large areas of the Strait were closed to trawling due to concerns that the rapidly developing fishery was conflicting with the long-established handline fishery for lingcod and was having a negative impact on juvenile lingcod (Forrester and Ketchen 1963). Investigations into trawl catch alleviated these concerns and by 1955, most fishing grounds were reopened to the trawl fishery (Forrester and Ketchen 1963). During the 1950s through 1970s, the proportion of lingcod landed by trawl averaged 7%, and increased to 19% in the final ten years of the Strait of Georgia commercial fishery (1980-1989).

The handline fishery in the Strait of Georgia typically used live bait, usually herring or young rockfish or flatfish. Lingcod in the handline fishery were kept alive in live-wells onboard and then in submersed live-boxes until required for market (Wilby 1937). Lingcod were removed from the live-boxes and landed dressed (head off and gutted).

Catches in the Strait of Georgia reached a historic high level in the 1930s and 1940s (Figure 4.1). The handline catch in the Strait of Georgia (Statistical Areas 13-19; 28-29) averaged 2,800 tonnes in the 1930s and 1940s. Historic high landings of approximately 3,700 and 4,300 tonnes occurred in 1936 and 1944 respectively. By the 1950s, the handline catch had declined to an average of 1400 tonnes. The handline catch declined through to the early 1980s, when it reached an average of 280 tonnes, an approximate 80% decline from the catches in 1950s and a 90% decline from handline catches in the mid-1940s (Richards and Hand 1989).

In 1931, a winter closure (January and February) for lingcod fishing was initiated to protect spawning fish and in 1946 this closure was extended to include December (Forrester and Ketchen 1963). In addition, a size limit of approximately 58 cm (head-on) for retained lingcod was applied to the commercial fishery in 1942 (Forrester and Ketchen 1963). In 1979 the winter closure was extended for November 15 – April 15 and this was again extended in 1988 to November 15 – April 30. Since 1990, the retention of lingcod by the commercial fishery in the Strait of Georgia (Minor Statistical Areas 13-19, 28 and 29) has been prohibited in response to conservation concerns (Richards and Hand 1989).

4.1.2 Records of commercial catch

1927-1946

Commercial landings for lingcod from 1927-1946 were reported in the annual Fisheries Statistics reports compiled by the Dominion Bureau of Statistics (1927-1946). Catch statistics were not reported by gear type. The catch are recorded as dressed weight (Wilby 1937; Chatwin 1958) in hundreds of pounds (lbs.) of landed lingcod recorded on sales slips. All commercial catch used in this report have been converted to tonnes and converted to round weight using a conversion

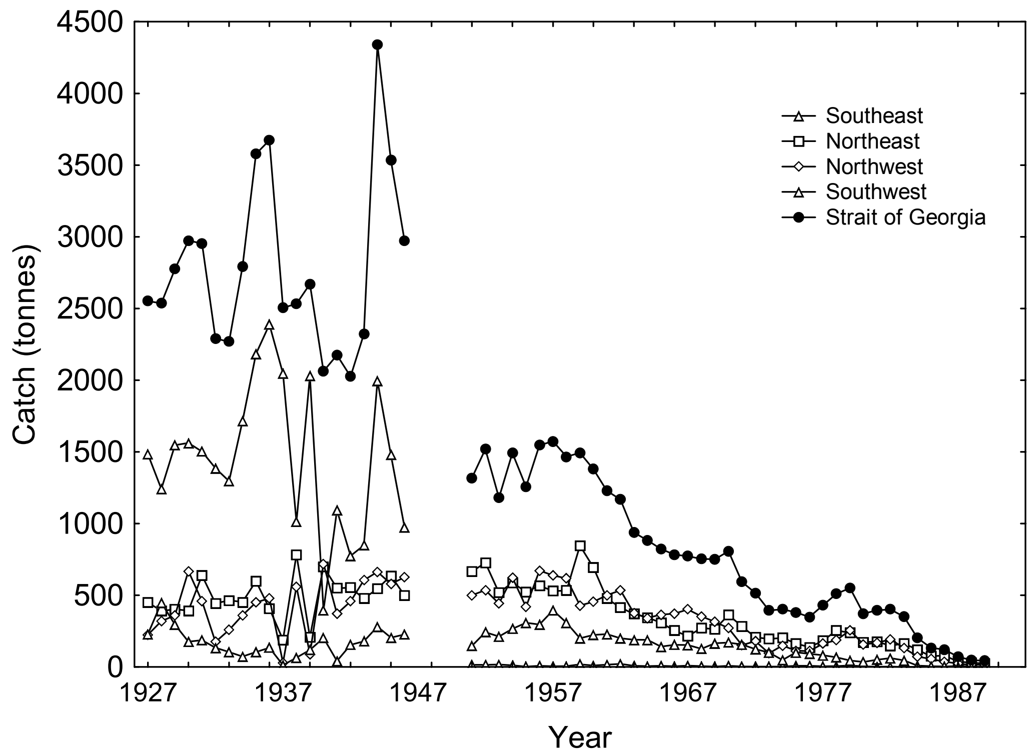


Figure 4.1. Commercial catch (tonnes) of lingcod in the Strait of Georgia 1927-1989 by geographic area, as used by the population model, and the total catch for the whole Strait of Georgia. Data for 1947-1950 are available as a coastwide total only. Data are in Table C 1and Table C 2 and referenced in Section 4.1.2.

factor of 1.39 (K. Rutherford, pers. comm., Pacific Biological Station, Nanaimo, British Columbia, V9T 6N7). During this period, the commercial catch statistics for British Columbia were reported for three major districts: District 1 (Fraser River and Howe Sound); District 2 (northern British Columbia, typically from Prince Rupert to Smiths Inlet); District 3 (southern British Columbia, including the west coast of Vancouver Island, Johnstone Strait, Strait of Georgia, and the Juan de Fuca Strait). Only District 1 and District 3 landings are used in this report. Commercial landings for lingcod from 1947-1950 were not reported by District, but were reported for all of British Columbia (Dominion Bureau of Statistics 1947, 1948, 1949, 1950). These data were not used in this report since they could not be allocated to specific geographic areas within the Strait of Georgia. However, Chatwin (1958) estimates that during this period, the Strait of Georgia lingcod catch was between 57-60% of the total lingcod catch for all of British Columbia.

District 1: Fraser River and Howe Sound - The port of Vancouver was a major landing location for the commercial fishery. There are some concerns that lingcod catch reported for District 1 (1927-1946) may include lingcod caught outside District 1 (Fraser River and Howe Sound), but landed in Vancouver. In 1933, the allocation of lingcod landings to District 1 were adjusted to account for lingcod caught outside the Strait of Georgia but landed in Vancouver (A.W. Argue, pers. comm., British Columbia Ministry of Agriculture, Food and Fisheries, 808 Douglas Street, Victoria, British Columbia, V8W 9B4). District 1 catches could have also included lingcod caught in the region of the Gulf Islands or elsewhere in the Strait of Georgia, but landed in Vancouver. Another hypothesis is that lingcod caught elsewhere in the Strait of Georgia were recorded there, but then subsequently landed in District 1 and also recorded in District 1 again. Chatwin (1958) provides estimates of the proportion of lingcod caught in all of British Columbia that were caught in the Strait of Georgia as greater than 90% for the period of 1927-1942. Therefore prior to 1933, the proportion of District 1 lingcod landings that represent lingcod caught in the Strait of Georgia were likely 10% lower than those reported in the annual Fisheries Statistics reports.

Though District 1 catches could be adjusted to attempt to account for transfers of lingcod caught outside the Strait of Georgia (1927-1933), there was some concern that the District 1 landings either included lingcod caught elsewhere in the Strait of Georgia but landed and recorded for District 1 or included lingocd caught elsewhere (recorded there) and landed in and recorded again for District 1. There were no estimates of these proportions in the published literature to adjust the landings appropriately. As a consequence the final model version selected to estimate historic and current levels of biomass and recommend harvest levels (Section 5.4.2) does not include the portion of the Strait of Georgia encompassed by District 1 (referred to as the Southeast Strait of Georgia). If District 1 lingcod landings did include lingcod caught elsewhere in the Strait of Georgia (for example the Gulf Islands), then the exclusion of these data from a whole Strait of Georgia population model would underestimate the historic biomass levels of lingcod in the Strait of Georgia. District 1 catches were assigned to the large geographic area of southeast (Table C 1) in the population model of this report.

District 3: Southern British Columbia – This district was sub-divided into geographic areas. Within the Strait of Georgia, these sub-areas varied between 1927, 1928-29 and from 1930-1946, but roughly correspond to the boundary designations for Statistical Areas (13-19) currently used by Fisheries and Oceans Canada for the reporting of Strait of Georgia creel survey data and for the management of recreational fisheries (Figure 4.2). Because the population model in this report used large geographic areas (northeast, northwest, southwest) catches were assigned to these areas (Table C 1) based on the boundaries defined in Section 3.0. If the designated sub-areas covered more than one Statistical Area, the catch was evenly allocated to each.

<u>1951-1989</u>
Starting in 1951, catch statistics were reported by gear type and by Statistical Area (13-19). Data for the handline fishery were obtained from Fisheries and Oceans Canada, British Columbia Catch Statistics Annual Reports which summarize catch from sales slip records. These data are reported in the Annual Reports as dressed weight, and have been converted to round weight using the 1.39 conversion factor as above. Handline data from 1982-1989 were obtained from the sales slip database, PacHarv3 (Fisheries and Oceans Canada, Pacific Region, Catch Statistics Unit, Vancouver BC). These data are reported in the database as round weight. Trawl data from 1951-1953 were obtained by Port Observers, supplemented with sales slip data as reported in Thomson and Yates (1960; 1961a; 1961b). Trawl data from 1954-1989 are based on logbook records and sales-slip data and were obtained from the groundfish catch database, GFCatch (Fisheries and Oceans Canada, Pacific Region, Groundfish Data Unit). All trawl data are published as round weight. The combined handline and the trawl fisheries catch data for each Statistical Area were assigned to the geographic areas used in the population model based on the boundaries described in Section 3.0 (Table C 2).

4.1.3 <u>Commercial Catch per unit Effort</u>

Stock assessments on Strait of Georgia lingcod have used commercial handline and longline catch per unit effort (CPUE) data determined from sales slip records as an index of lingcod abundance (Richards and Hand 1988; Richards and Hand 1989). Sales slip data with catch and effort information are available for 1967 to 1989. Since commercial trawl landings of lingcod in the Strait of Georgia were typically small (Richards and Hand 1988), commercial CPUE was calculated using commercial handline and longline catch and effort data only. Historically, these fisheries targeted lingcod until the late 1970s when increased effort was directed on rockfish (Richards and Hand 1988). To avoid including directed rockfish effort in the lingcod CPUE calculation, Richards and Hand (1988) suggested using only sales slip records with reported lingcod catch of at least 100 kg. On average, the proportion of Strait of Georgia catch that satisfied the qualification criteria was 83.5% with an overall decline from approximately 89% of the catch in 1967-1971 to approximately 71% of the catch in the final five years (Richards and Hand 1989). Though the commercial fishery was closed in 1990, these data were used as an estimate of historical relative of abundance from 1967-1989. Mean qualified CPUE exhibited a 60% decline from 1967 through 1989 (Figure 4.3; Table C 3).

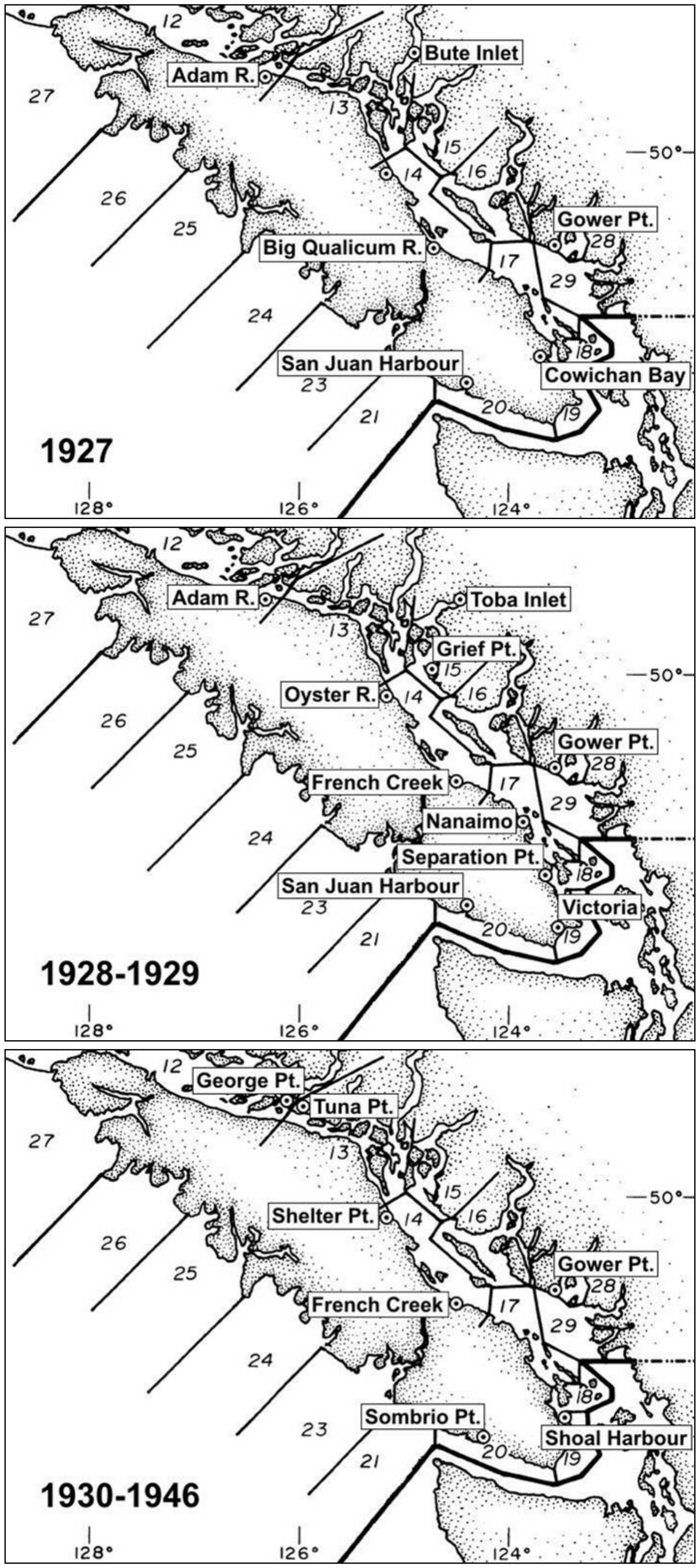


Figure 4.2. Locations used to sub-divide the Strait of Georgia for the reporting of commercial catch data from 1927-1946. The locations roughly correspond to boundary designations for Statistical Areas (13-19; outlined in solid line and numbered) currently used by Fisheries and Oceans Canada.

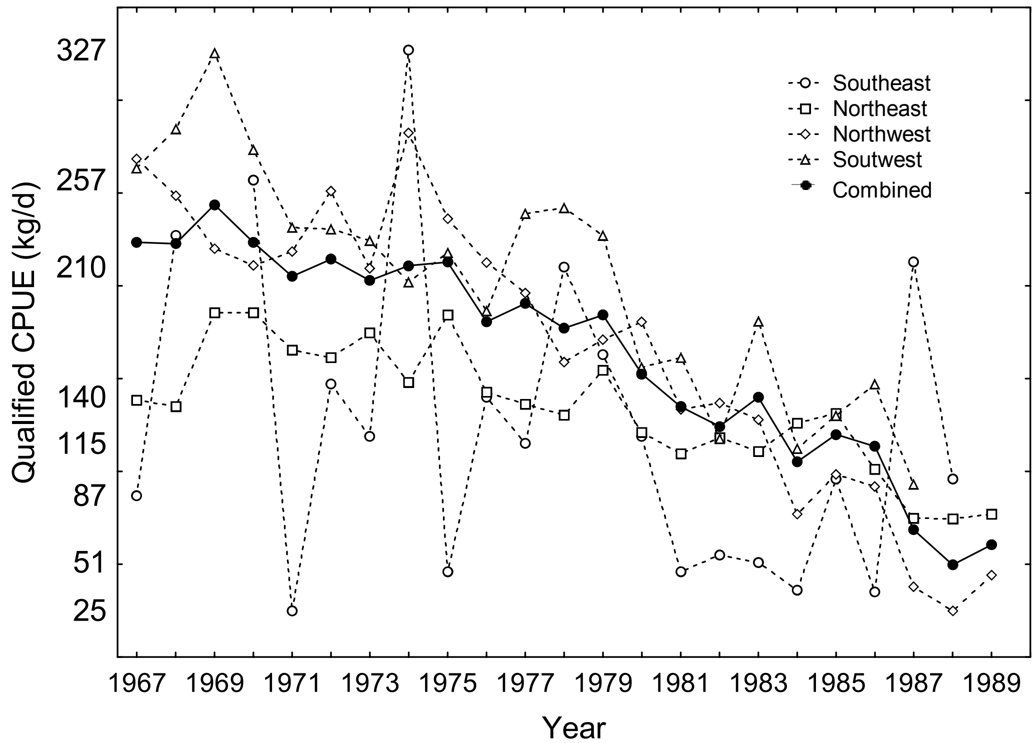


Figure 4.3. Qualified mean commercial catch per unit effort (CPUE; kg/d) by geographic areas as used in the population model, and the overall mean CPUE for the whole Strait of Georgia. Data are in Table C 3 and referenced in Section 4.1.3.

4.2 RECREATIONAL FISHERY

4.2.1 Historic Overview

There have always been non-commercial (recreational) fisheries in the Strait of Georgia, but during the 1960s recreational fisheries in the Strait of Georgia underwent a rapid expansion. Recreational fishing effort, as measured by boat trips, increased from about 200,000 boat tips in 1960 to approximately 770,000 in 1980 and 600,000 in 1988 (English et al. 2002). By the late 1990s, even though the recreational fishery effort had dropped to 162,000 boat trips, the Strait of Georgia recreational fishery was and remains the largest of such fisheries in British Columbia (English et al. 2002). The focus of the recreational fishery has historically been coho (*Oncorhynchus kisutch*) and chinook (*O. tshawytscha*) salmon (English et al. 2002). The expansion of the recreational fishery from the 1960s through to the 1990s reflects the recreational fishers' interest in these two species: prior to 1960 the catch by commercial troll fishery for coho and chinook salmon was double that of the recreational fishery; but by the 1980s the recreational fishery catch of coho and chinook salmon was actually triple the catch of the commercial troll fishery (English et al. 2002). As of 2002, the recreational fishery was the primary source of harvest for coho and chinook salmon in the Strait of Georgia (English et al. 2002). As a result of conservation concerns, a non-retention restriction of coho salmon was implemented in 1998, with allowance of limited selective fisheries (hatchery only) in some terminal areas. Though other species have historically been caught by recreational fishers, English et al. (2002) report that increased conservation concerns for coho and chinook salmon, resulted in the expansion of recreational fisheries directed at pink (*O. gorbushca*) and sockeye salmon (*O. nerka*), halibut (*Hippoglossus stenolepis*), rockfish (*Sebastes* spp.) and lingcod (*Ophiodon elongatus*).

As the catch in the commercial fisheries declined in the 1980s, the recreational fishery accounted for a relatively large proportion (approximately 35%) of lingcod landed in the Strait of Georgia. Despite recreational catches estimated to be on average 61,000 pieces, with an exceptionally high catch estimate of 137,400 pieces in 1984, lingcod have typically been a small component of the recreational catch in the Strait of Georgia. Lingcod accounted for approximately 7% of the recreational catch in the 1980s; 1.5% of the catch in the 1990s; and 2.5% of the catch since 1998 (English et al. 2002).

In conjunction with declining abundance of lingcod in the 1980s, a winter closure (November 15-April 15) for the recreational fishery was implemented in 1981, as was a voluntary size limit of 58 cm. With the closure of the commercial fishery in 1990, extended regulations were initiated in the Strait of Georgia recreational fishery for lingcod. In 1991, a mandatory size limit of 65 cm was implemented, along with a reduced bag limit (from 3 to 1 fish per day), an annual limit (10 fish per year) and an extended winter closure (October 1 to May 31). Due to conservation concerns, the recreational fishery was closed for the retention of lingcod in 2002; the non-retention regulation currently remains in effect. It should also be noted that in 2002, conservation concerns regarding rockfish also resulted in the reduction in the annual allowable catch of rockfish and in the designation of several non-retention areas (Rockfish Conservation Areas) throughout the Strait of Georgia.

4.2.2 Estimates of Recreational Catch

Information on recreational catch of lingcod in the Strait of Georgia was not routinely collected until the initiation of the Strait of Georgia Recreational Creel Survey in 1980. An extensive review of the Strait of Georgia Recreational Creel Survey program is provided by English et al. (2002). Briefly, dock-side interviews provide records of lingcod landed by a subsample of recreational fishers. Interviewed recreational fishers voluntarily provide information on the following: the number and species of fish caught including the number of lingcod caught and released and the number of lingcod caught and kept (landed); approximate duration of fishing activity (hours); location of fishing; and fishing gear used. For lingcod landed, biological data are opportunistically collected by dock-side observers and include, when possible, total length and sex, and collection of ageing structures. Since 1999, information on the size (sub-legal, i.e. <65 cm; or legal, i.e. >65 cm) of lingcod caught but released was also collected. Biological data on landed lingcod are summarized in King et al. (2003). Aerial boat counts are conducted throughout the creel survey period and are used to expand the observed catch data (from interviews) to estimate total catch by Statistical Area. No measures of accuracy of the estimated catch statistics are available.

The timing of the Strait of Georgia Recreational Creel Survey has varied considerably across the years. In 1980 the survey began in June and ran throughout the winter months and through June of 1981. There was no survey conducted from July 1981 through April 1982. Since 1982, the survey period has continued to vary with some years not covered in April, some years not covered in the winter months, and some years with complete coverage. However, since 1982 there has been a survey conducted from May through September every year. Given the winter closure for lingcod, the average number of lingcod reported as landed by interviewed recreational fishers between May through September has been over 90% of the total reported in years with complete survey coverage. In this report we consider creel survey data from 1982 to 2002 only.

The estimates of lingcod catch are based on interview data; therefore, for months in which no interviews were conducted, there are no available estimates of lingcod catch. English et al. (2002) attempted to expand the estimates of lingcod catch for the months not surveyed to derive an annual lingcod catch estimate. In this report we did not expand estimates of lingcod catch to attempt to derive an annual estimate. We used the estimates of lingcod catch as provided by the Catch Statistics Unit (Fisheries and Oceans Canada, Vancouver, BC) reported by Statistical Area (Table C 4). It is important to note that a sub-area of Statistical Area 29 (29-5) which is the eastern coast of the Gulf Islands is included in the Statistical Area 17 catch reported by the Strait of Georgia Recreational Creel Survey program.

4.2.3 Recreational Catch per unit effort

Several stock assessments for Strait of Georgia lingcod (Beamish et al. 1995; Haist 1995; King 2001) have used catch per unit effort indices derived from the Strait of Georgia creel survey program as indices of the relative abundance of lingcod. There are several types of data obtained from angler interviews that can be used to calculate CPUE, including fishing effort expressed as either number of boat trips or fishing hours, and fish caught either as retained lingcod or released lingcod. Changes in the daily and annual limits, along with implementation of a 65 cm size limit in 1991 resulted in a reduction of the number of lingcod kept (landed) and an increase in the number of lingcod released. By 1999, over 90% of lingcod encountered were released. Length data collected in interviews in 1999 and 2000 indicate that over 95% of released lingcod were considered sub-legal, i.e. less than 65 cm (King 2001). A review of the Strait of Georgia creel survey data suggested that, given the observed changes in the fishery in 1991 and the consistent coverage between May through September in the creel survey, the most suitable CPUE to use as an index of relative abundance would be based on the total lingcod encountered (landed and released) and calculated using interview data for the May through September period only (English 2003). Effort can be expressed as boat-trips or 100 hours of fishing, and can be based on interviews that identified directed effort for lingcod, interviews that did not identify directed effort (i.e. non-directed) for lingcod, or all interviews combined. English (2003) reported that the trends in lingcod CPUE for the different measures of effort were essentially identical, and as such recommended that the best indication of relative lingcod abundance would be CPUE based on lingcod encountered (kept and released) per 100 hours of fishing (directed and non-directed effort). In this report we used CPUE provided by English (2003) based on May through September interviews for lingcod encountered (kept and released) per 100 hours of fishing (directed and non-directed effort) by Statistical Area for 1982-2002 (Figure 4.4;Table C 5).

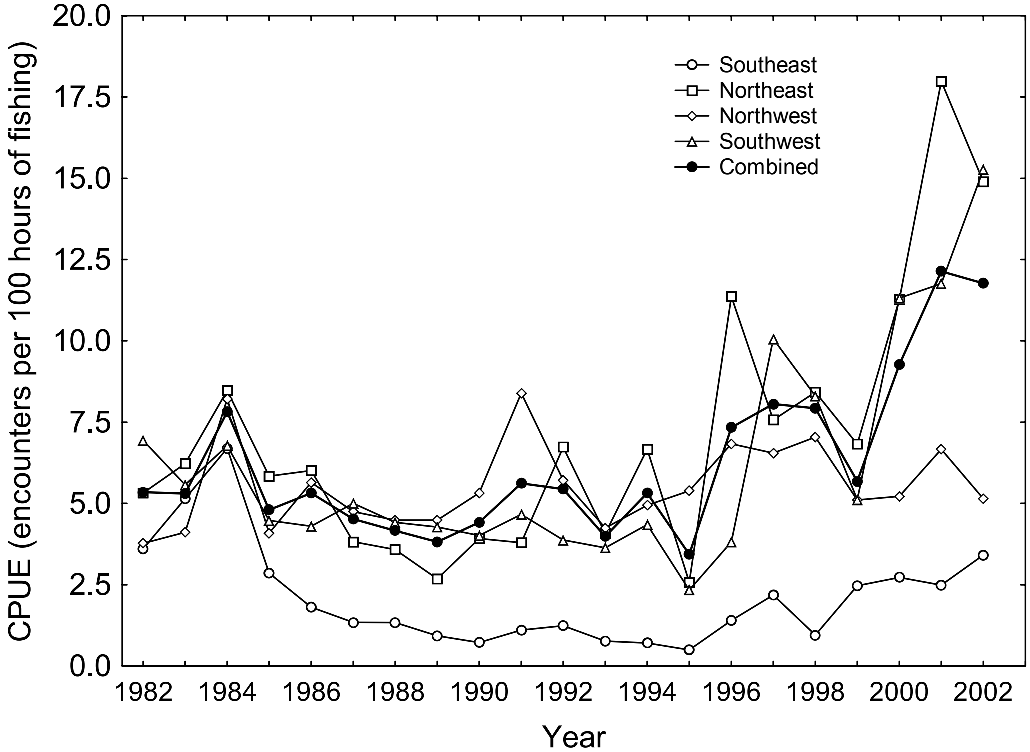


Figure 4.4. Mean catch per unit effort (CPUE; lingcod kept and released per 100 hours of fishing) by geographic area as used in the population model, and the mean combined CPUE for the whole Strait of Georgia. Data are in Table C 5 and referenced in Section 4.2.3.

5.0 STRAIT OF GEORGIA LINGCOD POPULATION MODEL

The Lingcod Management Framework Committee provided a range of hypotheses on the causes of the decline of the stocks and on whether, and if so why, recovery under reduced catches appears to be protracted. A summary of a range of these hypotheses is given in Appendix D, Table D 1. To assist the Lingcod Management Framework Committee in choosing an appropriate model or models in developing their recommendations for Strait of Georgia lingcod management, we developed a flexible population model that could incorporate these hypotheses. The variants of the model are fitted to catch per unit effort data (described in Section 4.0) to examine which hypotheses have substantial effects on estimates of abundance and recovery.

Having selected an appropriate set of models, we can then fit them to abundance data to estimate depletion as required to apply the decision rules identified by the committee (Section 2.0). The models are also used to estimate the probability required identified in the decision rules by projecting the stock ten years into the future, using plausible values of recruitment variability. The allowable catch is that which has a relative frequency of stock decline relative to current abundance over the next ten years equal to that specified by the decision rule. The projections use Monte Carlo methods and the Bayes' posterior distribution to take into account both recruitment variability and uncertainty in the estimates of abundance and productivity.

Projections can also be used to give management advice on the effects of catches on the likely range of recovery times.

A comprehensive model-based assessment of the state of lingcod stocks has not been undertaken since Martell (1999). Earlier assessments did not take into direct account the sexual dimorphism found in this species, but modelled both sexes combined using an averaged growth curve. For the current analysis a new, age-based, population model that separates the sexes was developed (described in Appendix F). The model uses the demographic parameters set out in Table 5.1.

5.1 CATCH DATA

The commercial and recreational catch series outlined in Section 4.0 were used in the assessment. Each catch series has a separate age-dependent selectivity function for both males and females shown in Figure 5.1. Catches are not available by sex, and so these are calculated in the model in each year assuming that the catch of each sex for a given catch type is in proportion to its abundance in the corresponding segment of the population. Missing commercial catch data from 1947-1950 were estimated by linear interpolation between values for 1946 and 1951. Early catch data for the recreational fishery were generated by linear interpolation from zero in 1961 to 70 000 fish in 1981. Recreational fishing pre-dates the collection of recreational catch data; however, the choice of the initial year from which to interpolate recreational catches is unlikely to have an important effect on the results because recreational catches would be expected to be substantially less than commercial catches prior to the 1970s. However, from the 1970's onwards the recreational catch would have made an increasingly substantial contribution to the total removals from the stock; ignoring these catches would bias the results of the assessment.

5.2 FITTING CPUE DATA

Two series of catch per unit effort (CPUE) data are available (outlined in Section 4.0): qualified commercial CPUE data for the years 1967 to 1989 and recreational CPUE data after 1982 from the Strait of Georgia Recreational Creel Survey program. The qualified commercial CPUE is unlikely to be linearly related to abundance, and so CPUE was modelled as a power function of exploitable biomass (Cooke 1985), that is:

$$\varsigma_{i,t} = q_i \eta_{i,t}^{\lambda_i} \tag{5.1}$$

where:

$\varsigma_{i,t}$	CPUE in series *i* and year *t*
q_i	catchability coefficient for data series *i*
$\eta_{i,t}$	exploitable abundance of population component in series *i* in year *t*
λ_i	exponent determining degree of linearity between CPUE series *i* and abundance

If $\lambda < 1$, a given change in CPUE implies a greater relative change in exploitable abundance (sometimes termed hyperstability), when $\lambda = 1$ CPUE is proportional to abundance and when $\lambda > 1$ a given change in CPUE implies a lesser relative change in biomass. For the commercial CPUE, the required component of abundance is the exploitable biomass as defined by an age-specific selection function and the calculated mass at age. The recreational CPUE is measured in terms of numbers of fish encountered per day. Consequently, η_t refers to numbers of fish in the component of the population vulnerable to the recreational gear, and which changes when the 650mm size limit is introduced in 1991.

The parameters λ_i, q_i and $\hat{s}_i$ (defined in Appendix F) are 'nuisance parameters'. These parameters contribute to uncertainty in the estimates of abundance and productivity. The methods of analysis take this uncertainty into account by allowing the nuisance parameters to be estimated freely when fitting the model (although λ_i is constrained to the range [0.3, 2.0]). No point estimates of these parameters are made or used for any purpose in evaluating the future trajectories of the stocks, and hence they play no direct role in the application of the decision rule.

Table 5.1. Base-case demographic and related parameters used in the Strait of Georgia lingcod population simulation model.

A) Base-case demographic parameters

	Females	Males
Natural mortality (year^{-1})	0.2	0.2
Maximum age (pooled class)	20	20
von Bertalanffy k (year^{-1})	0.2	0.2
von Bertalanffy asymptote (mm)	1040.	900.
von Bertalanffy intercept (t0)	0.	0.
Age at 50% maturity (years)	5.0	knife edge maturity
Age at 95% maturity (years)	6.0	at 2 yrs
Fraction of male recruits at age 1	0.5	
Recruitment CV (when fitting model)	0.	
Recruitment CV (for projections)	0.5 (low)	1.0 (high)

B) Mass (g) at length (mm) parameters (same for both sexes)

Scale parameter A	1.126×10^{-6}
Exponent	3.329

C) Density dependence in growth and mortality

	Females	Males
von Bertalanffy k (unexploited abundance)	0.2	0.2
von Bertalanffy k at zero abundance	0.22	0.22
Asymptotic length (unexploited abundance)	1040.	900.
Asymptotic length at zero abundance	1144.	990.
Natural mortality (unexploited abundance)	0.20	0.20
Natural mortality at zero abundance	0.18	0.18

D) Fixed regime shift parameters

Period	Relative carrying capacity
Before 1946	1.00
1947 – 1976	0.50
1977 – 1988	0.75
1989 – 1998	0.25
1999 -	1.20

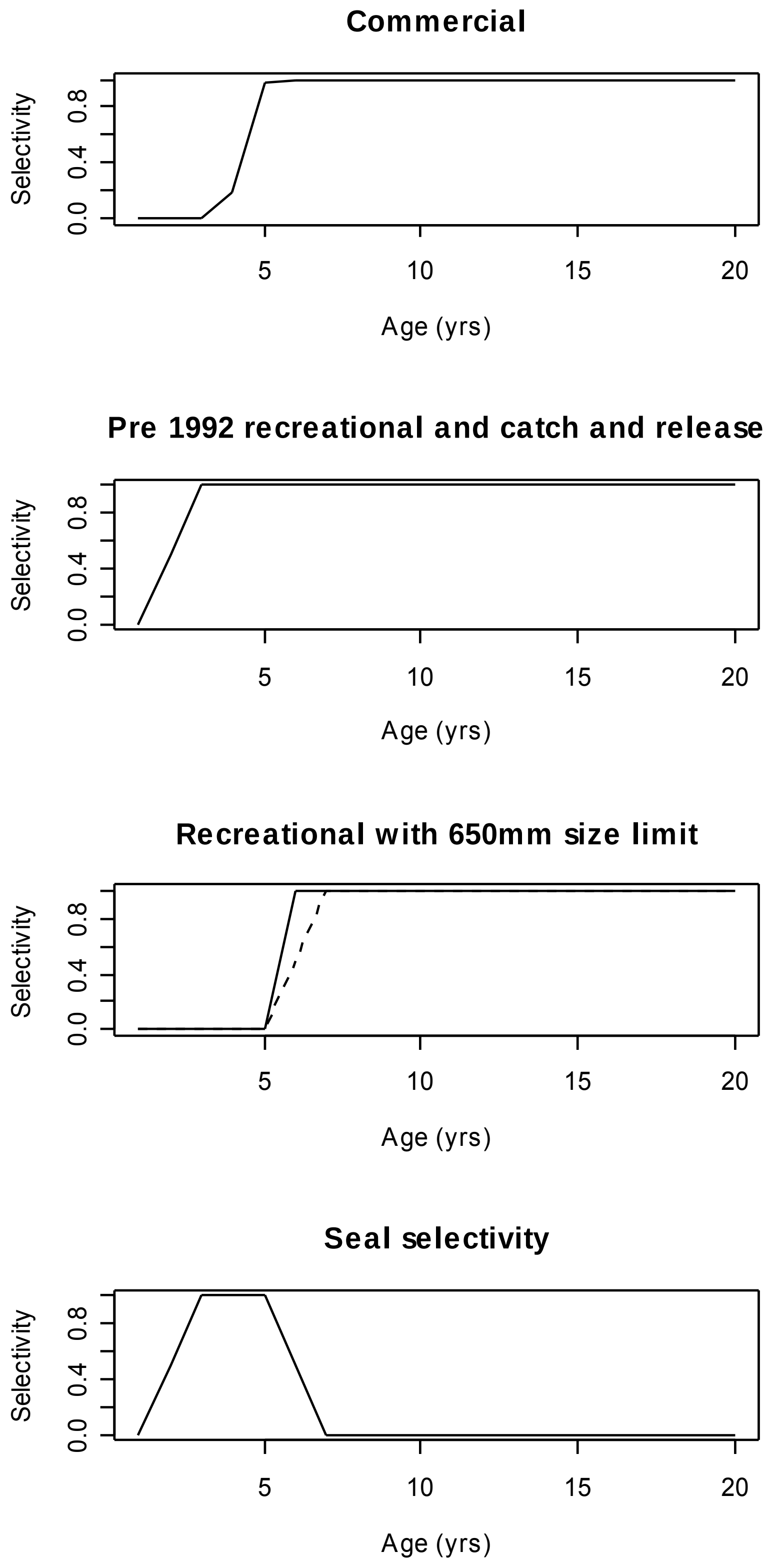


Figure 5.1. Selectivities at age used with the different catch series. When male and female selectivities differ, the females are represented by the solid line, and the males by the dashed line. Catches by seals (predation) are only included in one specific estimate.

5.3 FITTING THE MODEL TO THE WHOLE STRAIT OF GEORGIA

The initial population model discussed by the Lingcod Management Framework Committee collated all commercial and recreational catch data for the whole Strait of Georgia combined (Statistical Areas 13-19; 28 and 29). We present the results of the fitting the model to these collated catch data and outline the selection of hypotheses and subsequent refinement of area of the Strait of Georgia modelled.

Maximum likelihood estimates of abundance and depletion from fitting the model to the CPUE data are given in Table 5.2. Several features of the analyses used in the assessment method are most easily clarified by looking at an example, and for this purpose we use the unmodified data set for the whole Strait of Georgia and the stock recruitment relationship adopted by the Lingcod Management Framework Committee. The committee, after considering the range of modelling results, and taking into account that lingcod are cannibals, decided to use a Ricker stock recruitment relationship (SRR) as the base model. The resulting point estimates are given in line 1 of Table 5.2. Figure 5.2 shows the population trajectory giving the best fit of the base model to the data, the total catch and the exploitation rate. A comparison of observed with expected CPUE for both commercial and recreational CPUE series (Figure 5.3) shows that a reasonable fit of the model to the data has been obtained.

An asymptotic estimate for the joint confidence interval $\theta_k = y_1, \cdots, y_k$ for a set of k parameters based on likelihood ratios (Cox and Hinkley 1974) is given by:

$$c_{\theta_k^*} = \sup\left(\mathrm{L}\left(\boldsymbol{\theta} \middle| \theta_k = y_1, \cdots, y_k\right)\right) - \sup\left(\mathrm{L}(\boldsymbol{\theta})\right) \tag{5.2}$$

Table 5.2. Maximum Likelihood Abundance estimates from the various model fits to the CPUE data for the whole Strait of Georgia, with the start year being 1927. The lowest population abundance occurs somewhere in the period 1985 to 1990. The log-likelihood indicates how well the model fits the data; higher numbers indicate a better fit.

Model	Spawner abundance (tonnes)			Depletion (%)		Log-likelihood
	Start	Lowest	Current	Lowest	Current	
Ricker	44 029	1 902	3 992	4.32	9.07	59.5308
Ricker (corrected data)	43 355	1 900	3 990	4.38	9.20	59.5297
Beverton & Holt (B&H)	45 844	1 862	3 947	4.06	8.61	59.5096
B&H (corrected data)	42 386	1 843	3 926	4.35	9.26	59.5016
B&H (District 1 catch data deleted)	27 569	1 709	3 779	6.20	13.71	59.4394
Fixed regime impacts on recruitment	35 570	431	2 160	1.21	6.07	56.1710
Seal predation	37 535	1 605	3 000	4.28	7.99	51.4294
B&H (high M)	29 160	738	1 997	2.53	6.85	59.6018
Density dependent growth	38 700	2 982	5 530	7.70	14.29	59.4843
Depensatory recruitment	43 719	1 828	4 007	4.18	9.17	59.7799

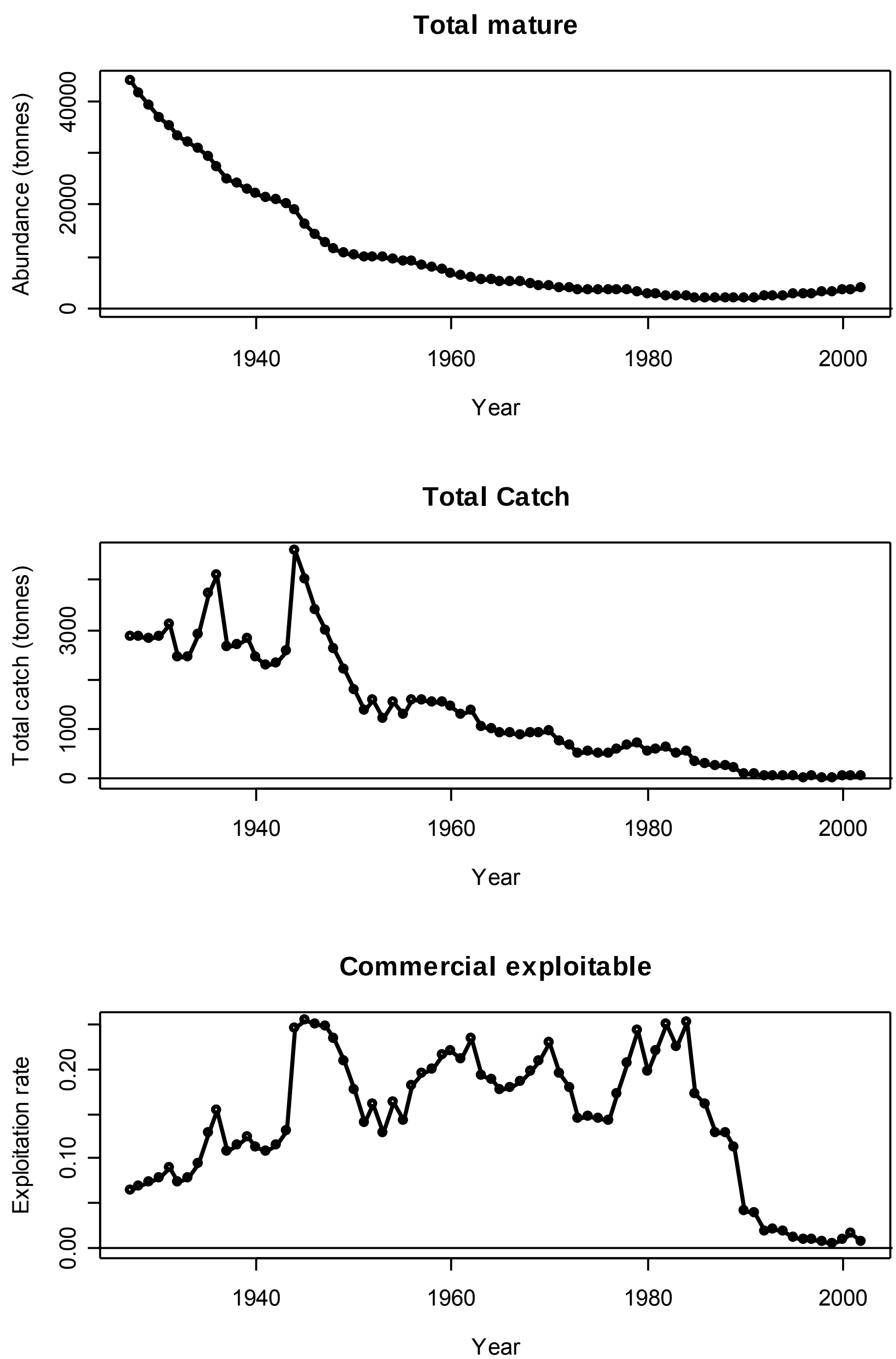
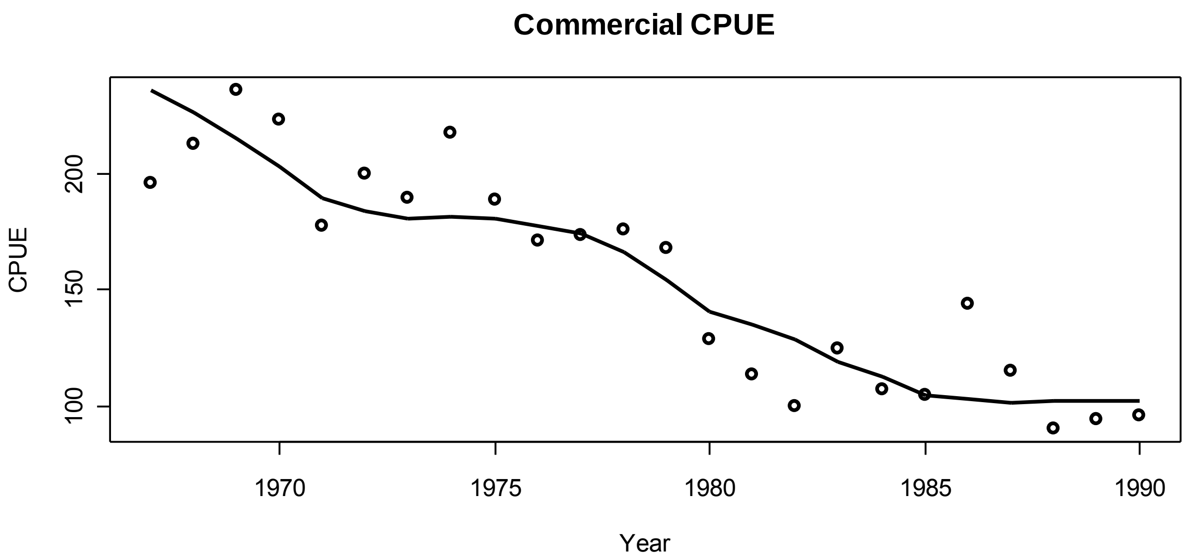


Figure 5.2. Mature biomass trajectory, total catch and exploitation rate for whole Strait of Georgia – Ricker recruitment model.



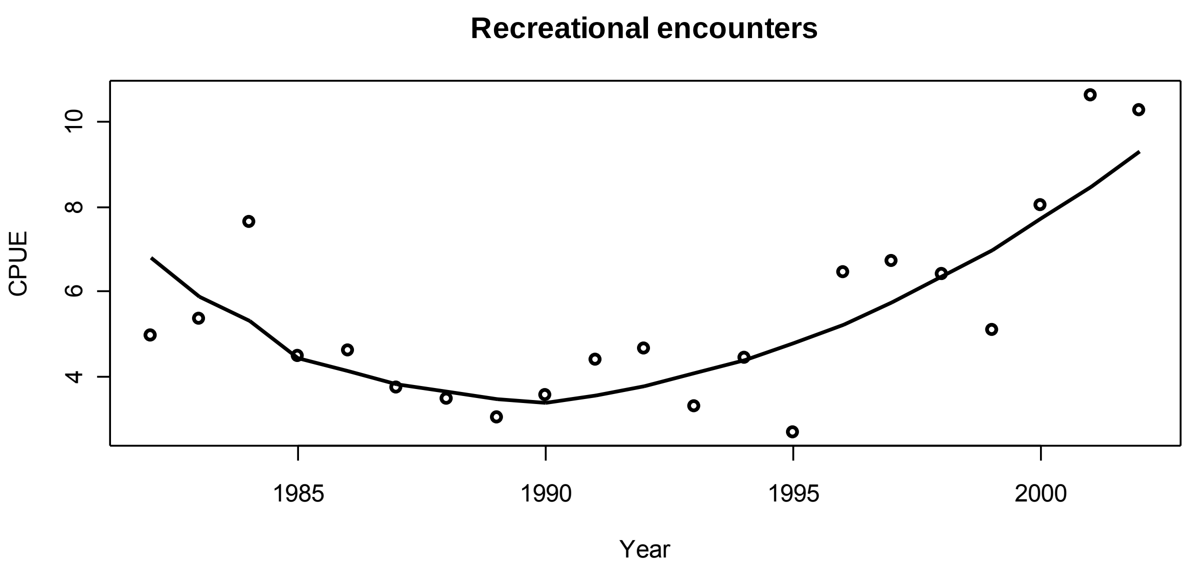


Figure 5.3. Observed and expected CPUE for Ricker model fit.

where **L(.)** denotes a log-likelihood function of a vector of parameters **θ**. This statistic has critical values given by:

$$c_{\theta_k^*} \leq 0.5\chi^2{}_{k,1-\alpha} \tag{5.3}$$

where $\chi^2{}_{k,1-\alpha}$ is a chi-square distribution with *k* degrees of freedom, and α is the coverage probability for the confidence interval.

Figure 5.4 shows that the marginal likelihood associated with the compensation multiplier (defined in Appendix F) is very narrow. The asymptotic estimator above gives a conditional confidence interval for the compensation multiplier 1.9635 to 1.9711. The conditional confidence interval represents only a fraction of the uncertainty relating to the compensation multiplier because it is calculated assuming that the maximum likelihood estimate of abundance is the true abundance. The width of the conditional confidence interval is only about 0.4% of the point estimate. This illustrates that the surface of the negative log-likelihood surface is a very narrow valley (illustrated with a randomly resampled scatterplot in Figure 5.5). This has the consequence that conventional resampling methods used to develop Bayes' marginal posterior distributions, such as Sampling-Importance-Resampling (SIR) and Monte Carlo Markov Chain (MCMC) (both described in Carlin and Louis, 1996) methods may not work efficiently.

Attempts to apply the SIR algorithm resulted in only a handful of resampled points landing in the valley, out of two million samples; which clearly illustrates the inefficiency of this algorithm with such a narrow posterior distribution. Before attempting to develop an MCMC version of the estimation method, we used a simplified bivariate normal test-case to determine whether an MCMC algorithm (Gibb's sampler, see Carlin and Louis 1996) would converge efficiently in a case where the posterior distribution is extremely narrow. We found this algorithm to be inefficient in reaching into the tails of narrow joint marginal distributions. Although we subsequently found an efficient solution to this problem (which is currently being prepared for publication) we did not develop the new algorithm in time for resampling from joint marginal posterior distributions for the current lingcod assessment.

For the results presented here, uncertainty in abundance estimates is characterised by resampling from the marginal distribution of the abundance estimates (an example indicating the shape of the marginal distribution is given in the top histogram of Figure 5.6). The marginal probability density function is found by numerical minimisation of the negative of the posterior likelihood for fixed values of abundance. A cubic spline is used to form a continuous distribution of the posterior marginal probability density. This method is valid for characterising the uncertainty in the abundance estimates, but has some consequences (minor in the present application) when developing a method for stock projection (discussed in the next section). The results from this procedure are shown in Figure 5.6 for initial (1927) abundance, minimum abundance and current abundance. Figure 5.7 shows the posterior distributions of depletion relative to 1927 abundance. In all cases abundance refers to the spawning stock.

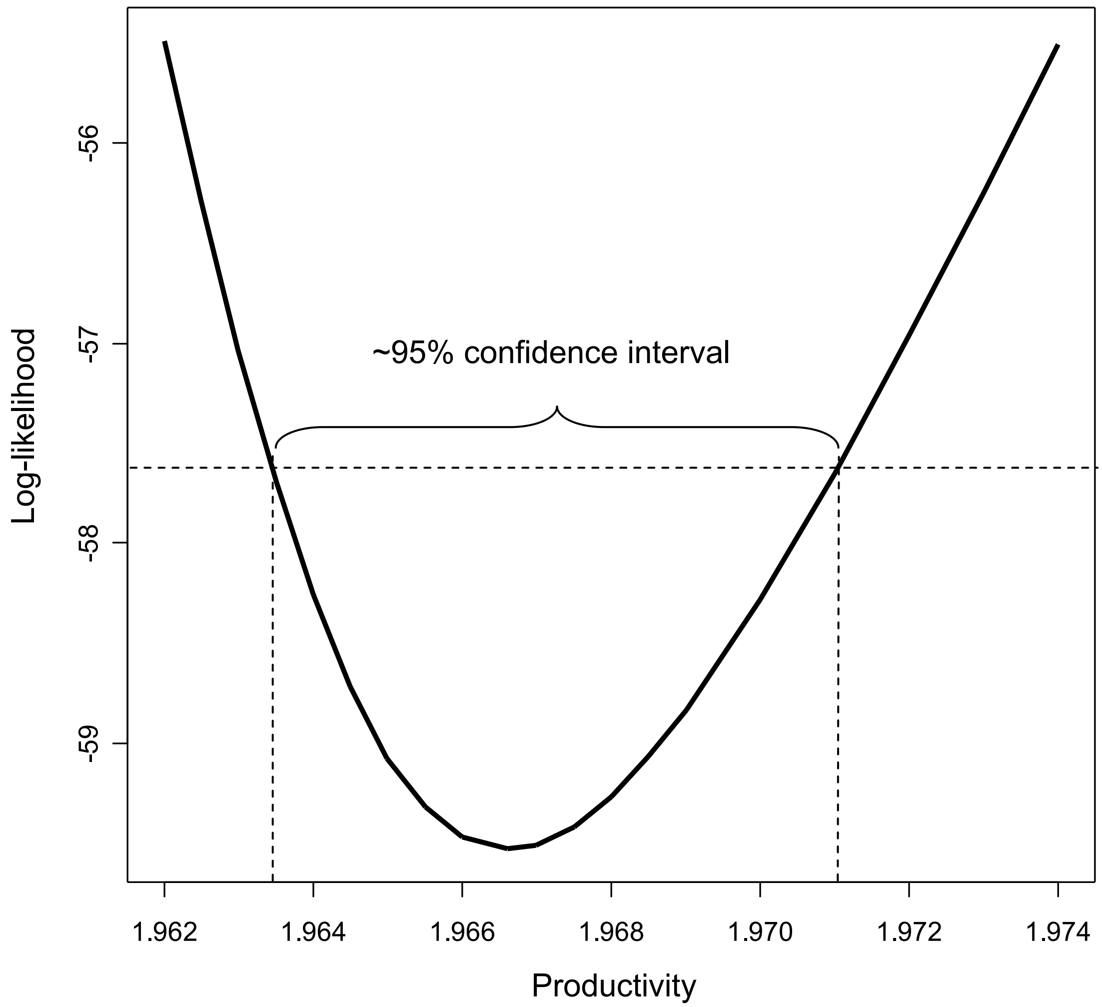


Figure 5.4. Conditional likelihood profile for the productivity multiplier (given that abundance is equal to the maximum likelihood estimate) from fitting the Ricker model. The asymptotic 95% confidence interval is 1.9635 to 1.9711. Note that this confidence interval is conditioned on a specific level of abundance, and so this profile does not reflect the full uncertainty about the productivity multiplier.

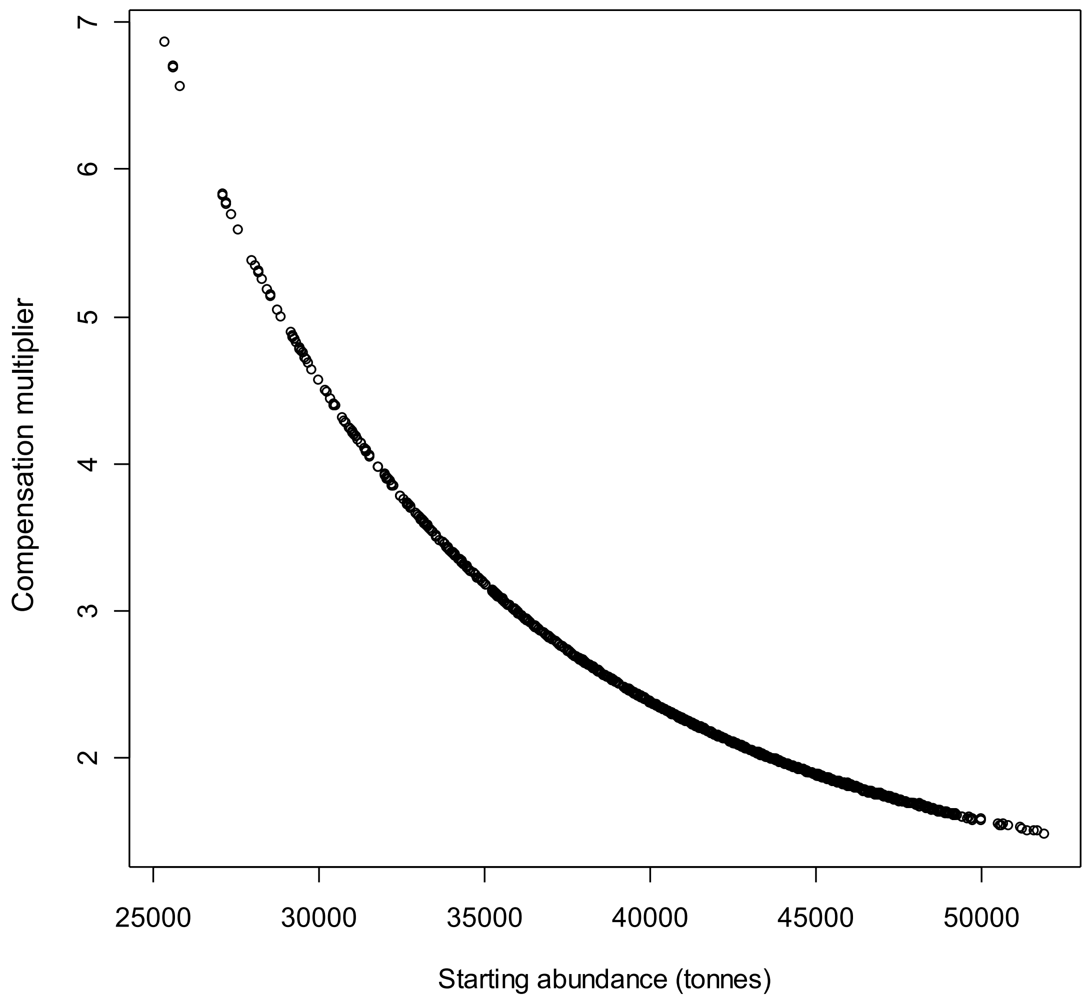


Figure 5.5. Joint distribution of 1000 samples of abundance and resilience parameters drawn from the joint posterior probability density using the marginal-conditional algorithm. The distribution of the points also illustrate that there is a well defined curve for the relationship between a given initial abundance and the conditional estimate of the compensation multiplier.

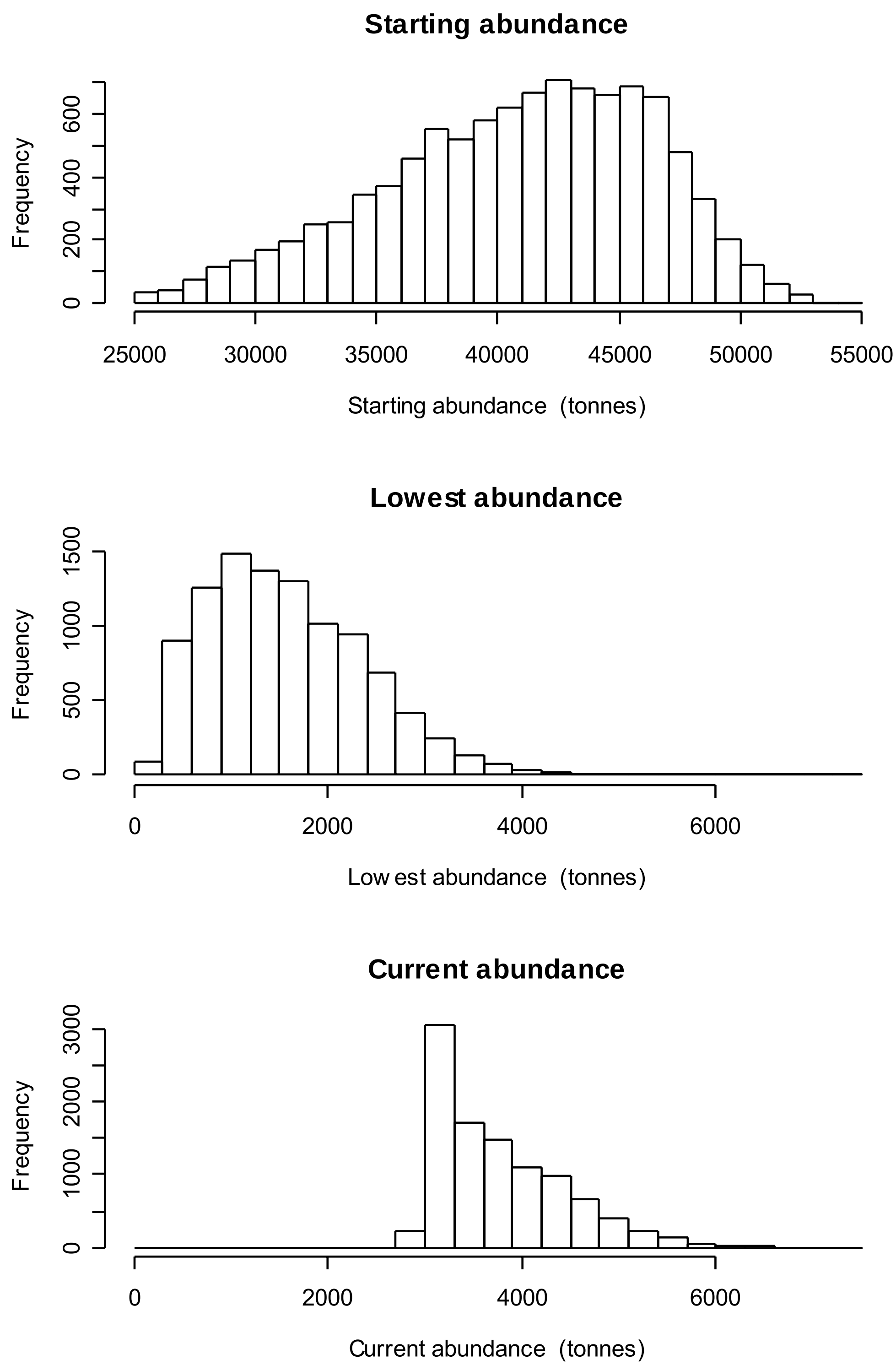


Figure 5.6. Posterior distributions of abundance from likelihood-importance-resampling of Ricker model (10000 samples). Starting abundance refers to 1927, lowest abundance usually occurs in 1987 and current abundance refers to 2003.

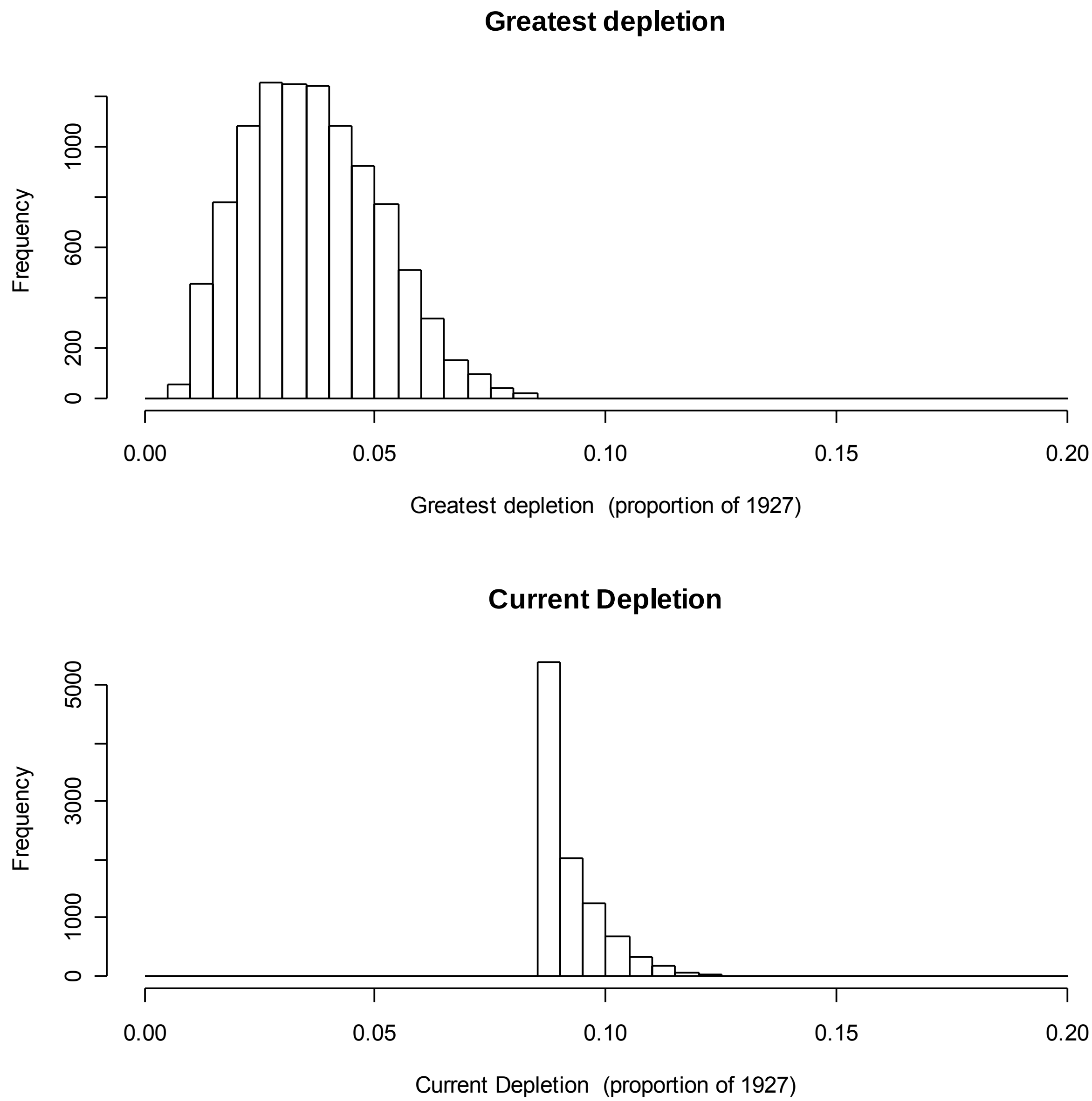


Figure 5.7. Posterior distributions of depletion from likelihood-importance-resampling of Ricker model (10000 samples). Lowest depletion usually occurs in 1987 and current depletion refers to 2003.

5.3.1 Stock projections

Ideally, the procedure for calculating stock projections would be to choose at random an initial abundance and compensation multiplier from their Bayes' joint posterior distribution. Unfortunately, as described earlier, the standard algorithms for generating these random numbers were inefficient and possibly biased. As an interim procedure, we used the marginal posterior distribution of initial abundances. Each point on the marginal abundance distribution has a conditional maximum likelihood estimate of the productivity multiplier (Figure 5.5 shows the shape of the relationship between them). For the projection results presented in this assessment, we drew a random initial abundance from the marginal distribution and then combined it with the conditional estimate of the productivity multiplier to form the parameter pair for each stock projection. Continuous values for the likelihood of the marginal distribution and the relationship between initial abundance and productivity were both calculated using cubic splines fitted to several hundred point estimates conditioned on fixed values of the abundance. This method means that the small contribution from the uncertainty in the estimates of the compensation multiplier is not taken into account in the stock projections presented in this assessment.

We were initially unable to investigate the properties of this procedure because of the lack of a suitable algorithm for resampling from the extreme form of posterior distribution found in this assessment. However, our recently developed algorithm is an efficient alternative to MCMC methods. In this algorithm we first draw a random deviate from the marginal distribution of abundance, $f_X(x)$ say, and then draw a random deviate from the conditional distribution for productivity, say $Y|X$, $f_{Y|X}(y|x)$. Both random numbers are generated using a rejection algorithm. The resampling algorithm is based on the joint distribution $f_{X,Y}(x,y)$ of X and Y being given by:

$$f_{X,Y}(x,y) = f_X(x) f_{Y|X}(y|x) \tag{5.4}$$

Sampling from the marginal distribution for abundance ensures that random numbers are returned from the tails of the distribution, thus overcoming the inefficiency of the MCMC methods. In Appendix G, we show some results that indicate that the effects of ignoring uncertainty in the productivity multiplier are tolerable in the current assessment. However, the improved algorithm should be used in future assessments.

The results of 1000 stock projections in terms of times to recovery to various proportions of initial abundance are shown in Table 5.3 and Table 5.4 for two levels of recruitment variability (low variability coefficient of variation [CV] = 0.5; and high variability CV = 1.0) and minimum or maximum size limits of 650 mm. The information for determining an allowable catch from the decision rule can be found in Figure 5.8, which shows the relationship between specified constant catches and the frequency of stock trajectories that do not have a positive trend in abundance over the next ten years. The four curves derive from the combination of two levels of recruitment variability and two size limits. One of the management options suggested for lingcod is to have a 'slot' size limit so as to reduce the catch of large females with high fecundity. The effect of a slot limit will be somewhere between the two size limits presented in the curves. Given an estimate of depletion, the decision rule provides the acceptable relative

Table 5.3. Year of first surpassing specified proportions of initial abundance using the Ricker model and a size limit > 650mm. The first column is the proportion of initial abundance achieved. The columns labelled nil are the number of instances in 1000 that the population did not surpass the specified abundance. The other 3 columns are given percentiles on the distribution of recovery times to the specified level of abundance. The year 2103 means ≥ 2103.

Recruitment CV = 0.5

Catch ->	0				5000				10000				20000			
	nil	5%	50%	95%	nil	5%	50%	95%	nil	5%	50%	95%	nil	5%	50%	95%
>0.1K	0	2004	2005	2005	0	2004	2005	2006	0	2004	2005	2006	0	2004	2005	2006
>0.2K	0	2009	2016	2026	0	2009	2016	2027	0	2009	2016	2029	0	2009	2018	2032
>0.3K	0	2012	2023	2038	0	2012	2024	2040	0	2012	2024	2042	1	2013	2026	2047
>0.4K	0	2015	2028	2050	1	2015	2029	2052	1	2015	2030	2053	1	2015	2032	2058
>0.5K	1	2017	2034	2058	1	2017	2034	2061	1	2017	2035	2064	4	2018	2037	2070

Catch ->	30000				40000				50000				60000			
	nil	5%	50%	95%	nil	5%	50%	95%	nil	5%	50%	95%	nil	5%	50%	95%
>0.1K	0	2004	2006	2006	0	2004	2006	2007	0	2004	2007	2008	2	2004	2007	2015
>0.2K	1	2010	2019	2037	3	2010	2020	2043	8	2010	2023	2055	33	2010	2025	2079
>0.3K	2	2013	2027	2053	4	2013	2029	2060	14	2014	2032	2075	44	2014	2034	2098
>0.4K	4	2016	2034	2064	7	2016	2036	2075	23	2017	2039	2089	70	2017	2043	2103
>0.5K	6	2018	2040	2078	17	2019	2043	2087	48	2019	2046	2101	103	2019	2050	2103

Recruitment CV = 1.0

Catch ->	0				5000				10000				20000			
	nil	5%	50%	95%	nil	5%	50%	95%	nil	5%	50%	95%	nil	5%	50%	95%
>0.1K	0	2004	2005	2005	0	2004	2005	2006	0	2004	2005	2006	0	2004	2005	2006
>0.2K	9	2008	2017	2059	11	2009	2018	2065	21	2009	2019	2071	52	2009	2020	2103
>0.3K	20	2011	2026	2084	35	2011	2027	2091	44	2011	2027	2099	86	2012	2029	2103
>0.4K	49	2013	2032	2103	60	2013	2033	2103	80	2013	2035	2103	118	2014	2037	2103
>0.5K	79	2015	2038	2103	91	2015	2039	2103	108	2015	2040	2103	143	2016	2043	2103

Catch ->	30000				40000				50000				60000			
	nil	5%	50%	95%	nil	5%	50%	95%	nil	5%	50%	95%	nil	5%	50%	95%
>0.1K	0	2004	2006	2006	2	2004	2006	2008	49	2004	2007	2049	105	2004	2007	2103
>0.2K	100	2009	2022	2103	176	2009	2024	2103	239	2010	2026	2103	317	2010	2030	2103
>0.3K	142	2012	2032	2103	218	2012	2035	2103	282	2012	2039	2103	370	2013	2044	2103
>0.4K	177	2014	2039	2103	248	2014	2043	2103	311	2014	2049	2103	392	2015	2057	2103
>0.5K	215	2016	2047	2103	277	2016	2051	2103	335	2017	2057	2103	422	2017	2068	2103

Table 5.4. Year of first surpassing specified proportions of initial abundance using the Ricker model and a size limit < 650mm. The first column is the proportion of initial abundance achieved. The columns labelled nil are the number of instances in 1000 that the population did not surpass the specified abundance. The other 3 columns are given percentiles on the distribution of recovery times to the specified level of abundance. The year 2103 means ≥ 2103.

Recruitment CV = 0.5

Catch ->	0				5000				10000				20000			
	nil	5%	50%	95%	nil	5%	50%	95%	nil	5%	50%	95%	nil	5%	50%	95%
>0.1K	0	2004	2005	2005	0	2004	2005	2005	0	2004	2005	2005	0	2004	2005	2006
>0.2K	0	2009	2016	2026	0	2009	2016	2026	0	2009	2016	2027	0	2009	2016	2029
>0.3K	0	2012	2023	2038	0	2012	2023	2039	0	2012	2024	2040	0	2012	2024	2042
>0.4K	0	2015	2028	2050	1	2015	2029	2051	1	2015	2029	2052	1	2015	2030	2053
>0.5K	1	2017	2034	2058	1	2017	2034	2059	1	2017	2034	2061	2	2017	2035	2065

Catch ->	30000				40000				50000				60000			
	nil	5%	50%	95%	nil	5%	50%	95%	nil	5%	50%	95%	nil	5%	50%	95%
>0.1K	0	2004	2005	2006	0	2004	2005	2006	0	2004	2005	2006	0	2004	2005	2006
>0.2K	0	2009	2017	2030	0	2009	2018	2032	1	2009	2018	2035	1	2009	2019	2039
>0.3K	1	2012	2025	2045	1	2013	2026	2048	1	2013	2027	2052	3	2013	2027	2055
>0.4K	1	2015	2031	2056	1	2015	2032	2059	4	2016	2033	2063	4	2016	2034	2068
>0.5K	3	2018	2037	2069	4	2018	2038	2071	6	2018	2039	2075	7	2018	2040	2081

Recruitment CV = 1.0

Catch ->	0				5000				10000				20000			
	nil	5%	50%	95%	nil	5%	50%	95%	nil	5%	50%	95%	nil	5%	50%	95%
>0.1K	0	2004	2005	2005	0	2004	2005	2005	0	2004	2005	2005	0	2004	2005	2006
>0.2K	9	2008	2017	2059	9	2009	2018	2062	11	2009	2018	2066	26	2009	2019	2075
>0.3K	20	2011	2026	2084	30	2011	2026	2087	35	2011	2027	2092	49	2011	2027	2101
>0.4K	49	2013	2032	2103	57	2013	2033	2103	61	2013	2033	2103	82	2013	2035	2103
>0.5K	79	2015	2038	2103	88	2015	2039	2103	93	2015	2039	2103	114	2015	2040	2103

Catch ->	30000				40000				50000				60000			
	nil	5%	50%	95%	nil	5%	50%	95%	nil	5%	50%	95%	nil	5%	50%	95%
>0.1K	0	2004	2005	2006	0	2004	2005	2006	0	2004	2005	2006	0	2004	2005	2006
>0.2K	41	2009	2019	2096	62	2009	2020	2103	88	2009	2021	2103	123	2009	2022	2103
>0.3K	71	2011	2029	2103	99	2011	2029	2103	130	2012	2031	2103	166	2012	2033	2103
>0.4K	107	2013	2036	2103	126	2014	2037	2103	161	2014	2038	2103	199	2014	2040	2103
>0.5K	133	2015	2042	2103	156	2016	2043	2103	200	2016	2045	2103	231	2016	2047	2103

frequency of stock decline over ten years, and so the corresponding catch limit can be found on the selected curve. In the case of lingcod, recruitment variability has not been estimated, and the curves show that the results are sensitive to this parameter.

5.3.2 Selection of hypotheses

The remaining entries in Table 5.2 give the results for the various hypotheses initially considered to be relevant in assessing the state of lingcod in the Strait of Georgia. Appendix D, Table D 2 gives a synopsis of how the hypotheses were implemented in the model. The table shows the hypotheses divided into "structural hypotheses", i.e. those that deal with the form of the model, and "uncertain data hypotheses", i.e. those that are related to uncertainties in model parameters and data. Rather than going through the results in detail we will give a brief outline of whether the results suggest that each particular hypothesis is an important source of uncertainty in the current assessment of lingcod.

The goodness of fit of the model to the data, based on the log-likelihood, under the various hypotheses are given in Figure 5.9 sorted with the best fitting model at the top. The figure shows that the log-likelihoods for the eight top hypotheses are close in value, and so the data do not provide statistical support for rejecting any of these hypotheses. However, the bottom two hypotheses provide significantly worse fits to the data, and so can be rejected. Figure 5.10 shows the point estimates of 1927 spawning stock abundance under each hypothesis in the same rank order as Figure 5.9 The point estimates are generally similar except for the hypotheses of high natural mortality (which increases productivity, and hence the historic catch can be supported from a smaller initial stock) and the hypothesis that all of the District 1 catch originated from outside the Strait of Georgia (which also implies a smaller stock since fewer catches had to be supported; see Section 4.1.2 for discussion of District 1 commercial catch statistics).

Figure 5.11 shows the point estimates of lowest point and current (2003) abundance and the corresponding estimates of depletion (as a percentage of the 1927 abundance). The left hand pair of plots shows that the estimates of lowest and current abundance are quite similar for the various hypotheses, except for high mortality and density dependent growth and mortality (ignoring the rejected fixed-regime and seal-predation hypotheses). The plots also show in most cases a similar increase in abundance from slightly less than 2000 tonnes at the low point to just less than 4000 tonnes currently. The right hand pair of plots shows that all but three hypotheses indicate similar low point and current depletions, the exceptions being density dependent growth and mortality, suspect District 1 catches and high natural mortality.

The key points of these results are that most of the hypotheses give very similar fits to the data and also yield similar conclusions about the state of the stock. Of the six structural hypotheses, we can reject the regime shift and seal predation hypotheses because of their significantly worse fit to the data, and additionally, they do not lead to substantially different conclusions on the state of the stock. Of the remaining four structural hypotheses, only density dependence in growth and mortality produces a different, less pessimistic, outcome in estimates of lowest and current depletion. However, the extent of density dependence in growth and mortality used is entirely speculative, and so further consideration of this hypothesis for use in assessments requires further research. The results show that current assessments will not be substantially affected by the choice of any of the three stock recruitment relationships.

For the uncertainty on whether natural mortality (M) is high, the results show that the estimate of initial stock size is substantially reduced by a large (twofold) difference in the estimate of M. The estimates of lowest and current depletion are about two percentage points lower.

The results on the status of the stock are not very sensitive to the corrections in the catch record relating to the origins of catches recorded in the District 1. It is only with the deletion of all the catches recorded in District 1 that we see any appreciable difference. As would be expected, these results are less pessimistic about the depletion of the stock.

Based on the evaluation of the hypotheses, the Lingcod Management Framework Committee selected the Ricker model, and to use historically supported corrections (Chatwin 1958) to the catch data for the whole Strait of Georgia.

5.3.3 Estimated status of the lingcod stocks in the whole Strait of Georgia

Based on the selected model and the corrected catches, the state of the lingcod stocks in the whole Strait of Georgia can be summarised as follows:

1927 spawning stock abundance	43 360 tonnes	100.00%
Lowest (1987) spawning stock abundance	1 900 tonnes	4.38%
Current (2004) spawning stock abundance	3 990 tonnes	9.20%
Compensation multiplier	1.967	

5.3.4 Comparison with estimates by Martell (1999)

1889 spawning stock abundance	41 500 tonnes	100.00%
Lowest (1984) spawning stock abundance	2 175 tonnes	5.24%
Current (1998) spawning stock abundance	5 102 tonnes	12.30%
Compensation multiplier	2.435	

Overall, there is good agreement between the current assessment and that of Martell (1999), with the current estimate being slightly more pessimistic. The reasons that they may differ are

- Current assessment has more years of data,
- Current assessment uses both commercial and recreational CPUE
- The current model separates the sexes.
- There are some recent corrections to the catch data
- Catches are modelled differently
- Martell used a Beverton and Holt model (unlikely an important source of difference)
- Martell assumes that CPUE is proportional to abundance
- Martell uses catches back to 1889.

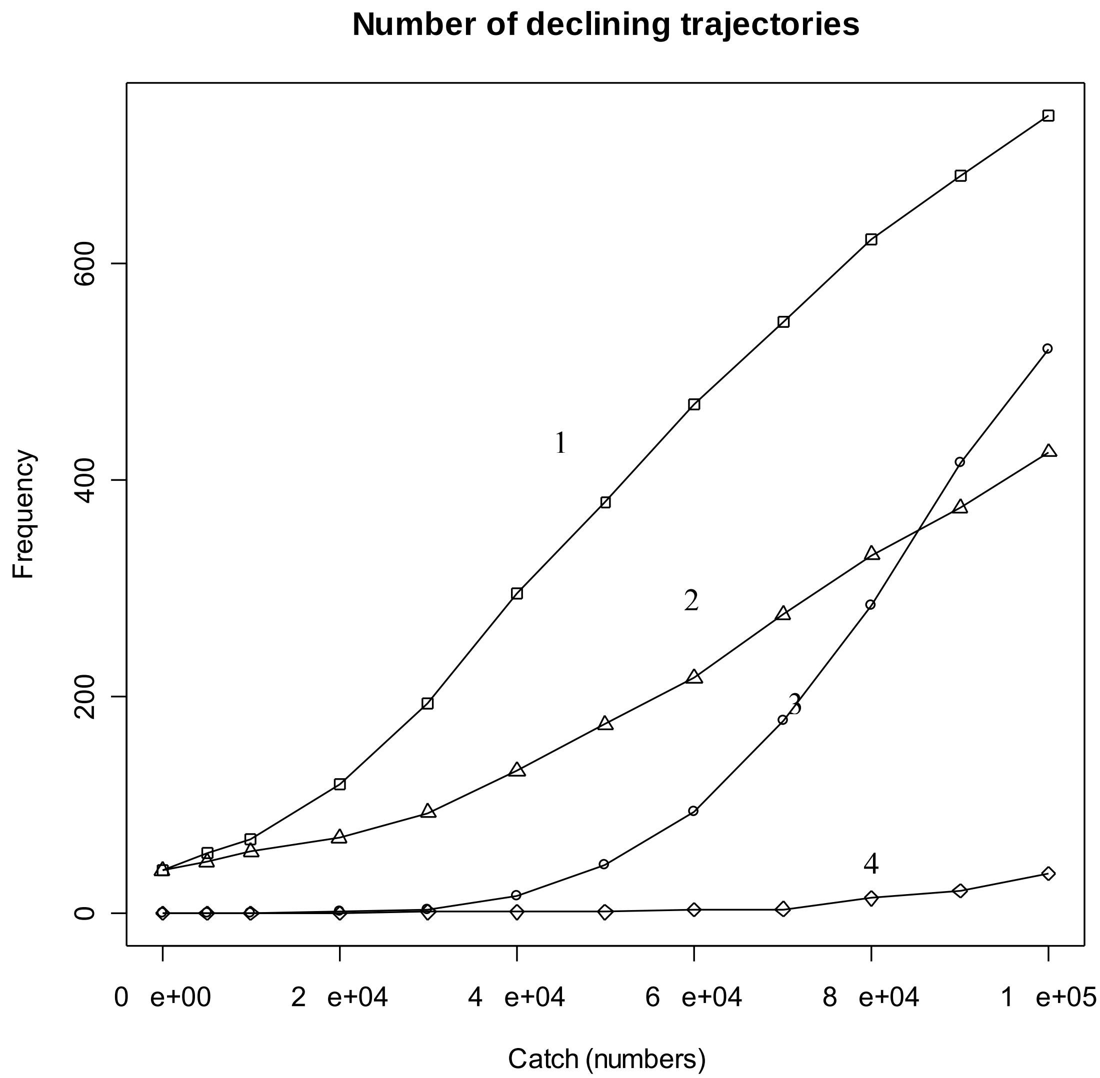


Figure 5.8. Projections to 2013 showing the number of trajectories (from one thousand) that decline relative to current abundance for various levels of catch using Ricker model. The curves are as follows:

1. High recruitment variability, current size limit
2. High recruitment variability, alternative size limit
3. Low recruitment variability, current size limit
4. Low recruitment variability, alternative size limit

The recruitment variabilities are as follow: low = 0.5, high = 1.0. The current size limit is a minimum length of 650mm; the alternative size limit is a maximum length of 650mm.

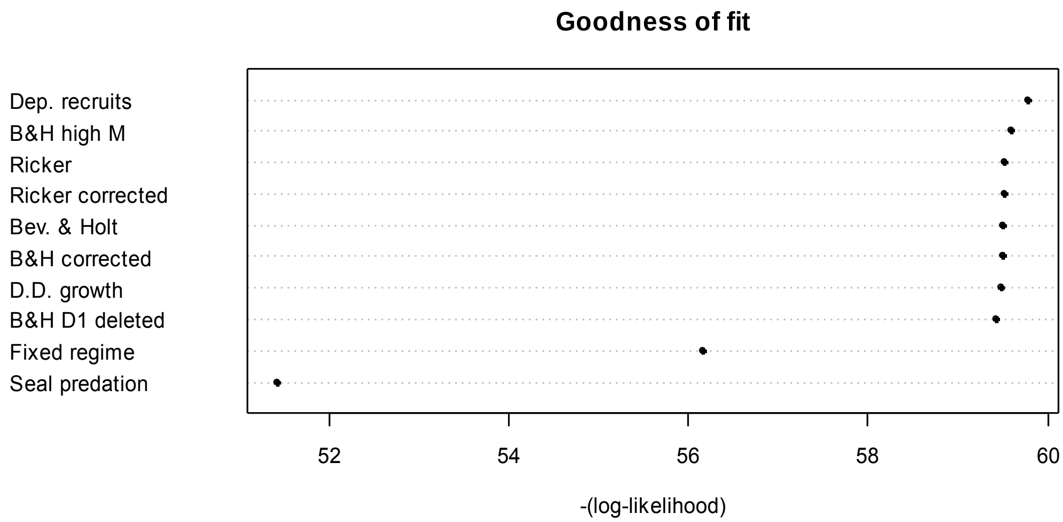


Figure 5.9. Residual function values for the various hypotheses fitted to the data, sorted in best fit order (higher values mean a better fit). Only the lower two hypotheses represent significantly poorer fits to the data; the differences in fit for the top eight hypotheses are not statistically significant.

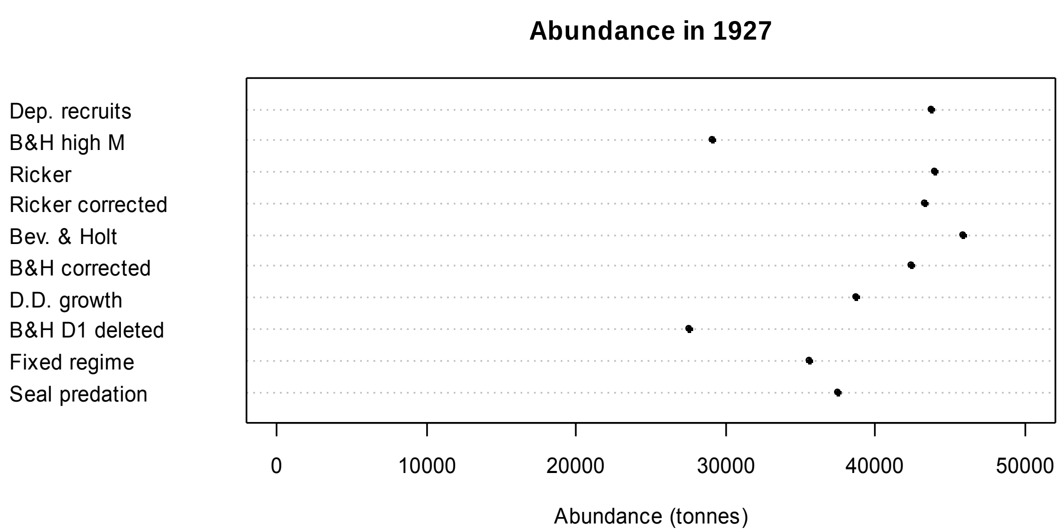


Figure 5.10. Initial (1927) abundance estimates under the various hypotheses (in the same rank order as Figure 5.10).

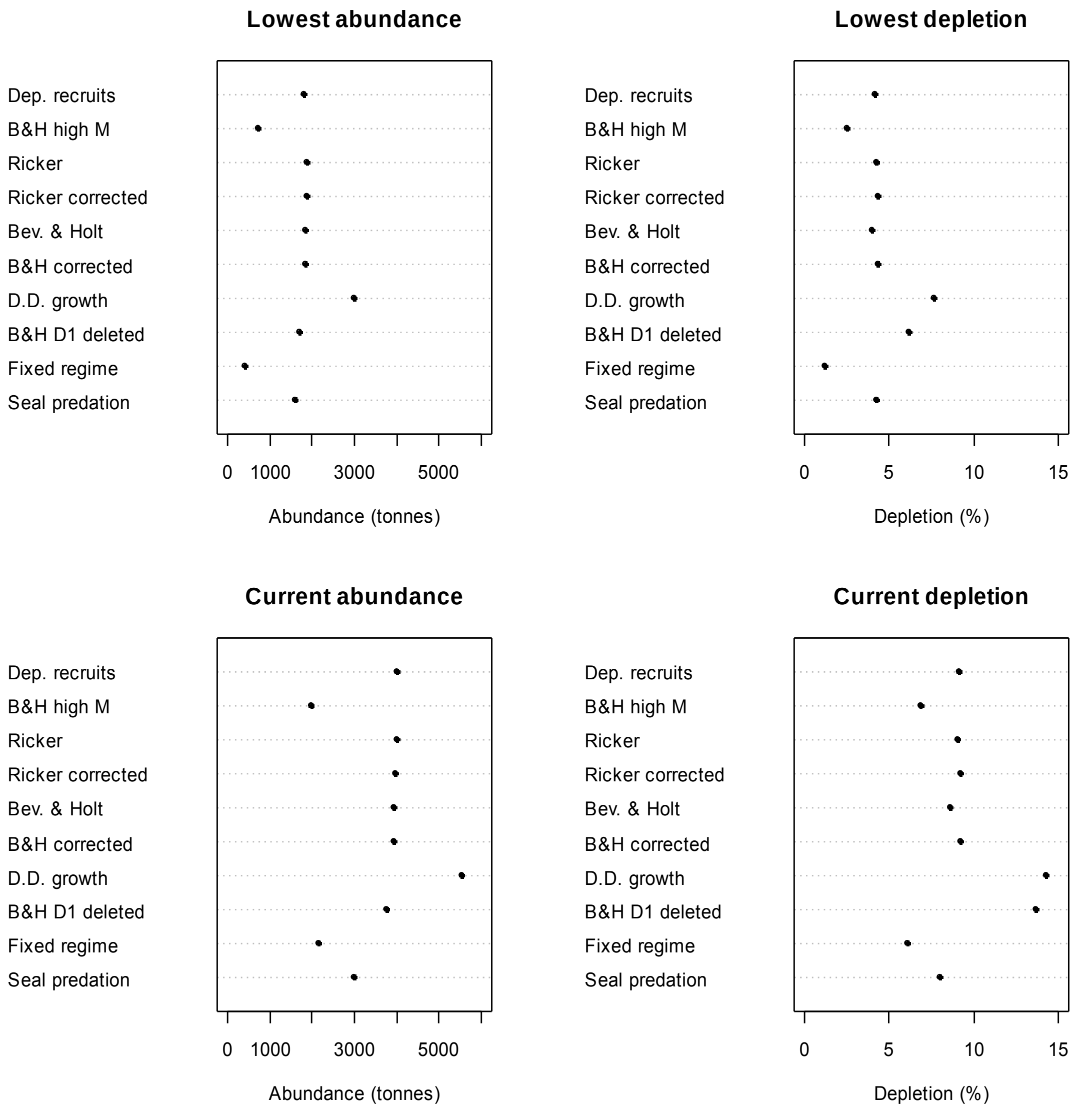


Figure 5.11. Estimates of current and lowest abundance and depletion relative to abundance in 1927 under the various hypotheses (in the same rank order as Figure 5.9). The lowest two hypotheses are rejected because of lack of support from the data.

5.4 FITTING THE MODEL TO SUBDIVISIONS OF THE STRAIT OF GEORGIA

5.4.1 Fitting the model to four geographic areas

The model was fitted to spatial subdivisions of the data to determine whether there might be a regional difference in the state of 'local' stocks, i.e. under the assumption that each subdivision represents a unit stock (Holden and Raitt 1974). Data for Statistical Areas were aggregated into large geographic categories: southeast (Statistical Areas 28 and 29); northeast (Statistical Areas 15 and 16); northwest (Statistical Areas 13 and 14) and southwest (Statistical Areas 17-19). The results from fitting the standard model to four geographic areas are shown in Table 5.5. The fitted trajectories, goodness of fit plots and posterior marginal distributions of abundances and depletions are shown in Appendix E, Figures E 1 – E 16. The same general pattern applies in each geographic area; the stock is estimated to be depleted, although to different extents and with differing estimated rates of recovery. The Southeast quadrant is estimated to be the most depleted, and also to exhibit the least recovery. However, the fit of the model to the data in this quadrant is poor and the model does not follow the recent increase in recreational CPUE. The poor fit is possibly due to uncertainties in recorded catches. Interestingly, the Southwest sector is estimated to have been very depleted, to around 1.4% in 1987, but to be making a steady recovery to just over 20% depletion in 2004. Another interesting result is that while the sum of the initial abundance estimates of 37 300 tonnes is roughly comparable with the estimate for the whole Strait of Georgia, the sums of the minimum and current stock sizes, 600 and 2200 tonnes respectively, are substantially less than the whole Strait estimates of 1900 and 3900 tonnes. Applying the decision rule using the model results gives the acceptable probabilities as shown in Table 5.6 and the allowable catches shown in Table 5.7. Two quadrants, the Southeast and the Northwest, are currently estimated to be depleted to less than 10% of initial abundance, and the decision rule gives zero catch.

5.4.2 Exclusion of the Southeast quadrant

Given that the Southeast quadrant is estimated to be deeply depleted and has the least secure assessment, the committee considered that retaining fish from this segment of the population should continue to be prohibited. The committee also decided that excluding District 1 catches (Southeast quadrant) would address concerns regarding lingcod commercial landings in the 1920s and 1930s that were recorded for District 1, but caught outside of or perhaps elsewhere in the Strait of Georgia. The committee also considered whether the Strait of Georgia, with the Southeast sector excluded, could support some level of fishing under the decision rule. The results of fitting the model to the combined segments, excluding the Southeast are given in Table 5.8. Figures 5.12 – 5.15 show the trajectories, fit and the posterior distributions of abundance and depletion. Figure 5.16 shows the distributions of projected depletion levels in 2013 for total removals of 5 000 and 7 000 fish, and for 26 930 fish using the decision rules. Figure 5.17 gives more detail at the lower tail of the distribution below the median of the estimates of current depletion. Application of the decision rules gives the catch limits shown in the last section of Table 5.7. The table also gives for each catch level, the median and one percentiles (1%) of the proportional change in stock size predicted at the end of the next ten years.

The information required for the application of the decision rule is shown in Table 5.9 for the minimum size limit of 650 mm and Table 5.10 for the same size as a maximum size limit.

Application of the decision rule gives the annual limit on total removals shown in the last section of Table 5.7. We can use Table 5.9 to illustrate how the calculation for total removals is based on the decision rule. For a median depletion of 15% the decision rule gives an acceptable probability of decline over 10 years of 3.33% (Table 5.7). From the fourth column of Table 5.9 we can see that the probability 3.33% lies in the interval of total removals of 20 000 to 30 000 pieces. Simple linear interpolation gives the result 26 932. The third column of Table 5.9 shows the probability of declining to below 10% of initial abundance, and because this is less than 1%, the $B_{10\%}$ constraint is not binding in this case. The second column of Table 5.9 shows that the stock size exceeds the catch in every year, and so no adjustments in catch levels were made during the projections (the catch in the model is reduced in any year that it exceeds the exploitable stock size). Table 5.9 also shows the median and the upper and lower one percentile of the ratio of the spawning stock abundance in ten years to current spawning stock abundance. Interpolating from Table 5.9 shows that total removals at the level specified by the decision rule has a median relative increase in spawning biomass of 2.271 over ten years, with lower and upper one percentiles of 0.827 and 10.631 respectively.

Table 5.5. Parameter estimates from the various model fits to the CPUE data. All models use a Ricker stock-recruitment relationship. The log-likelihoods from the sub-areas are for different data subsets, and so cannot be compared.

Model	Spawner abundance (tonnes)			Depletion (%)		Log-likelihood
	Start	Lowest	Current	Lowest	Current	
Northeast	3 488	151	405	4.33	11.61	43.0915
Northwest	8 781	273	586	3.11	6.67	38.6819
Southeast	19 394	100	118	0.51	0.61	2.5260
Southwest	5 350	74	1 095	1.38	20.47	46.0760
All	37 013	598	2 204	1.62	5.95	

Table 5.6. Acceptable risk of population decline for each depletion level

Quadrant	Depletion	Acceptable probability (%)
Northeast	11.61	1.07
Northwest	6.67	<0.1
Southeast	0.61	<0.1
Southwest	20.47	6.98

Table 5.7. Total removals (including release mortality) consistent with acceptable probability of decline, for recruitment CV = 1.0, calculated from posterior distributions of projected population to 2013, based on 10 000 stock projections. Note that the depletion estimate used in applying the decision rule is the median of the posterior distributions of depletion estimates, not the maximum likelihood estimates shown in Table 5.5 and Table 5.8.

Southwest quadrant	
Median of depletion estimates	15.8%
Acceptable probability of decline over 10 years	3.87%
Acceptable catch in numbers with minimum size limit	12 780
Acceptable catch in numbers with maximum size limit	22 580
Northeast quadrant	
Median of depletion estimates	11.8%
Acceptable probability of decline over 10 years	1.20%
Acceptable catch in numbers with minimum size limit	0
Acceptable catch in numbers with maximum size limit	0
Three quadrants - Southeast omitted	
Median of depletion estimates	15.0%
Acceptable probability of decline over 10 years	3.33%
Acceptable catch in numbers with minimum size limit	26 930
Acceptable catch in numbers with maximum size limit	57 060

Table 5.8. Parameter estimates from the Ricker model fit to the CPUE data from the Strait of Georgia with the Southeast quadrant omitted, with the start year being 1927. The lowest population abundance occurs in 1990.

Model	Spawner abundance (tonnes)			Depletion (%)		Log-likelihood
	Start	Lowest	Current	Lowest	Current	
Ricker – No SE	13 898	307	2 222	2.21	15.99	49.6992

Strait of Georgia with the Southeast quadrant omitted – Ricker recruitment model

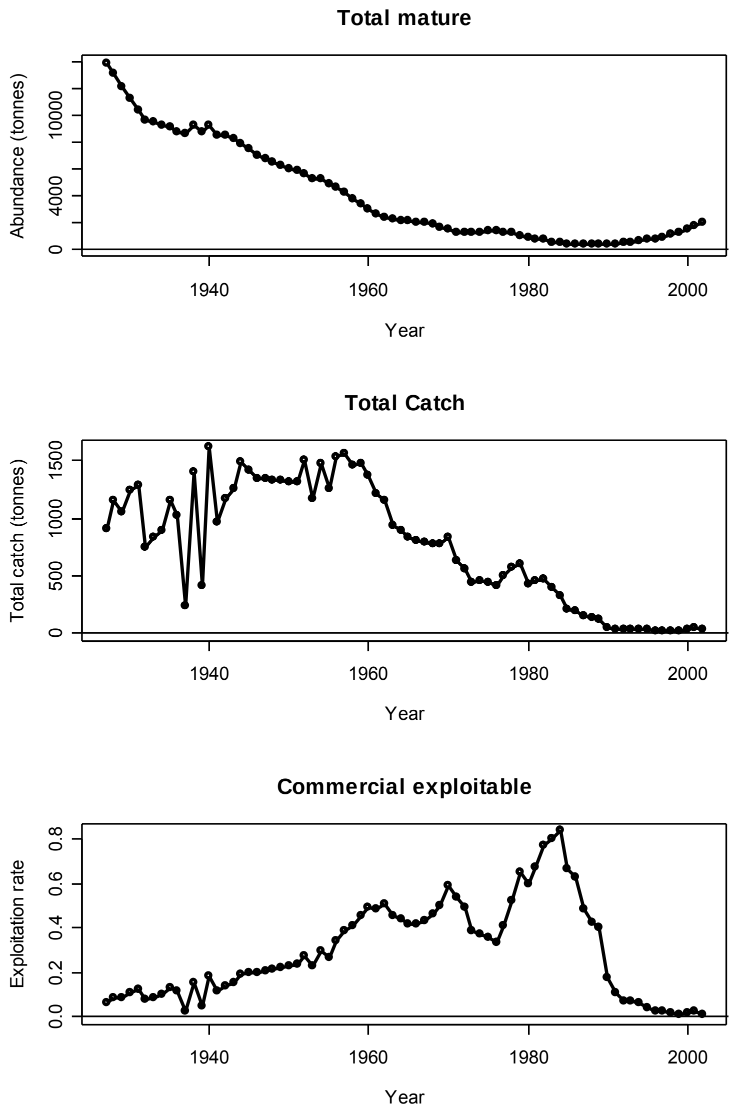


Figure 5.12. Mature biomass trajectory, total catch and exploitation rate for the Strait of Georgia – Ricker recruitment model with Southeast quadrant omitted.

Strait of Georgia with the Southeast quadrant omitted – Ricker recruitment model

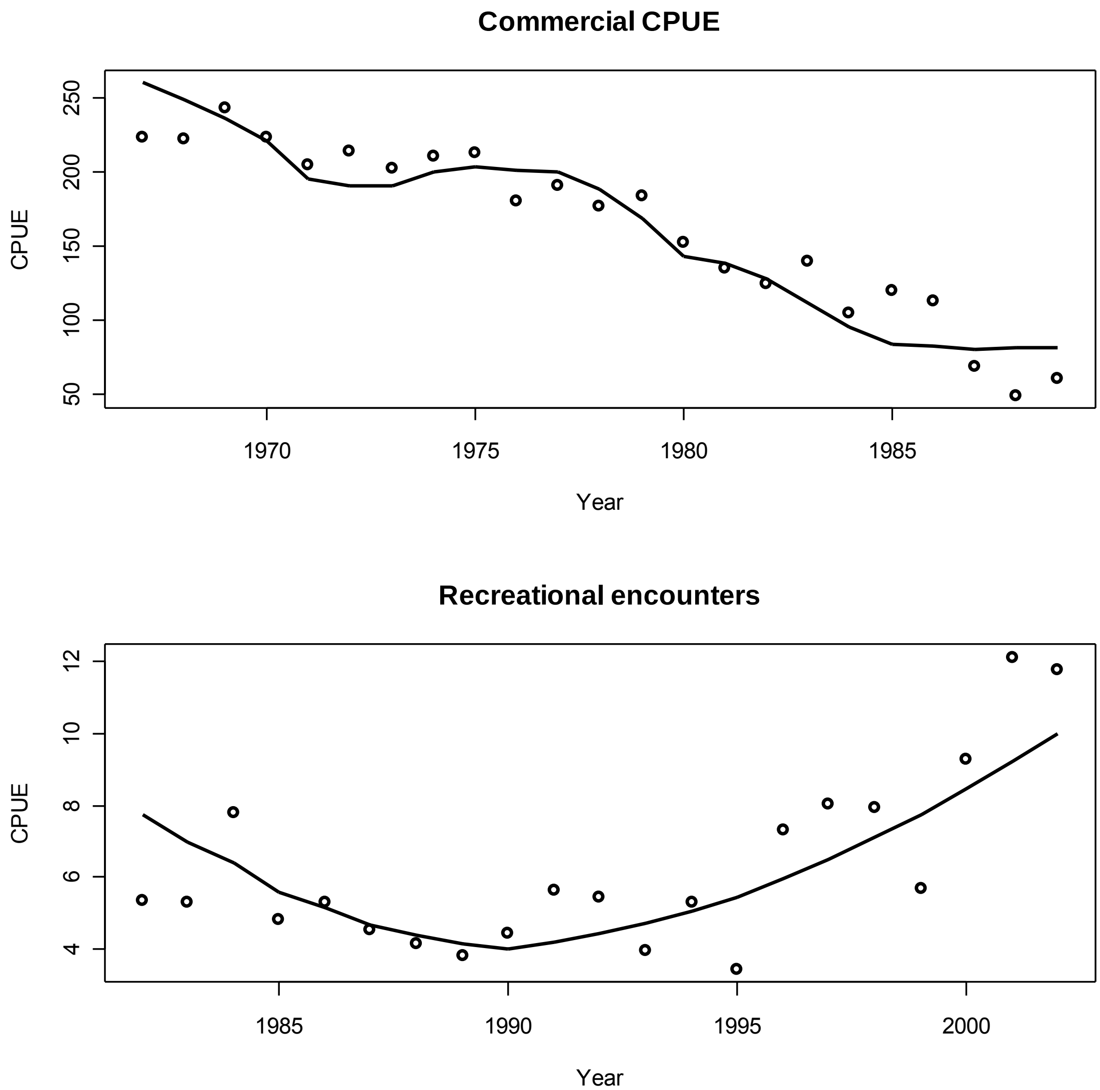


Figure 5.13. Observed and expected CPUE for Strait of Georgia Ricker model fit with Southeast quadrant omitted.

Strait of Georgia with the Southeast quadrant omitted – Ricker recruitment model

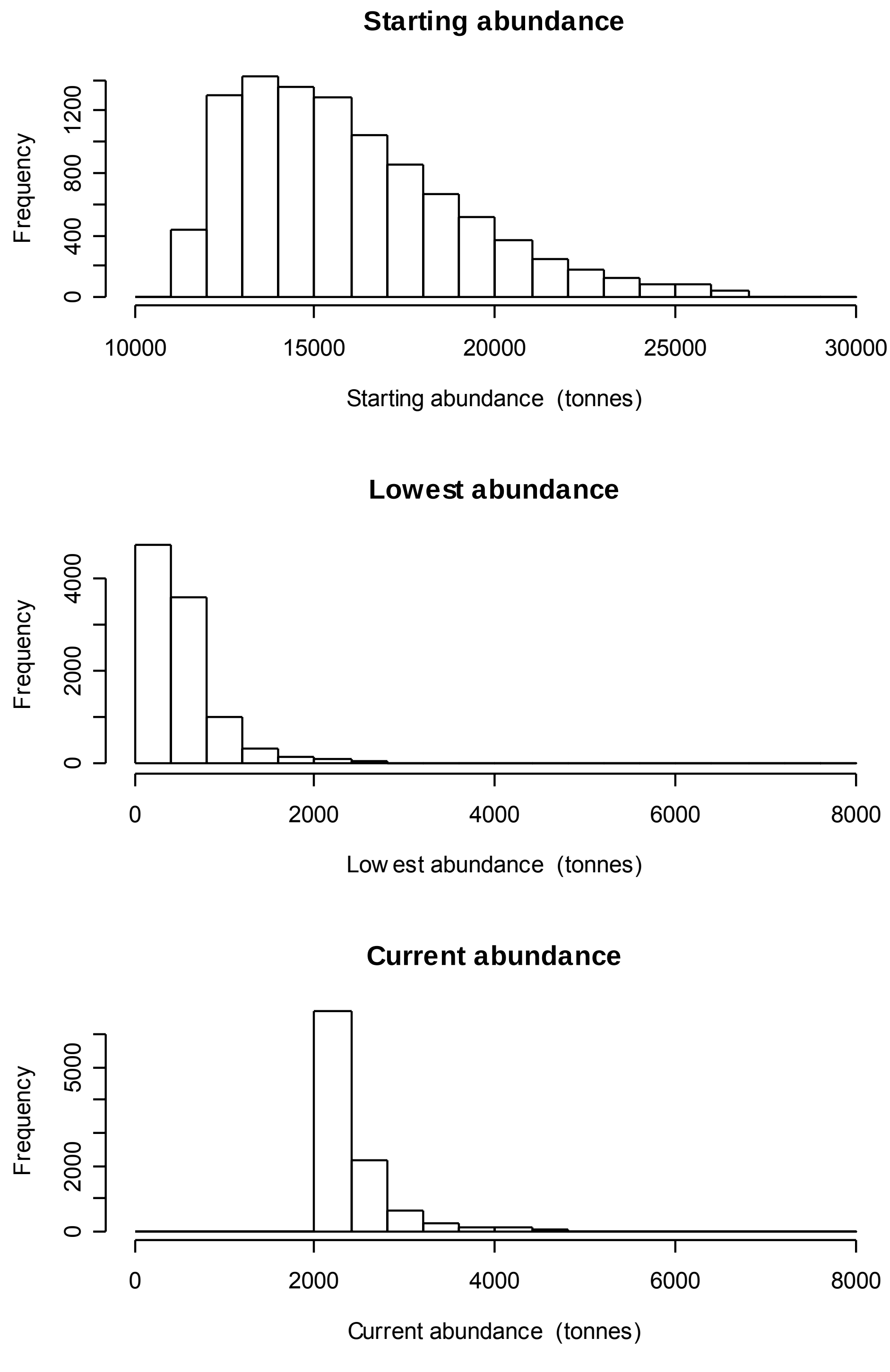


Figure 5.14. Posterior distributions of abundance from likelihood-importance-resampling with Ricker model (10000 samples) with Southeast quadrant omitted. Starting abundance refers to 1927, lowest abundance occurs in 1990 and current abundance refers to 2003.

Strait of Georgia with the Southeast quadrant omitted – Ricker recruitment model

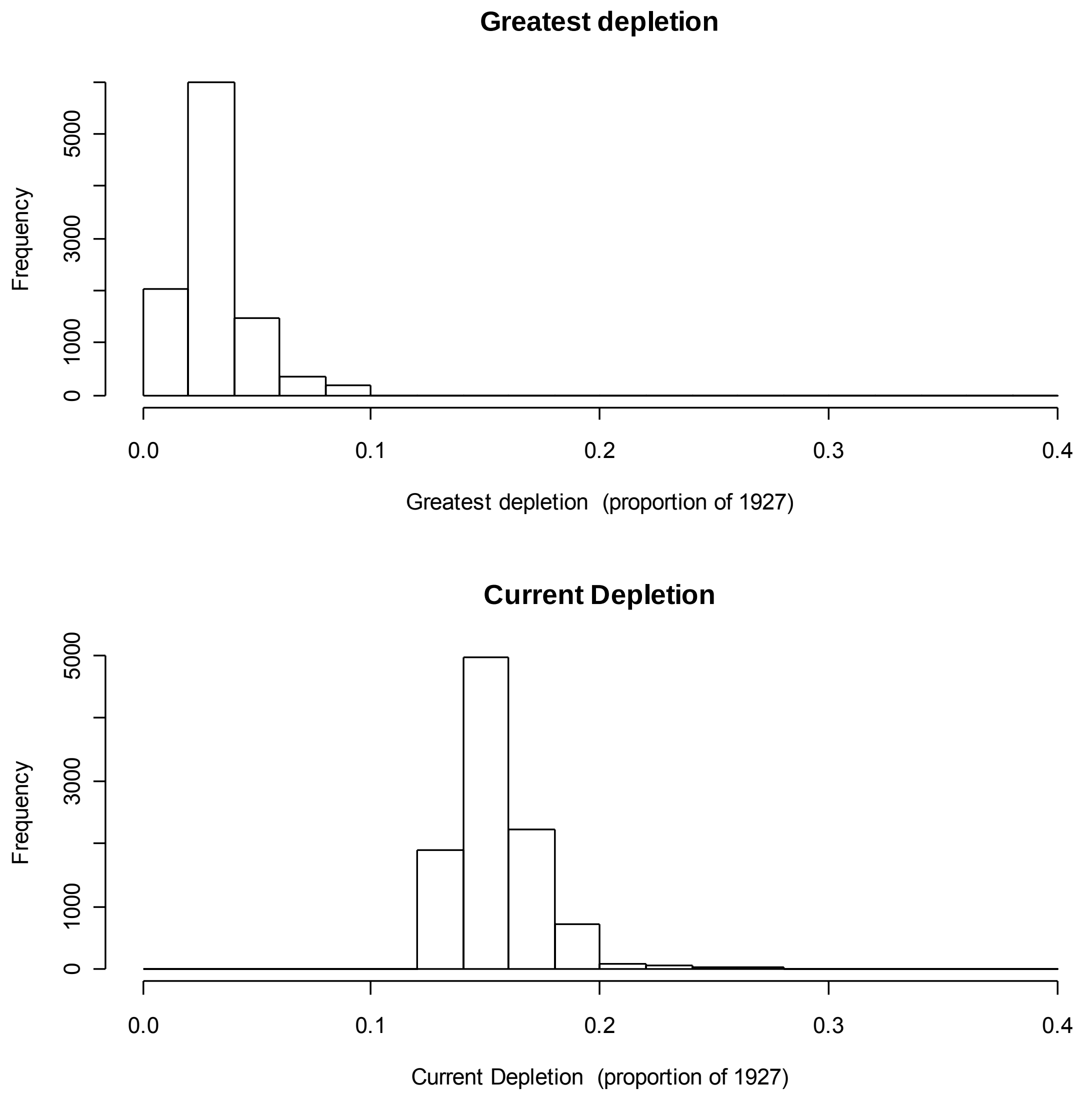


Figure 5.15. Posterior distributions of depletion from likelihood-importance-resampling of Ricker model with Southeast quadrant omitted (10000 samples). Lowest depletion usually occurs in 1990 and current depletion refers to 2003.

Table 5.9. Results of stock projections over 10 year period, with constant removals, using minimum size limit of 650 mm and high recruitment variability.

Total removals (pieces)	Probability that catch cannot be supported every year (%)	Probability of decline to less than 10% of initial (%)	Probability that stock will be lower in 10 years (%)	Relative change in stock size over next 10 years		
				Lower 1 percentile	Median	Upper 1 percentile
0	0.	<0.01	0.43	1.100	2.843	11.263
5000	<0.01	<0.01	0.60	1.046	2.763	11.160
6000	<0.01	<0.01	0.67	1.035	2.747	11.139
7000	<0.01	<0.01	0.74	1.024	2.684	11.110
10000	<0.01	<0.01	1.04	0.995	2.531	11.009
20000	<0.01	0.03	2.03	0.891	2.376	10.783
30000	<0.01	0.21	3.91	0.799	2.225	10.564

Total removals consistent with acceptable probability of decline = 26 932 pieces

Table 5.10. Results of stock projections over 10 year period, with constant removals, using maximum size limit of 650 mm and high recruitment variability.

Total removals (pieces)	Probability that catch cannot be supported every year (%)	Probability of decline to less than 10% of initial (%)	Probability that stock will be lower in 10 years (%)	Relative change in stock size over next 10 years		
				Lower 1 percentile	Median	Upper 1 percentile
0	0.	<0.01	0.43	1.100	2.843	11.263
5000	<0.01	<0.01	0.50	1.073	2.803	11.219
6000	<0.01	<0.01	0.52	1.068	2.795	11.211
7000	<0.01	<0.01	0.54	1.063	2.787	11.202
10000	<0.01	<0.01	0.60	1.048	2.765	11.175
20000	0.01	<0.01	0.99	1.000	2.687	11.036
30000	0.01	<0.01	1.44	0.952	2.611	10.881
40000	0.01	0.01	1.95	0.904	2.536	10.754
50000	0.03	0.06	2.67	0.858	2.460	10.666
60000	0.08	0.16	3.61	0.807	2.384	10.592

Total removals consistent with acceptable probability of decline = 57 057 pieces

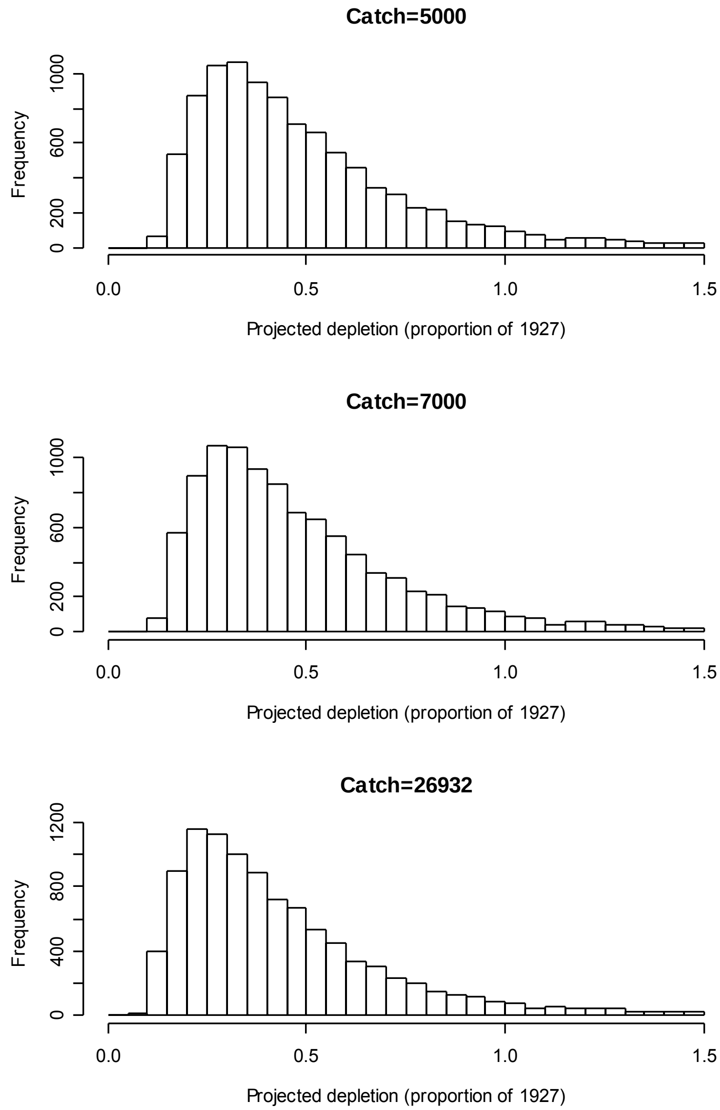


Figure 5.16. Frequency distribution of projected depletions for the year 2013, cut off at 1.5 times the estimates of initial abundance. There is a total of 10 000 observations in the full distribution of projected depletions. The distribution from annual catch levels of 26932 has a median depletion in ten years of 0.376.

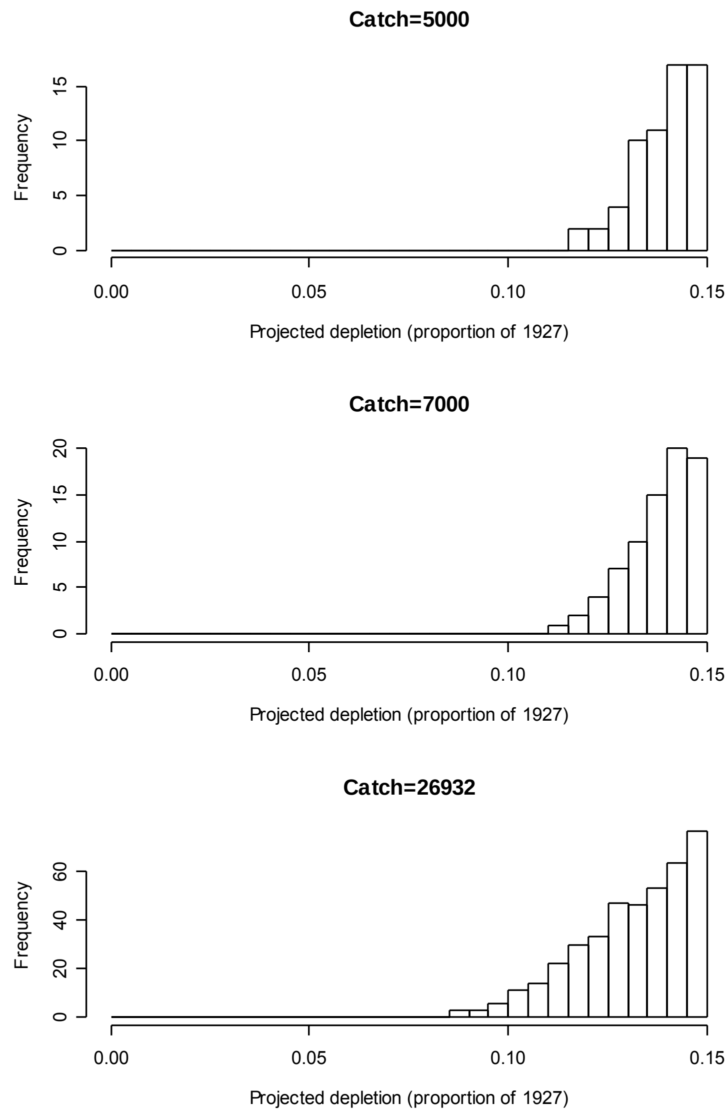


Figure 5.17. Lower tails of the frequency distribution of projected depletions for the year 2013, cut off at the median of the distribution of current depletion estimates. There is a total of 10 000 observations in the full distribution of projected depletions. The distribution moves further to the left with increasing catch. At the projected annual catch levels of 5 000 to 7 000 there are no instances of the projected depletion declining to below 0.1.

6.0 RESEARCH SURVEY DATA ESTIMATES OF THE RELATIVE ABUNDANCE OF LINGCOD

In 2003, a Stock Assessment Framework for Strait of Georgia lingcod recommended the development of fishery-independent sources of relative abundance data to monitor changes in the Strait of Georgia lingcod population (King *et al.* 2003). Funding from the Rockfish and Lingcod Sustainability Strategy was made available in 2003 to implement the research and monitoring plan laid out in the Stock Assessment Framework. Rather than initiating brand new surveys, it was decided that the best use of the resources available would be to conduct surveys using methodologies comparable to past surveys. In this way, past surveys could serve as points of reference to which modern results could be compared. Three components of the monitoring plan are described in this section:

- Hook and line surveys of nearshore reef fishes;
- Lingcod young-of-the-year bottom trawl surveys;
- Lingcod egg mass dive surveys.

We compare the results from these three relative abundance measures to the lingcod population simulation model results (Section 5.4.2). It is important to note that the research survey data presented in this section were not used as input data for the model, since none of the time series are continuous. They are presented here as a source of data to groundtruth the biomass estimates provided by the population model which was based on fishery-dependent data.

6.1 HOOK AND LINE SURVEY OF NEARSHORE REEF FISHES

In 1984, Richards and Cass (1985) developed hook and line surveys to estimate lingcod and rockfish catch per unit of effort (CPUE) which were subsequently conducted in Statistical Areas 13, 15 and 16 in 1985-1988 (Richards *et al.* 1985, Richards and Cass 1987, Richards and Hand 1987), in Statistical Area 17 in 1985, 1987 and 1988 (Cass and Richards 1987; Hand and Richards 1987; Hand and Richards 1989) and in Statistical Areas 18 and 19 in 1993 (Yamanaka and Murie 1995). Two recent hook and line surveys have been completed to date (Haggarty and King 2004 and Haggarty and King 2005). Statistical areas 17, 18 and 19 were surveyed October 6-31, 2003 (Haggarty and King 2004) and Statistical Areas 13, 14, 15 and 16 were surveyed June 14-July 9, 2004 (Haggarty and King 2005). Two depth strata have been used in the recent hook and line surveys: shallow=0-25 m, and deep=26-50 m (Haggarty and King 2004 and 2005).

Lingcod catch per unit effort (fish/hour) is presented as an index of lingcod relative abundance. Research CPUE is probably a good index of lingcod relative abundance since a close correlation between research CPUE and the density of lingcod obtained from visual counts during a dive survey has been found (spearman rank correlation: r_s=0.8571, p=0.01) (Haggarty and King, in preparation). Hook and line survey CPUE data can be used to construct a relative abundance index comparing lingcod abundance in the 1980s and early 1990s to current (2003 and 2004) abundance estimates. Mature biomass estimates from the population simulation model over the same time period show a 4.5-6.9 times increase in biomass (Table 6.1).

Direct comparison between model estimates and research CPUE is difficult because model estimates are spawning biomass (tonnes) and research CPUE is fish per effort. However, in a

Table 6.1. Mature biomass estimates (tonnes) from the lingcod population simulation model, the suggested relative increase in biomass (calculated by dividing the final biomass estimate, B_{2003}, by the biomass estimated for each year, B_{year}), and the mean research CPUE (fish per hour) observed in each Statistical Area surveyed by year. Relative changes in CPUE are calculated as $CPUE_{current}/CPUE_{year}$. Values less than 1.0 denote a decrease in research CPUE.

Year	Mature Biomass Estimate (Tonnes)	B_{2003}/B_{year}	Statistical Area	Research CPUE	$CPUE_{current}/CPUE_{year}$.
1985	357.5	6.2	15	1.4	4.9
			16	2.4	2.4
			17	2.0	0.8
1986	341.8	6.5	13	9.2	1.4
			15	1.4	4.9
			16	3.3	1.7
1987	318.1	6.9	13	5.1	2.5
			17	0.5	3.1
1988	322.8	6.9	13	3.7	3.4
			17	0.3	5.3
1993	498.0	4.5	18	1.6	0.4
			19	2.3	0.6

relative sense it is useful to compare the relative increase suggested by the model to the relative increase suggest by the research surveys (Table 6.1). The model selected by the committee collates input data for Statistical Areas 12-19; research data are available by Statistical Area.

While research CPUE in Statistical Areas 13, 15, and 17 exhibited significant increases from the late 1980s (Table 6.2), none of the areas surveyed exhibited the magnitude of increase suggested by the model results (Table 6.1). An increase in research CPUE was observed in Statistical Area 16, while it actually decreased in Statistical Areas 18 and 19, though none of the changes were statistically significant (Table 6.2).

The population simulation model uses recreational fishery CPUE (lingcod encountered per total effort) as input data for 1982 onwards. Comparison of research CPUE to recreational fishery CPUE can be made by statistical area. Note that the CPUE values are compared in a relative sense only as they are not directly comparable, since research CPUE is measured in fish per hour while recreational CPUE is given in fish per 100 hours of directed plus non-directed lingcod effort.

Statistical Area 13

The hook and line survey in Statistical Area 13 shows an improvement in lingcod CPUE in both depth strata, although only the shallow depth stratum showed significant pair-wise differences. The 2004 CPUE in the shallow stratum shows an improvement over 1987 and 1988 but not 1986 (Table 6.2). The lowest CPUE in all years sampled occurred in 1987 in the shallow stratum and 1988 in the deep. The 2004 shallow CPUE (16.2) is almost 10 times the 1987 CPUE (1.7). CPUE in the deep stratum increased by 4 times. The model biomass increased by 6.9 times in this same time period. Creel survey CPUE in Statistical Area 13, decreased between 1986 (7.3) and 2003 (4.4) (Figure 6.1).

Table 6.2. Inter-annual comparison of lingcod research CPUE (fish/hour) from hook and line surveys in the Strait of Georgia, 1985-2004, by Statistical Area and depth stratum (Shallow=0-25m, Deep=26-50m) using the Kruskal-Wallis test (H) and the Mann-Whitney test (U). Significant differences are shown in bold print (Haggarty and King 2004 and 2005). For each depth stratum the number of sets (N), the mean CPUE with associated standard deviation (SD) along with the median CPUE and the range of CPUE are listed.

	Shallow					Deep				
	N	Mean	SD	Med	Range	N	Mean	SD	Med	Range
Area 13										
1986	20	10.6	8.9	11.0	0–34.2	11	7.8	5.8	8.6	0–17.1
1987	20	1.7	1.8	1.7	0–5.2	8	8.4	11.0	4.8	0–30.0
1988	24	3.9	4.6	2.2	0–13.0	24	2.4	3.0	1.6	0–12.0
2004	10	16.2	7.5	15.7	6.7–33.2	9	9.1	8.0	9.7	0–23.4
Difference among years:										
	H=27.9, **p=<0.0001**, df=3					H=9.0, **p=0.0287**, df=3				
Area 14										
2004	6	2.6	1.6	2.3	0–5.1	7	0.6	1.1	0	0–2.9
Area 15										
1985	28	2.8	5.7	0	0–27.7	8	0	0	0	0–0
2004	9	8.1	3.3	7.8	3.4–12.7	9	5.5	8.0	3.8	0–25.0
Difference among years:										
	U=12.5, **p=0.0004**, df=1					U=5.7, **p=0.0169**, df=1				
Area 16										
1985	29	3.6	4.5	3.3	0–16.4	19	1.2	1.9	0	0–4.6
1986	39	5.2	5.6	4.0	0–23.1	24	1.3	2.5	0	0–8.0
2004	11	8.7	9.8	5.5	0–34.3	9	2.6	2.5	3.8	0–6.1
Difference among years:										
	H=4.4, p=0.1136, df=2					H=2.6, p=0.2751, df=2				
Area 17										
1985	14	3.0	3.4	2.1	0–8.6	27	1.0	2.7	0	0–11.3
1987	46	0.9	2.0	0	0–6.0	83	0.1	0.9	0	0–6.0
1988	33	0.5	1.2	0	0–5.6	51	0.1	0.4	0	0–2.1
2003	15	1.5	2.0	0	0–5.7	28	1.6	1.8	1.0	0–5.8
Difference among years:										
	H=13.2, **p=0.0042**, df=3					H=62.5, **p<0.0001**, df=3				
Area 18										
1993	20	2.2	3.0	0	0–8.6	30	1.0	2.4	0	0–11.4
2003	9	1.0	1.7	0.9	0–5.5	9	0.4	0.5	0	0–1.1
Difference among years:										
	U=0.03, p=0.8564, df=1					U=0.83, p=0.3616, df=1				
Area 19										
1993	20	3.1	4.1	2.9	0–17.9	10	1.4	2.7	0	0–8.3
2003	11	1.6	2.6	0	0–8.6	11	0.9	1.6	0	0–5.4
Difference among years:										
	U=2.0, p=0.1612, df=1					U=0.06, p=0.8090, df=1				

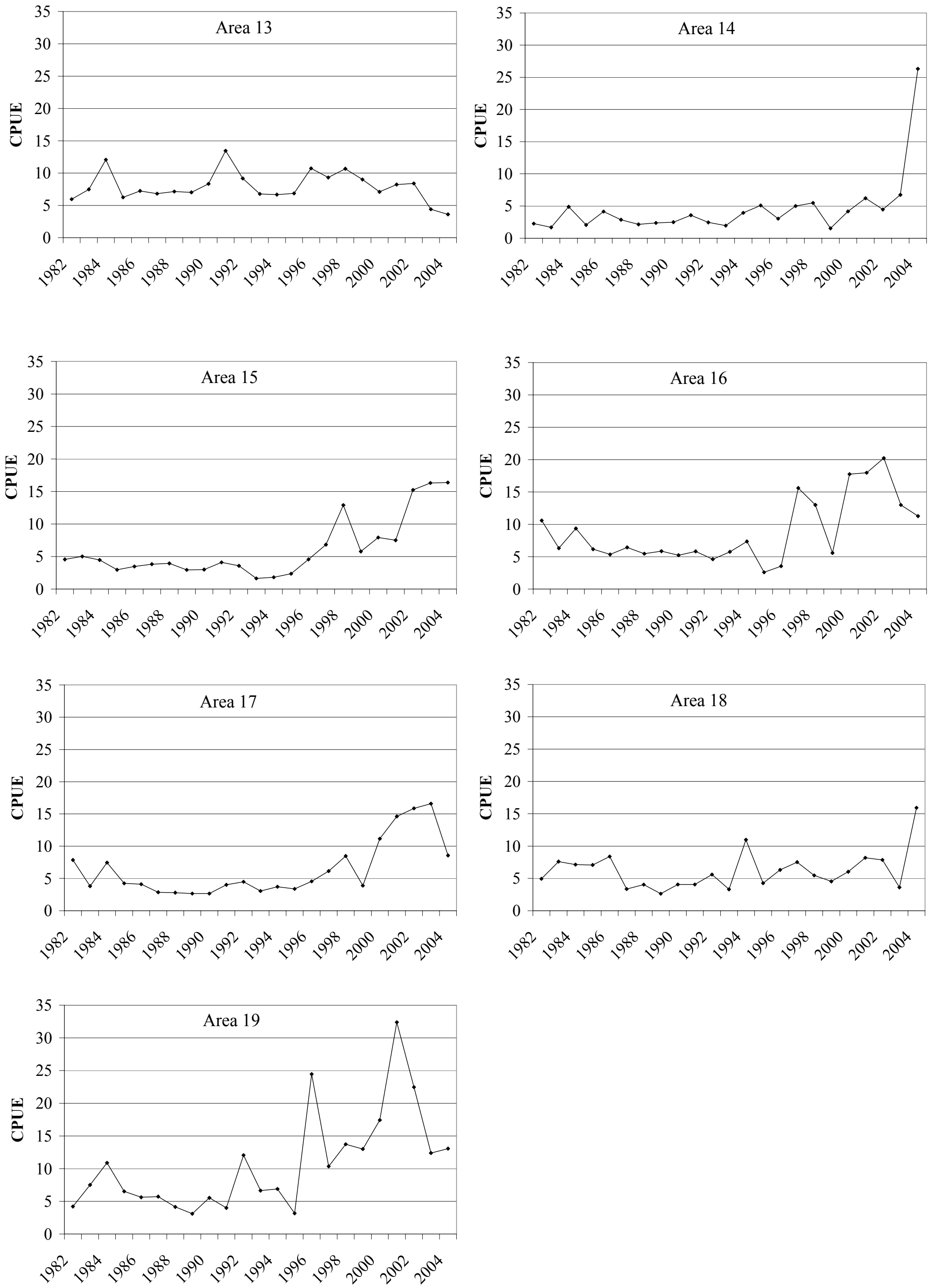


Figure 6.1. Strait of Georgia Creel Survey catch per unit of effort (CPUE; lingcod encounters per 100 hours of fishing), May through September, 1982-2003.

Statistical Area 15

2004 CPUE in Statistical Area 15 was significantly higher than it was in 1985 in both depth strata (Table 2). The shallow CPUE was 2.9 times greater and the deep stratum had a CPUE of 5.5 in 2004 while it had been 0 in 1985. Model biomass increased 6.2 times between 1985 and 2003. Recreational CPUE in Statistical Area 15 also increased between 1985 (3.0) and 2003 (16.3), with an increase of 5.4 times (Figure 6.1).

Statistical Area 16

No significant difference was found in the research CPUE in Statistical Area 16 (Table 6.2). Model biomass at the whole Strait of Georgia increased by 6.5 times between 1986-2003 and recreational CPUE in Statistical Area 16 shows a moderate increase of 2.5 times in Statistical Area 16 between 1986 (5.3) and 2003 (13.0) (Figure 6.1).

Statistical Area 14

Previous hook and line surveys were not conducted in Statistical Area 14, so no historical research CPUE exists. We surveyed five sites in Statistical Area 14 in order to look at spatial differences in catch rates in the Strait of Georgia (Haggarty and King 2005). Research CPUE was significantly lower in Statistical Area 14 in the summer of 2004 than it was in Statistical Area 13, 15, and 16 (Table 6.2) (Haggarty and King 2005). Creel survey data from Statistical Area 14 shows a sharp increase in recreational CPUE (to 26.3) in 2004 (Figure 6.1). This dramatic spike in the lingcod catch rate was not apparent in the other northern Statistical Areas (13, 15 and 16) recreational CPUE and was not reflected in the 2004 survey (Haggarty and King 2005).

Statistical Area 17

The 2003 research CPUE in both depth strata in Statistical Area 17 was significantly greater than it was in 1988 and 1987 but not different from 1986 (Table 6.2).The shallow CPUE from 2003 was 3 times higher than it was in 1987 and 16 times greater in the deep strata. Model biomass increased by 6.5 times between 1986-2003. The recreational CPUE increased by 5.9 times in Statistical Area 17 between 1987 (2.8) and 2003 (16.6).

Statistical Area 18

No significant differences in CPUE were found between 2003 and 1993 in either depth stratum in Statistical Area 18 (Table 6.2) while the model biomass increased by 4.5 times. The recreational CPUE for Statistical Area 18 shows little increase between 1993 (3.3) and 2003 (3.6) (Figure 6.1).

Statistical Area 19

As in Statistical Area 18, there was no significant difference in the research CPUE between 2003 and 1993 in either depth stratum in Statistical Area 19 (Table 6.2) but the model biomass increases by 4.5 times. The recreational CPUE in Statistical Area 19 nearly doubled (1.9 times) between 1993 (6.7) and 2003 (12.4). Statistical Area 19 experienced some exceptional recreational CPUE values of 24.5 and 32.4 in 1996 and 2001, respectively (Figure 6.1).

Research CPUE and the model results both showed upward trends in Statistical Area 13, 15, and 17, although recreational CPUE decreased in Statistical Area 13. Model results and research CPUE did not correspond in Statistical Area 16, 18 or 19. Trends in the research CPUE and recreational CPUE in Statistical Area 19 are alarmingly different. Statistical Area 13 and 17 each have 4 years of research CPUE data. Lowest points in the index occur in 1987 and 1988 in Statistical Area 13 for the shallow and deep depth stratum, respectively; and in 1988 in both depth strata in Statistical Area 17. The model's lowest biomass usually occurs in 1987. The research CPUE from the hook and line surveys indicates that while some Statistical Areas show an improvement in CPUE, other Statistical Areas show no improvement. This result can not be obtained with the model when it is run at the scale of the whole Strait of Georgia.

6.2 YOUNG-OF-THE-YEAR LINGCOD TRAWL SURVEY

In 1991 a bottom trawl survey for young-of-the-year lingcod was initiated (Workman *et al.* 1992). Two subsequent surveys have been completed in 2003 (Haggarty et al. 2004) and 2004 (Haggarty et al 2005). These surveys provide an index of relative year class success for lingcod based on young-of-the-year densities (fish per km^2).

A striking difference in young-of-the-year lingcod density exists between the northern Strait of Georgia (north of Nanoose Bay) and southern Strait of Georgia for all three years, with significantly greater densities of lingcod in the north (Haggarty *et al* 2004, Haggarty *et al.* 2005). Young-of-the-year lingcod density was significantly higher in 2003 and 2004 than in 1991 in the northern region (Table 6.3). Low densities of juvenile lingcod were found in the south in all time periods and lingcod were absent from many tows in all years. Young-of-the-year lingcod density decreased significantly in the south between 1991 and 2003 (U=4.585, p=0.032, df=1); however, no differences were detected when all three years were considered together and the 2004 density may be slightly greater than it was in 2003 (Table 6.3) (Haggarty et al. 2005).

The mean young-of-the-year lingcod density from 1991 to 2003 and 2004 increased by 1.6 times, and only in the northern region. Density did not increase in the south. The reasons for this

Table 6.3. Young-of-the-year lingcod density statistics for the northern region and the southern region for surveys conducted in 1991, 2003 and 2004 in the Strait of Georgia. Kruskal-Wallis test statistics for differences in lingcod density are presented for comparison between years within a region. A significant difference exists for lingcod density between the Northern and Southern region for each year, as well as a significant difference between 1991 and 2003-2004. Only sites sampled in all three years were included in this analysis.

	North					**South**				
	N	Mean	SD	Med	Range	N	Mean	SD	Med	Range
1991	19	1694.4	2564.7	770.0	122–11111	17	547.6	895.4	187.0	0–3376
Difference between regions: U=8.7, **p=0.0033**, df=1										
2003	23	2673.3	2302.2	1881.0	293–9839	19	124.6	286.9	0.0	0–1182
Difference between regions: U=29.7, **p<0.0001**, df=1										
2004	18	1861.3	1306.9	1348.0	0–4792	21	334.0	559.7	0	0–1846
Difference between regions: U=17.8, **p<0.0001**, df=1										
Difference among years by region:										
	H=8.5, **p=0.0144**, df=2					H=4.3, p=0.1168, df=2				

regional disparity in the young-of-the-year lingcod density are not yet understood. Reasons may include juvenile habitat distribution, larval dispersal, larval and juvenile survival rates, or regional spawning stock biomass. Hook and line surveys for year 2+ lingcod (76% of which were mature or maturing) for the Northern Strait of Georgia of showed that the relative abundance of lingcod in the northern-most areas of the Strait of Georgia (Statistical Areas 13 and 15) increased between the mid-to late-1980 and 2004 (Haggarty and King 2005) while survey in the southern Strait of Georgia showed fewer or no improvements in lingcod catch rates (Haggarty and King 2004). The influence of regional spawning biomass can not, however, be determined until larval dispersal in the Strait of Georgia is better understood.

6.3 LINGCOD EGG MASS SURVEYS AT SNAKE ISLAND

Lingcod egg mass SCUBA surveys were conducted at Snake Island outside Nanaimo (Statistical Area 17) in 1990, 1991, 1994, 2001, 2002, 2004 and 2005 (Yamanaka and Richards 1995, King and Beaith 2001; King and Winchell 2002; King and Haggarty 2004; Haggarty et al. 2005). Female lingcod lay masses of eggs on rocky reefs in the winter. After fertilizing the eggs, a male lingcod remains near the egg mass to guard it from predators until the larvae hatch. Egg masses are large (approximately 5 L in volume, King and Winchell 2002) and easy to visually locate. Different methodologies were used in some years, but all dives were conducted at depths up to 20 m between December and April. At Snake Island reef, transect counts (50 or 60 m length, 14 m width) were initially employed in 1990 at randomly selected sites, but in all other years circular quadrat counts with a 10 m radius were used. Recent genetic studies have discovered that more than one male will contribute genetic material to an egg mass, however each egg mass is comprised of eggs from one female only (Withler *et al.* 2003, King and Withler 2005). Egg mass counts can therefore be used to infer number of spawning females only. When divers encounter an egg mass, the presence of a guarding male and its total length (cm) as well as the volume of the egg mass was recorded. Egg mass volume (cubic cm) was estimated by measuring the length, width and height (cm) of the egg mass, adjusting for irregularities in shape. The total length of the guarding male was estimated using measuring tape pulled alongside the resting male.

Egg mass or nest density has been used as an index of relative abundance for lingcod in past stock assessments (King 2001; Yamanaka and Richards 1995). We compared the egg mass density at Snake Island over the years using a non-parametric ANOVA (Kruskal-Wallis test) and found two groups with significantly different mean ranks. 1994, 2002 and 1990 had higher egg mass density than 2001, 2004, 1991, and 2005 (Figure 6.2). King (2001) points out that slight differences in survey design might contribute to differences in nest density estimates since it is not known if an adequate spatial coverage of the reef was attained in all years and there seemed to be preferred spawning locations on Snake Island reef. Subsequent research has shown that male lingcod exhibit precise nest site fidelity as well as nest site affinity (King and Wither 2005), making the locations surveyed on the reef even more important. King (2001) also points out that since the survey only took place on one reef in Statistical Area 17, the abundance trends might be applicable to other locations in Statistical Area 17, but not necessarily indicative of trends throughout the Strait of Georgia. Egg mass surveys were completed at six additional sites around Nanaimo in Statistical Area 17 in 2004 (King and Haggarty 2004). In 2005 egg mass surveys using the same methodology were completed by volunteer SCUBA divers in Statistical Area 13 and Statistical Area 19 (Haggarty et al 2005). No significant difference in nest density among sites was found in either year (Figure 6.3; Figure 6.4) (King and Haggarty 2004, Haggarty et al 2005).

6.4 OVERALL COMPARISONS

The lingcod population simulation model shows a positive growth trajectory that began in the early 1990's and is projected to continue. Model biomass in 2003 has roughly attained biomass levels that existed in the early 1960's (Figure 5.12). Unfortunately, there is no fishery-independent research index that goes that far back in time. As a consequence, all we can look for are positive increases in the relative abundance indices as well as the relative amount of increase. Not all research indices point to significant increases in the relative abundance of lingcod. Moreover, there appears to be a clear spatial component to the increase in relative abundance in the Strait of Georgia, with a greater incidence of positive change in the north than in the south. This difference is most pronounced in the young-of-the-year trawl survey, but is also reflected in the hook and line survey for age 2+ lingcod.

The spatial pattern of relative abundance trends that is apparent in the research indices may be indicating that not all lingcod populations in the Strait of Georgia are recovering at the same rate or to the same extent. Model iterations which considered four different sectors in the Strait of Georgia (NE, NW, SE and SW) separately (Section 5.4.1), showed that lingcod populations were more heavily depleted in the southern regions than in the north (Table 5.5). The recovery time of marine fish populations is negatively correlated with the magnitude of the population decline (Hutchings 2001) therefore, these regions of the Strait should not be expected to recover at the same rate. Interestingly, the southwest quadrant, which was depleted to 1.38 % (the second lowest proportion, Table 5.5), shows the greatest recovery (20.47%); therefore, this case does not fit the pattern described by Hutchings (2001).

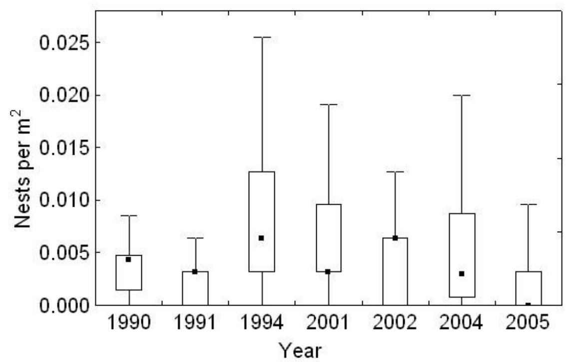


Figure 6.2. Median egg mass density estimates for each survey year at Snake Island reef. Whiskers denote maximum and minimum observed egg mass densities; boxes denote 25th and 75th quartiles. Two significantly different groups exist: 1990, 1994 and 2002; and 1991, 2001, 2004 and 2005 (H=26.7, p=0.0002, df=6).

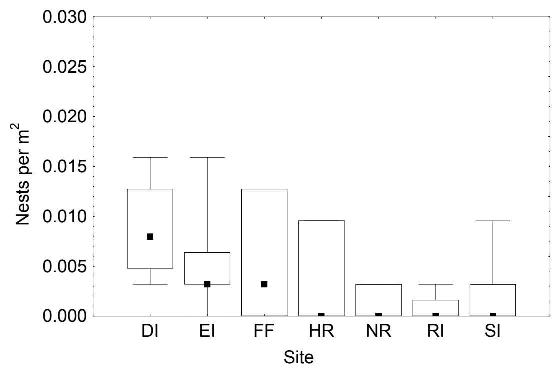


Figure 6.3. Median egg mass density estimates for sites surveyed in Statistical Area 17 of the Strait of Georgia in 2004: Douglas Island (DI), Entrance Island (EI), Five Fingers (FF), Hudson Rock (HR), Neck Reef (NR), Round Island (RI), Snake Island (SI). Whiskers denote maximum and minimum observed egg mass densities; boxes denote 25th and 75th quartiles. No significant differences exist (Kruskal-Wallis test, H=, 10.1 p=0.121, df=6).

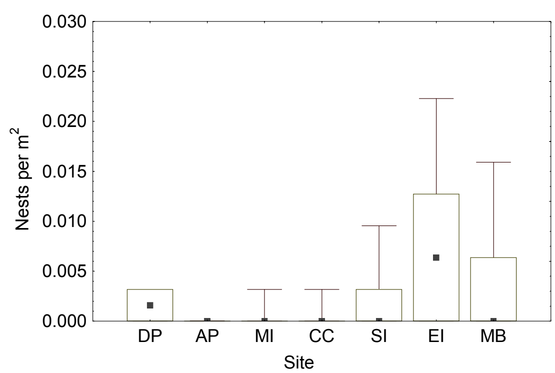


Figure 6.4. Median egg mass density estimates for each site surveyed in the Strait of Georgia in 2005. Discovery Passage (DP), April Point (AP), Maud Island (MI) and Copper Cliffs (cc) are in Statistical Area 13; Snake Island (SI) and Entrance Island (EI) are in Statistical Area 17; and Mackenzie Bight (MB) is in Statistical Area 19. Whiskers denote maximum and minimum observed egg mass densities; boxes denote 25th and 75th quartiles. No significant differences exist (Kruskal-Wallis test, H=10.2, p=0.117, df=6).

7.0 RECOMMENDATIONS

The Lingcod Management Framework Committee recommends that:

1. the criteria and recovery timeframe outlined in the Management Framework Section should be applied when formulating management strategies for Strait of Georgia lingcod. Namely that:
   a. if current biomass levels are estimated to be within 10-25% of historic biomass levels, that the population would be considered to be overfished. A suitable recovery target for the lingcod population would be 25% of historic biomass levels. Any harvest should be associated with at least a 90% probability
   b. no harvest should occur when biomass levels are estimated to be at or below 10% of historic biomass estimates.
2. resultant historic, current and projected biomass estimates based on the population model that excludes the Southeast portion (Statistical Areas 28 and 29) of the Strait of Georgia and assumes a high recruitment variability should be used to select harvest levels for Strait of Georgia lingcod.

The preferred model estimates that the current biomass of lingcod in the combined Statistical Areas 13-19 (including sub-area 29-5 which encompasses the eastern portion of the Gulf Islands) is approximately 16% of the historic biomass. The Lingcod Management Framework Committee recommends that:

1. fishery managers can consider a harvest of between 5,000 to 7,000 lingcod (pieces) for the 2005/2006 fishing year. Any harvest would be restricted to Statistical Areas 13 through 19, including sub-area 29-5 (of Statistical Area 29) only. Non-retention of lingcod should remain in effect for Statistical Area 28, and the remaining portions of Statistical Area 29.

Throughout discussions, the Lingcod Management Framework Committee did not consider allocation of potential harvest to users groups. If a *commercial fishery* is permitted, the Lingcod Management Framework Committee recommends that:

1. a fishery be conducted as an experimental fishery, structured to obtain reliable data on catch and effort by depth and location
2. all trips be observed
3. all lingcod landings be sampled for biological information

If a *recreational fishery* is permitted, the Lingcod Management Framework Committee recommends that:

1. the fishing season be limited to June through September. This is the fishing season that was in effect prior to the recreational closure in 2002, and are months in which it is anticipated that the Strait of Georgia Creel Survey program will be active.
2. the fishery must be closely monitored to ensure that the total allowable catch is not exceeded. Currently, recreational catch statistics are estimated and not verified, and the committee recommends that monitoring of the recreational fishery includes some measure of accuracy for the catch estimates. Additionally, the precision associated with the catch estimates need to be improved by addressing the precision of the effort estimate.

3. monitoring of the fishery must include reliable estimates of released lingcod. A 4% mortality rate would be applied to the estimates of released lingcod to estimate mortality due to capture and release. The released mortality would be included in the total allowable catch limit.
4. if, within the season, the total allowable catch is exceeded, the fishery will be closed.
5. the fishery be permitted for one year only, after which a review of the monitoring program for the lingcod recreational fishery is conducted to assess its success and ability to provide reliable information to manage the fishery.
6. restrictions to the fishery should include:
    a. minimum 65 cm size limit
    b. daily limit of 1; annual limit of 10
    c. spearfishing be prohibited

8.0 ACKNOWLEDGMENTS

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Appendix A. REQUEST FOR WORKING PAPER

Date Submitted: July 2004

Individual or group requesting advice: DFO Fisheries Management, GHLAC and SFAB

Proposed PSARC Presentation Date: May 2005

Subject of Paper (title if developed): Lingcod Management Framework for Strait of Georgia

Science Lead Author: Dr. Jackie King; Dr. Bill de la Mare

Resource Management Lead Author: Gary Logan

Rationale for request:
The lingcod fishery in the Strait of Georgia has been closed to commercial fishing since 1990 and recreational fishery since 2002. A rebuilding strategy needs to be developed that will identify the long and short term rebuilding goals and the time-frames associated with those goals. In addition, a management matrix should identify bench-marks for the potential for fishing mortality within the commercial and recreational sectors and the associated impacts to the rebuilding goals. The fishing mortality should be linked to indicators of stock abundance by statistical area.

Objective of Working Paper:
(To be developed by FM, StAD, Habitat Science, HEB/Oceans for internal papers)
To identify rebuilding goals and recovery times for the Strait of Georgia lingcod population. In support of developing a lingcod management framework, estimate historic and current levels of biomass and trajectories to assess impacts of various harvest rates on attaining rebuilding goals. The short term goal will provide a basis for management of the 2005/06 fisheries in Strait of Georgia for both the commercial and recreational sectors.

Question(s) to be addressed in the Working Paper:
(To be developed by initiator)

What are the rebuilding targets and acceptable recovery times for lingcod in the Strait of Georgia?

What is the estimated current biomass and age structure of Lingcod in Strait of Georgia and how does this relate to historical stock conditions?

What is the expected trajectory of the Lingcod in Georgia Strait projected for the next 10 to 15 years and how will this be affected by a range of annual fishing mortality?

What range of fishing mortality in the Strait of Georgia would be consistent with the Integrated Fisheries Management Plan (IFMP) conservation and rebuilding objectives for Lingcod stocks in strait?

Stakeholders Affected:

ZN inside, Lingcod commercial directed fishery and the Georgia Strait sport fishery.

How Advice May Impact the Development of a Fishing Plan:

The catch advice will directly affect TAC’s set in the IFMP for 2005-06

Timing Issues Related to When Advice is Necessary:

A lingcod management framework must be identified for lingcod before a fishery is reopened.

Approved:

Science Manager: ________________________________; Date:______________________

Fisheries/Habitat/Oceans
Manager: ________________________________; Date:______________________

Appendix B. LINGCOD MANAGEMENT FRAMEWORK COMMITTEE

Table B 1. Lingcod Management Framework Committee members.

Name	Affiliation
Gary Logan, Chair	Fisheries and Oceans Canada, Rockfish/Lingcod Sustainability Strategy
Devona Adams	Fisheries and Oceans Canada, Regional Recreational Sports Fishery Advisor
Sandy Argue	British Columbia Ministry of Agriculture, Food and Fisheries,
Bill de la Mare	Simon Fraser University
Valentyn de Leeuw	ZN Commercial Fisherman
Jeff Fargo	Fisheries and Oceans Canada, Groundfish Stock Assessment
Don Furnell	Sports Fish Advisory Board
Dana Haggarty	Fisheries and Oceans Canada, Groundfish Stock Assessment
Ann-Marie Huang	Fisheries and Oceans Canada, Lower Fraser River Management Unit
Jackie King	Fisheries and Oceans Canada, Groundfish Stock Assessment
Al MacDonald	Fisheries and Oceans Canada, Groundfish Management Unit
Bill Shaw	Fisheries and Oceans Canada, Southcoast Recreational Fishery Coordinator
Diana Trager	Fisheries and Oceans Canada, Groundfish Management Unit
Scott Wallace	Pacific Marine Conservation Caucus
Kim West	Fisheries and Oceans Canada, Regional Recreational Sports Fishery Advisor

Appendix C. LINGCOD CATCH STATISTICS FOR THE STRAIT OF GEORGIA

Table C 1. Commercial catch (tonnes) of lingcod in the Strait of Georgia 1927-1946. All data were obtained from annual Fisheries Statistics reports compiled by the Dominion Bureau of Statistics (1927-1946) and converted from dressed weight (hundred lbs) to round weight (tonnes). Catches assigned to the Southeast geographic area are District 1. From 1927-1932 approximately 10% (Chatwin 1958) of District 1 catches might have also included lingcod caught outside of the Strait of Georgia, but landed in Vancouver. Since 1933, the data contained in annual Fisheries Statistics reports for District 1 were corrected for these transfers. Allocation of catch to the other geographic areas are described in footnotes.

	Geographic Area				
Year	Southeast	Northeast	Northwest	Southwest	Total
1927	1648	229[a]	225[b]	450[c]	2552
1928	1379	447[d]	320[e]	391[f]	2537
1929	1719	295	360	402	2776
1930	1736	176[g]	668[h]	393[h]	2973
1931	1670	186	459	639	2954
1932	1540	134	175	443	2292
1933	1440	105	258	465	2268
1934	1905	73	361	453	2792
1935	2426	104	450	598	3578
1936	2653	135	479	407	3674
1937	2273	13	30	189	2505
1938	1124	65	561	783	2533
1939	2254	119	90	208	2671
1940	440	202	720	700	2062
1941	1214	41	371	549	2175
1942	861	155	457	553	2026
1943	1060	179	605	477	2321
1944	2849	281	663	546	4339
1945	2113	205	580	637	3535
1946	1623	226	626	499	2974

[a] Catch from Gower Point to Bute Inlet

[b] Catch from Adam River to Big Qualicum River;

[c] Catch from Big Qualicum River to Cowichan Bay; 50% of Cowichan Bay to San Juan Harbour catch

[d] Catch from Gower Point to Grief Point, from Grief Point to Toba Inlet (1928-1929)

[e] Catch from Adam River to Oyster River, from Oyster River to French Creek; 50% of French Creek to Nanaimo catch (1928-1929)

[f] 50% of French Creek to Nanaimo catch; catch from Nanaimo to Separation Point; Separation Point to Victoria (1928-1929)

[g] Catch from Gower Point to George Point (1930-1946)

[h] Catch from George Point to Shelter Point; from Shelter Point to French Creek; 33% of catch from French Creek to Shoal Harbour (1930-1946)

[i] 66% of the catch from French Creek to Shoal Harbour; 50% of catch from Shoal Harbour to Sombrio Point (1930-1946)

Table C 2. Commercial catch (tonnes) for handline and trawl fisheries. Catch is reported by Statistical Area and assigned to the geographic areas used by the population model.

	Statistical Area									
	Southeast		Northeast		Northwest		Southwest			
Year	28	29	15	16	13	14	17	18	19	Total
1951	2.0	3.5	46.3	99.3	398.9	102.0	369.5	263.5	32.7	1317.7
1952	7.0	5.7	73.2	169.7	441.2	95.0	452.9	244.7	29.2	1518.6
1953	4.4	2.6	46.1	166.2	346.5	96.0	293.4	186.3	39.0	1180.4
1954	4.8	7.6	21.5	244.9	437.5	186.9	368.6	184.7	35.1	1491.7
1955	0.0	6.5	64.7	243.0	330.0	88.8	344.1	135.2	44.7	1257.1
1956	1.2	10.1	60.6	235.0	564.8	108.0	407.8	113.9	45.4	1546.8
1957	0.3	8.7	107.3	288.4	542.5	96.4	371.0	104.7	54.4	1573.7
1958	0.6	6.2	79.3	229.7	502.1	114.9	358.9	97.8	76.6	1466.0
1959	0.7	19.9	31.4	167.8	339.2	89.6	352.6	90.1	402.9	1494.1
1960	1.3	7.0	47.1	174.7	340.1	114.7	388.2	100.9	205.5	1379.3
1961	7.7	11.7	45.6	186.4	393.7	106.8	305.3	78.5	93.2	1228.9
1962	8.9	9.8	60.4	139.0	412.5	122.8	244.5	67.1	102.9	1167.9
1963	0.1	2.8	30.5	159.6	301.6	73.3	254.6	50.1	64.8	937.3
1964	0.1	7.9	18.8	170.0	291.8	49.3	209.1	62.9	73.2	883.0
1965	0.0	7.8	6.6	135.8	303.2	61.5	172.3	61.5	74.0	822.7
1966	1.1	2.5	28.7	125.7	299.5	71.7	146.3	72.3	35.4	783.2
1967	0.0	2.7	19.8	133.3	335.2	66.6	117.6	75.9	21.3	772.4
1968	0.0	3.5	22.0	104.7	273.6	79.3	176.5	61.9	32.6	754.2
1969	0.0	7.3	56.0	109.5	228.2	87.0	158.9	63.9	41.0	751.8
1970	0.0	3.3	84.7	85.7	226.1	44.3	281.4	51.3	30.6	807.4
1971	0.1	2.2	66.8	89.7	119.3	32.9	211.0	36.7	34.3	593.0
1972	0.0	4.7	43.6	81.3	152.3	27.2	138.3	26.3	41.8	515.5
1973	0.6	2.4	62.0	38.2	85.9	9.2	130.2	37.9	27.7	394.1
1974	0.0	0.6	25.2	24.4	133.6	16.3	130.2	25.8	46.3	402.4
1975	0.0	1.4	76.0	26.5	96.2	16.4	124.7	15.5	24.5	381.2
1976	5.7	1.2	74.9	17.2	98.1	13.5	85.1	15.6	37.1	348.4
1977	2.2	0.4	63.4	19.0	128.0	34.3	109.4	44.0	28.9	429.6
1978	0.2	2.5	48.3	18.4	158.0	28.2	147.3	43.0	64.0	509.9
1979	8.6	2.0	28.9	15.7	217.1	39.7	161.8	31.7	44.9	550.4
1980	6.7	0.7	26.4	6.8	138.2	20.2	104.0	27.2	42.1	372.3
1981	0.3	0.7	34.7	15.6	138.4	29.7	84.5	23.1	68.4	395.3
1982	0.5	1.1	50.7	7.7	177.8	15.3	66.6	28.8	52.5	401.1
1983	0.3	0.7	33.0	19.6	112.6	19.6	58.6	27.2	78.5	350.2
1984	0.0	0.3	4.0	5.2	65.6	7.6	50.6	35.9	32.8	202.0
1985	0.0	0.3	4.2	0.5	46.0	8.6	34.3	18.7	21.4	133.9
1986	0.0	0.5	0.5	4.0	20.2	16.9	18.4	16.3	44.5	121.4
1987	6.7	0.0	0.9	0.1	22.6	2.6	11.7	9.4	17.6	71.7
1988	1.6	1.1	0.1	0.2	12.1	2.6	7.2	5.4	16.9	47.2
1989	0.0	0.0	0.3	0.9	12.9	5.3	4.7	5.3	14.6	44.0

Table C 3. Lingcod qualified catch per unit effort (kg/d) by Statistical Area from commercial handline and troll sales slip data. Catch per unit effort is determined for landings with at least 100 kg of lingcod. Missing data denotes years with no qualified landings. The mean CPUE for designated Statistical Areas was used as the CPUE for geographic areas used in the population model. Data from Richards and Hand (1991).

	Statistical Area							
	Southeast	Northeast		Northwest		Southwest		
Year	28&29	15	16	13	14	17	18	19
1967	87	314	213	301	236	127	124	164
1968	227	375	194	318	179	127	110	168
1969	--	438	213	272	168	136	129	292
1970	257	351	196	254	168	175	154	228
1971	25	267	196	266	171	166	113	217
1972	147	283	178	301	201	143	150	191
1973	119	264	185	287	132	167	150	207
1974	327	269	135	312	253	139	135	170
1975	46	242	194	312	160	171	189	193
1976	140	250	123	275	150	174	126	128
1977	115	256	222	200	192	148	125	131
1978	210	206	278	192	126	155	105	132
1979	163	270	184	198	144	224	116	124
1980	119	220	92	274	87	167	95	101
1981	46	194	129	177	90	148	87	94
1982	55	152	83	189	85	129	130	96
1983	51	235	127	138	118	144	95	93
1984	36	99	126	74	80	95	159	124
1985	96	104	156	107	90	132	71	191
1986	35	175	119	53	131	103	87	114
1987	213	93	--	32	44	84	87	53
1988	96	--	--	31	19	80	84	59
1989	--	--	--	44	--	114	61	56

Table C 4. Estimated recreational lingcod landings (pieces) by Statistical Area from the Strait of Georgia Recreational Creel Survey. Months that the survey was conducted varied between years; data used in this report were not expanded to estimate months without coverage. English et al. (2002) provided expanded annual estimates of lingcod catch to include months with no coverage and these are provided for comparison. The total catch (pieces) for designated Statistical Areas were used for lingcod catch for geographic areas used in the population model.

Year	Creel Survey Period	Statistical Area									Total	Expanded Annual Landings
		Southeast		Northeast		Northwest		Southwest				
		28	29	15	16	13	14	17	18	19		
1982	May-Dec	6126	3656	1285	17618	15004	5724	8886	6019	8986	73304	--
1983	Jan-Dec	5965	3636	1036	17263	14119	2137	5123	5621	4910	59810	62770
1984	Jan-Dec	8854	8101	1668	28706	39719	11435	16405	7148	9761	131797	137485
1985	Jan-Dec	3068	2669	858	13985	23177	6194	8863	5283	9008	73105	77113
1986	Jan-Dec	1885	1562	1272	9366	25788	9714	6332	4250	6611	66780	70820
1987	Jan-Dec	794	797	1432	8100	23494	10288	6916	3029	5426	60276	65810
1988	Jan-Dec	727	1697	1285	9802	22580	11540	5796	3479	3734	60640	65929
1989	Jan-Dec	319	755	799	7455	20905	8630	4764	2991	5714	52332	52329
1990	Feb-Oct	146	327	458	4993	13297	4763	2298	1002	1727	29011	31376
1991	Jan-Nov	177	266	51	976	2509	1153	1569	278	681	13860	8251
1992	Feb-Dec	303	234	24	1026	1635	468	1121	204	397	5412	5968
1993	Jan-Sept	191	382	53	2325	973	489	964	206	734	6317	7175
1994	April-Oct	249	333	85	2091	1427	758	939	462	259	6603	6996
1995	Mar-Oct	47	153	14	1124	843	662	977	314	260	4394	4899
1996	Apr-Sept	145	63	61	274	1232	76	619	387	468	3325	3901
1997	Apr-Oct	302	237	107	384	1035	324	289	554	273	3505	4152
1998	Apr-Oct	182	50	24	550	514	227	602	250	519	2918	3345
1999	Apr-Sept	155	47	25	197	1372	71	536	103	409	2912	3688
2000	Jan-Dec	332	128	22	1251	988	925	1097	226	229	5198	--
2001	Jan-Nov	251	109	124	1884	1460	1150	2134	563	544	8219	--
2002	Apr-Oct	237	223	0	2505	73	9	291	38	95	3471	--

Table C 5. Catch (lingcod landed and released) per 100 hours of fishing (directed and non-directed effort) calculated from Strait of Georgia Recreational Creel Survey interview data (May through September) by Statistical Area (English 2003). The mean CPUE for designated Statistical Areas were used as the CPUE for geographic areas used in the population model.

	Statistical Area								
	Southeast		Northeast		Northwest		Southwest		
Year	28	29	15	16	13	14	17	18	19
1982	4.5	2.71	4.45	9.42	5.83	1.72	7.11	4.76	4.1
1983	4.68	5.61	4.91	6.24	7.44	0.78	3.77	7.42	7.48
1984	10.17	3.22	4.33	9.22	11.98	4.44	7.43	7.09	10.89
1985	3.92	1.8	2.89	6.06	6.21	1.96	4.21	6.8	6.51
1986	2.45	1.17	3.46	5.14	7.22	4.07	4.05	8.38	5.61
1987	1.92	0.76	3.76	6.25	6.73	2.76	2.81	3	5.66
1988	1.24	1.43	3.53	5.31	7.12	1.85	2.74	3.9	4.1
1989	1.16	0.7	2.91	5.64	7.00	1.97	2.5	2.49	3.05
1990	1.13	0.31	2.96	5.07	8.3	2.35	2.6	3.94	5.22
1991	1.63	0.58	3.72	5.61	13.34	3.45	3.93	3.54	3.91
1992	1.84	0.63	3.41	4.34	9.15	2.28	4.39	4.35	11.46
1993	1.33	0.2	1.61	5.66	6.71	1.78	3.02	2.69	6.51
1994	1.08	0.33	1.73	6.97	6.57	3.32	3.62	10.13	6.25
1995	0.66	0.33	2.15	2.52	6.79	3.98	3.3	2.5	1.93
1996	1.92	0.88	4.29	3.34	10.7	2.96	4.45	5.96	23.69
1997	2.81	1.56	5.47	14.65	9.22	3.88	5.94	7.18	9.58
1998	1.29	0.61	7.42	9.19	10.62	3.46	8.19	3.91	13.18
1999	3.31	1.63	5.68	4.55	8.91	1.31	3.49	4.31	12.67
2000	3.93	1.52	7.29	15.34	6.83	3.61	10.98	5.5	17.33
2001	4.43	0.55	6.68	16.84	8.16	5.17	14.39	7.4	32.17
2002	4.98	1.84	13.34	17.19	7.13	3.16	15.44	7.62	21.62

Appendix D. PROPOSED AND TESTED HYPOTHESES

Table D 1. Hypotheses suggested by the Lingcod Management Framework Committee that may affect the status and trends of lingcod stocks in the Strait of Georgia.

<u>Uncertainties in catch data:</u>

- Uncertain prior to 1951 due to recording transfers as local catches (District 1 only)
  - After 1951 assumed reliable
  - Overestimated in some District 1 – try various corrections
  - Pro-rate pre 1951 to post 1951†
- Uncertain before 1927*

<u>Uncertainties in CPUE data:</u>

- Relationship between CPUE and abundance‡
- Use qualified 1967 to 1990†
- Proportions of trips that qualify†
- Commercial encounter rate*
- Post 1982 recreational CPUE directed vs. non-directed vs. combined*

<u>Uncertainties in demographic parameters:</u>

- Natural mortality (M=0.2, M=0.4)
- Density dependent growth and mortality
- Growth rates*
- Sex ratios*
- Age-fecundity relationship*

<u>Regime Shifts</u>

- Fixed effects
- Time boundaries*
- Other environmental trends*
- Forage species (index based on herring abundance)*

<u>Stock recruitment relationships</u>

- Beverton and Holt
- Ricker
- Logistic
- Depensatory Beverton and Holt

<u>Marine mammal predation</u>

- Predation proportional to marine mammal abundance and diet (Harbour seals)

<u>Stock structure/identity</u>

- S.O.G is a single closed population
- North - South division
- East - West division
- Four way division
- Common recruitment (from S.O.G.) – sedentary adults*
- Immigration/emigration*

* Not implemented in the time available
‡ Always included in fitted model
† Issue resolved – dropped from model fitting tests

Table D 2. Hypotheses tested when fitting the model to CPUE data from the whole Strait of Georgia

STRUCTURAL HYPOTHESES	
Hypothesis	***Method of implementation***
Ricker recruitment	Direct in model*
Beverton and Holt recruitment	Direct in Model*
Depensation in recruitment	Direct in model – modified Beverton and Holt*
Density dependent growth and mortality	Direct in model*
Fixed regime shifts	Multiplicative adjustment to K in specified time periods†
Predation by seals	Diet information and seal abundance used to calculate a 'catch series' due to predation (see Figure 5.1 for selectivity)
UNCERTAIN DATA HYPOTHESES	
Hypothesis	***Method of implementation***
Natural mortality is high	Set M = 0.4
Ricker corrected catch	Pre-1932 Catches reported in former District 1 reduced to account for transfers‡
Beverton and Holt corrected catch	Pre-1932 Catches reported in former District 1 reduced to account for transfers‡
Beverton and Holt deleted catch	All former District 1 catch prior to 1952 deleted

* See Appendix F for details
† Values and periods specified in Appendix C, Table C 1.
‡ See Section 4.1.2 for details on catch corrections

Appendix E. FIGURES ILLUSTRATING THE RESULTS OF FITTING THE STANDARD MODEL TO FOUR GEOGRAPHIC AREAS

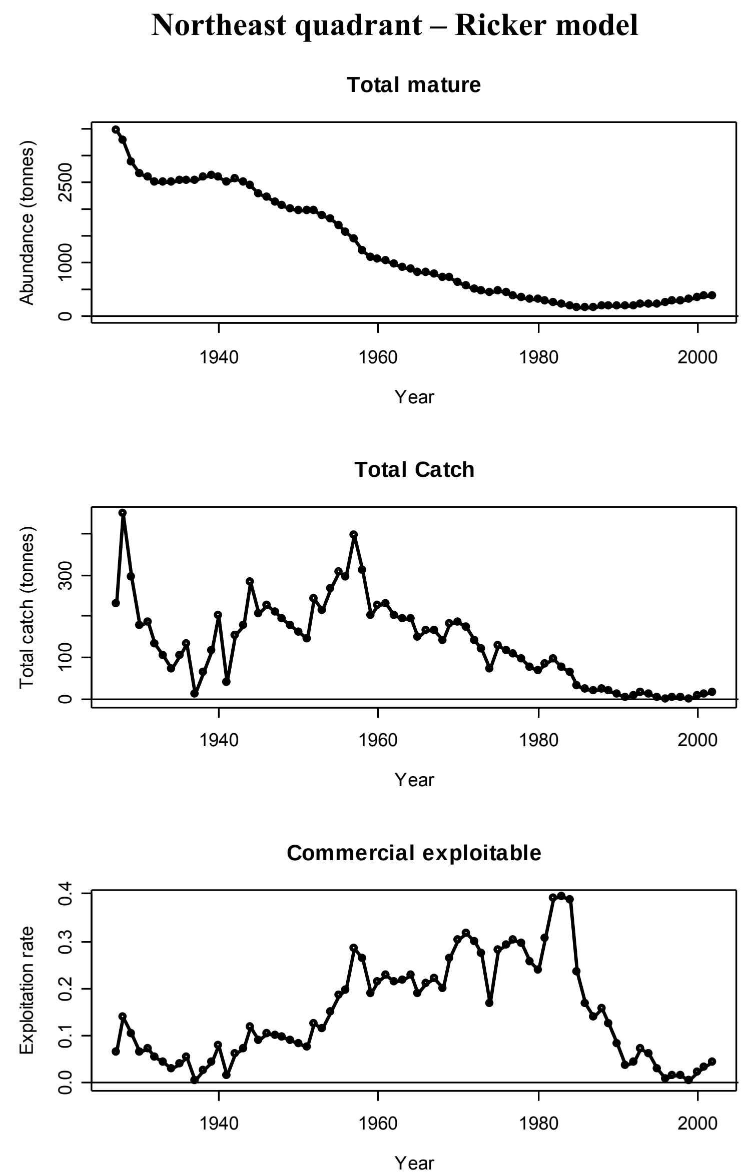


Figure E 1. Mature biomass trajectory, total catch and exploitation rate for Strait of Georgia Northeast quadrant – Ricker recruitment model.

Northeast quadrant – Ricker model

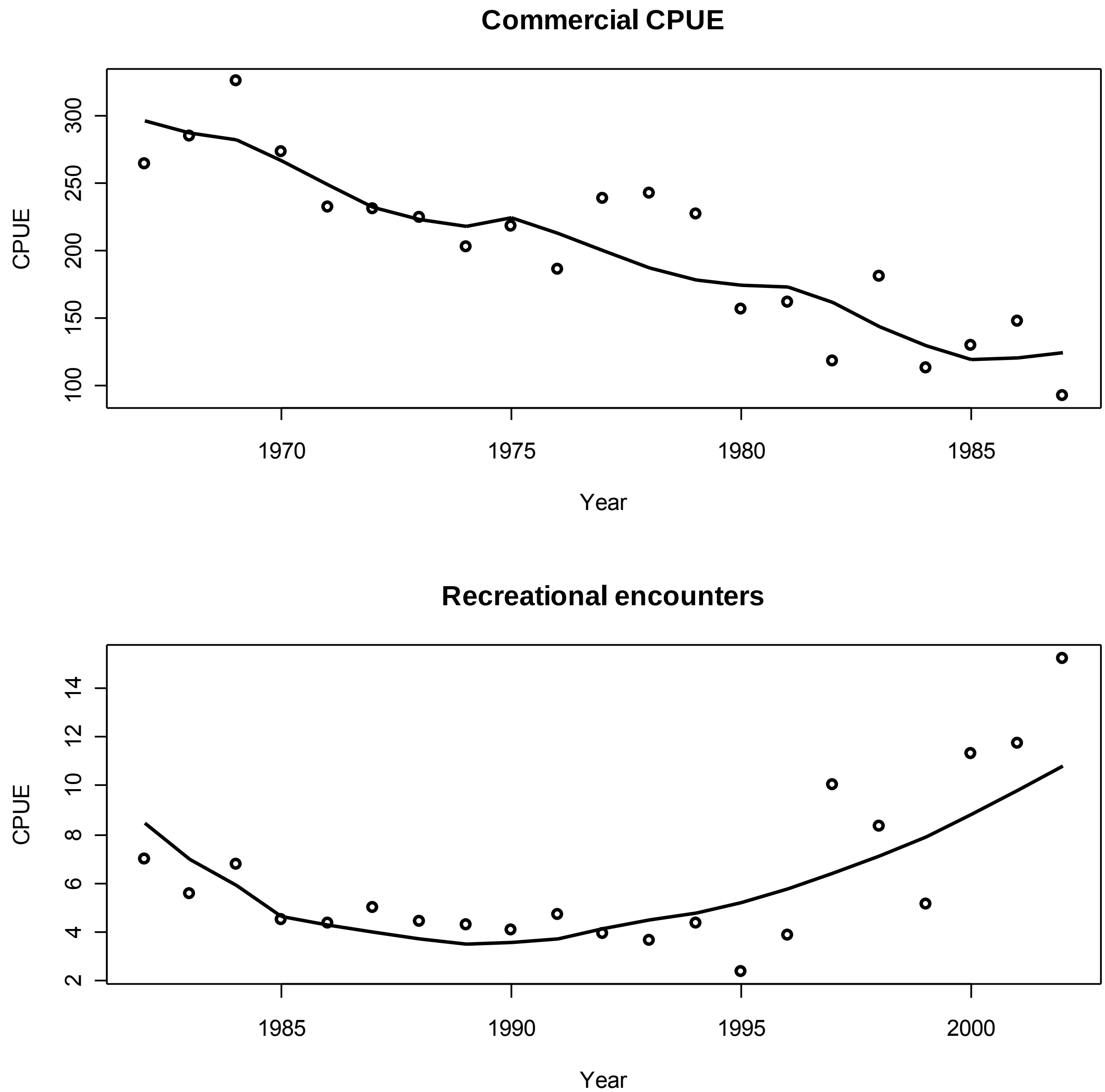


Figure E 2. Observed and expected CPUE for Ricker model fit to Northeast quadrant.

Northeast quadrant – Ricker model

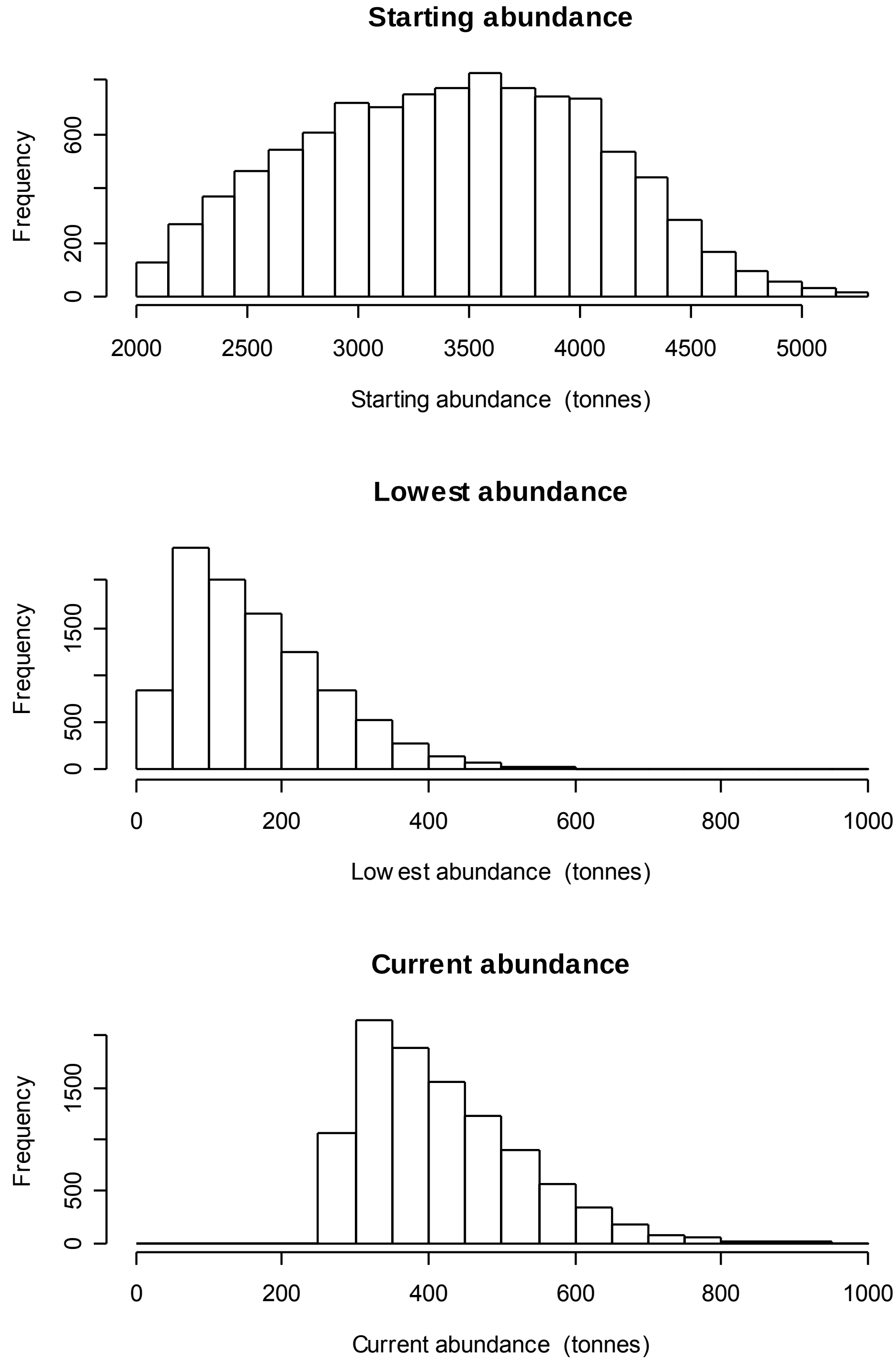
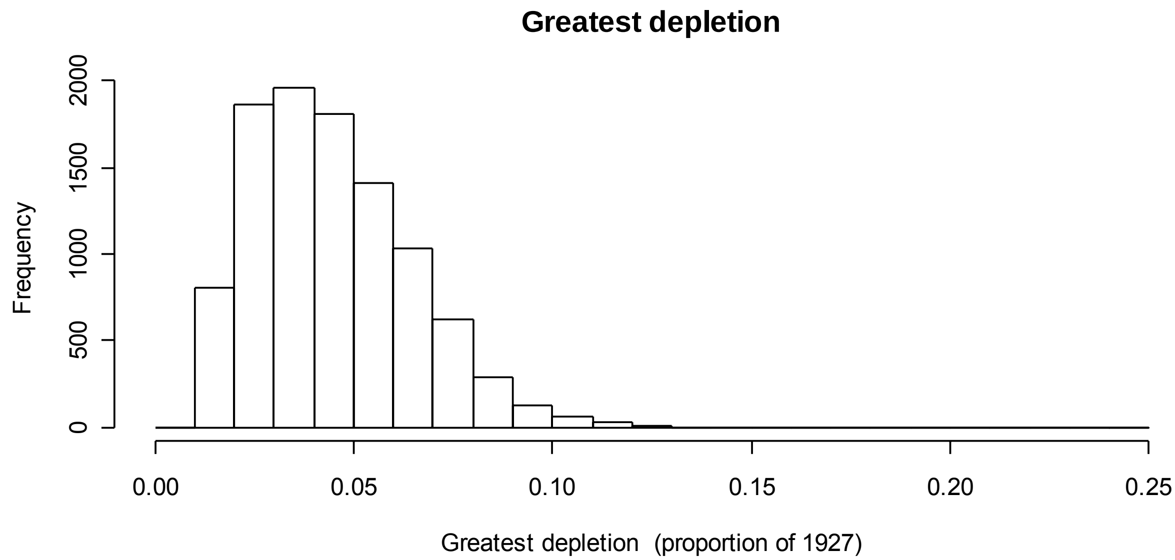


Figure E 3. Posterior distributions of abundance from likelihood-importance-resampling of Ricker model (10000 samples) in Northeast quadrant. Starting abundance refers to 1927, lowest abundance occurs in 1989 and current abundance refers to 2003.

Northeast quadrant – Ricker model



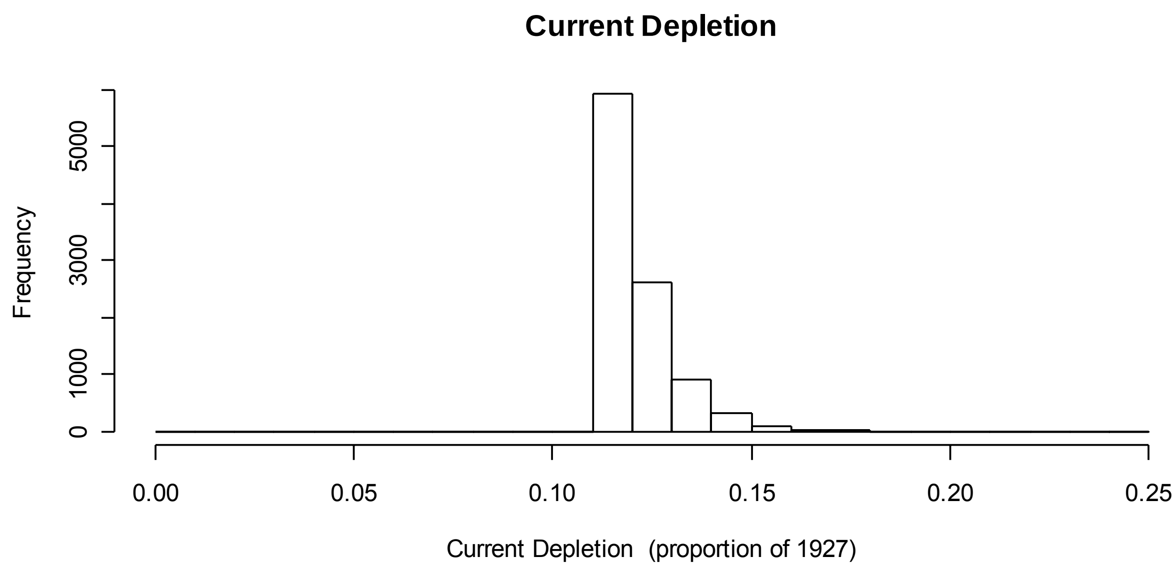


Figure E 4. Posterior distributions of depletion from likelihood-importance-resampling of Ricker model in Northeast quadrant (10000 samples). Lowest depletion usually occurs in 1989 and current depletion refers to 2003.

Northwest quadrant – Ricker model

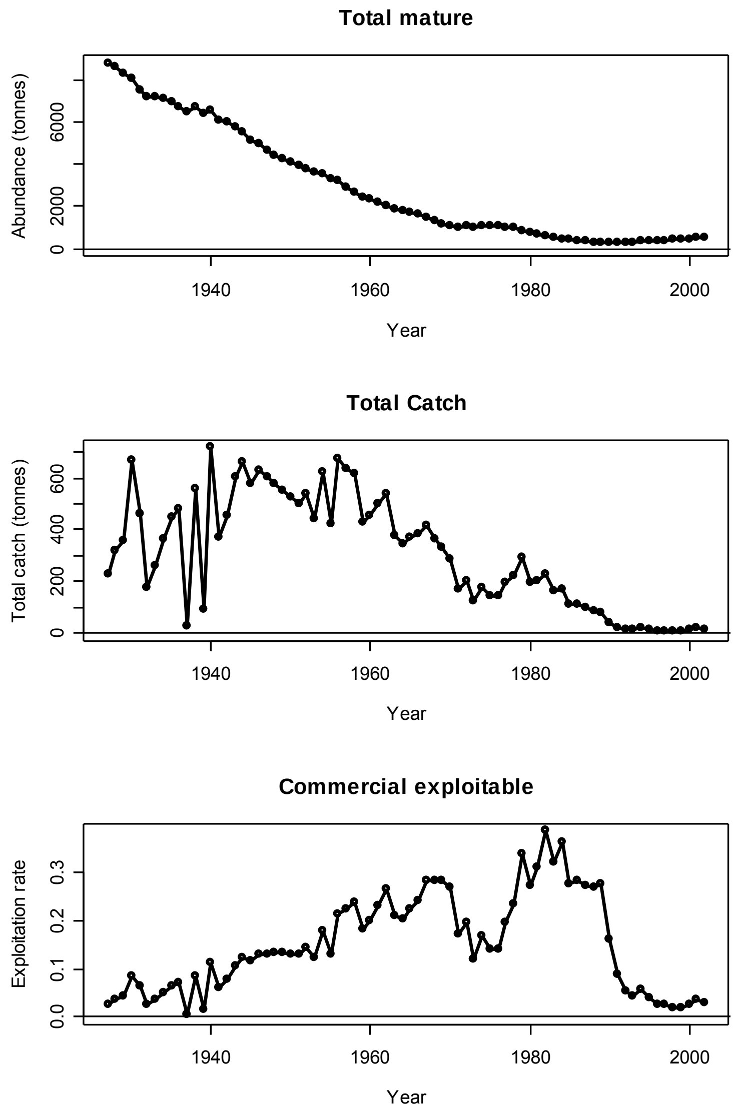


Figure E 5. Mature biomass trajectory, total catch and exploitation rate for Strait of Georgia Northwest quadrant – Ricker recruitment model.

Northwest quadrant – Ricker model

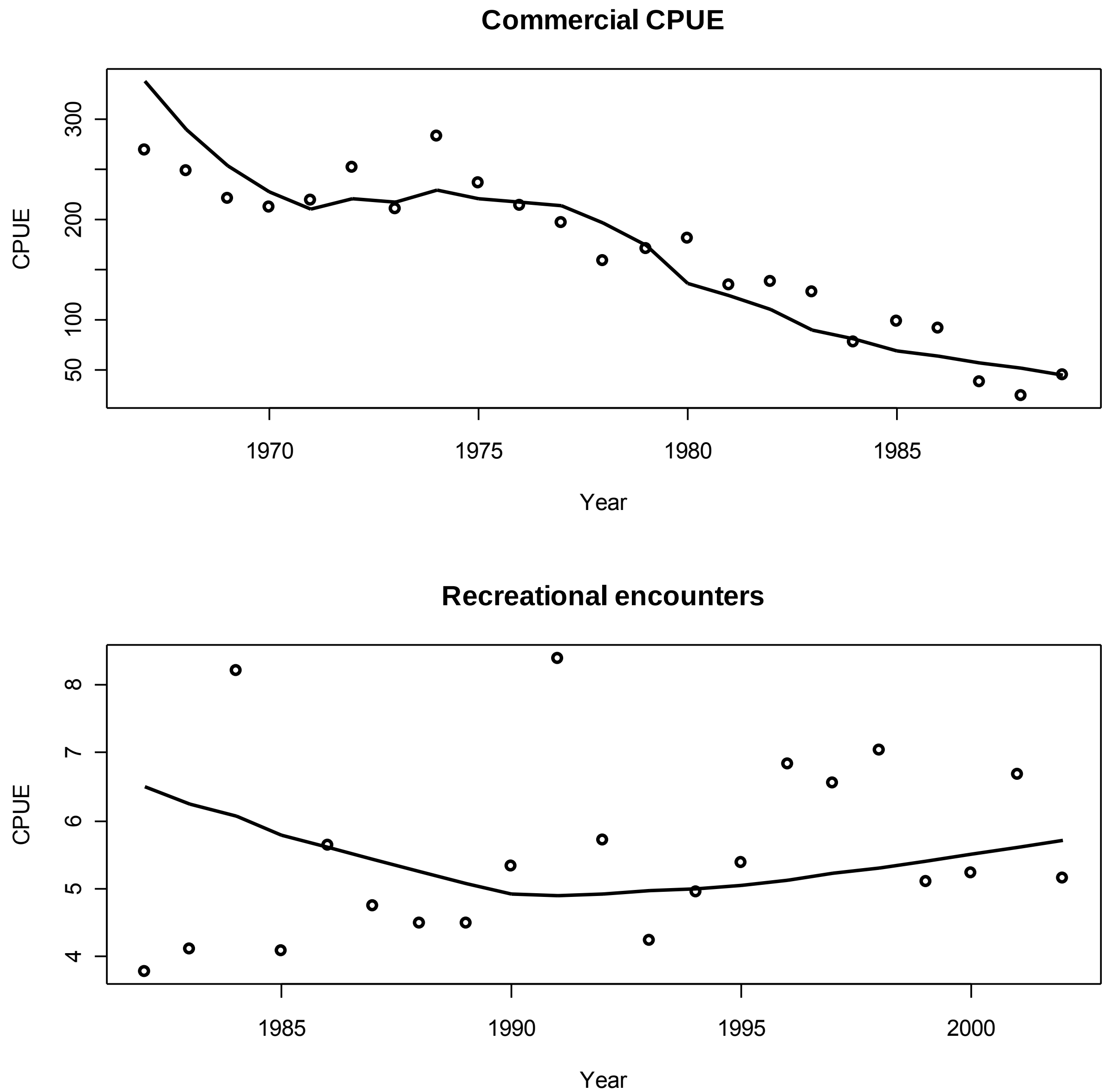


Figure E 6. Observed and expected CPUE for Ricker model fit to Northwest quadrant.

Northwest quadrant – Ricker model

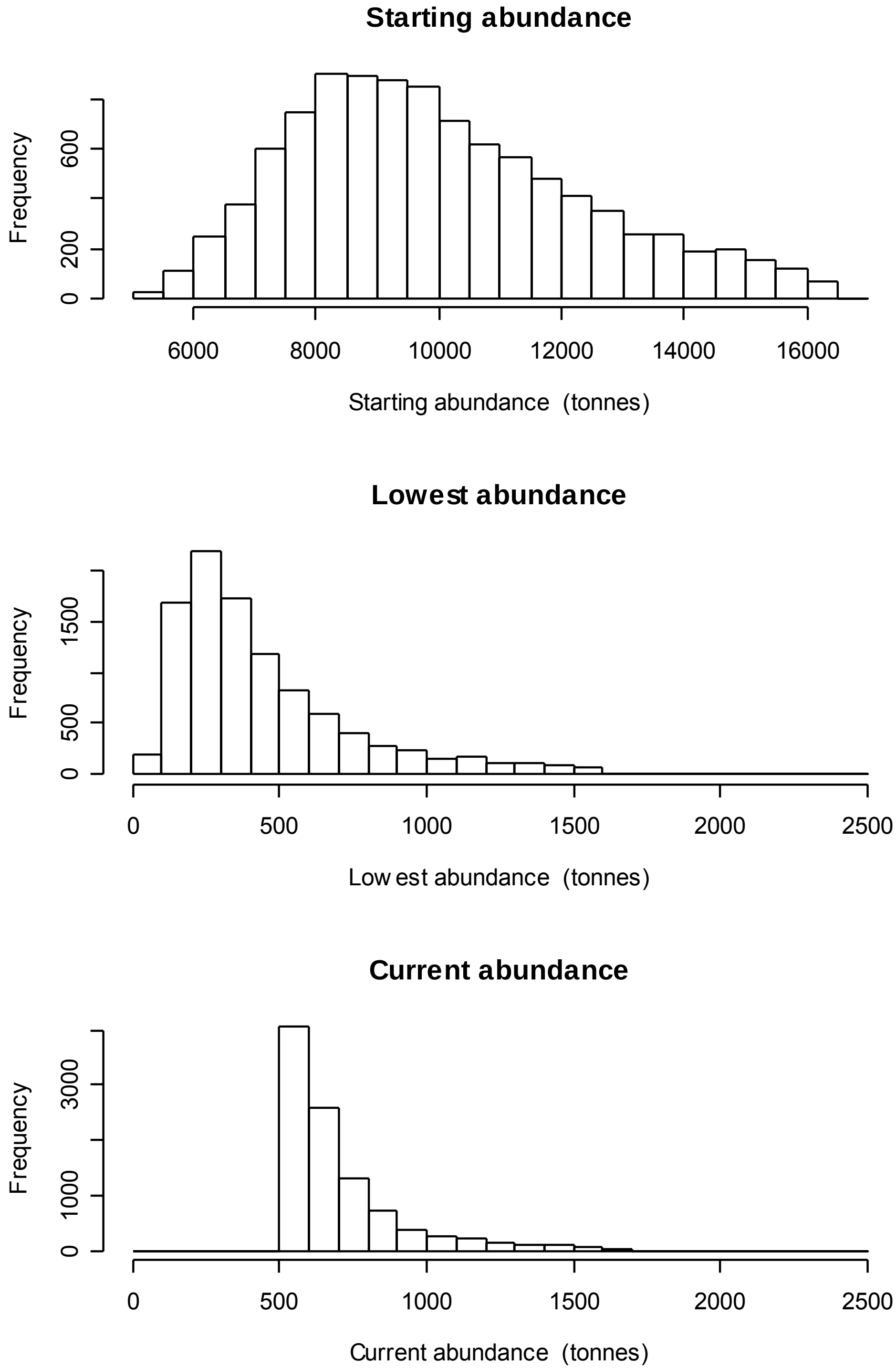


Figure E 7. Posterior distributions of abundance from likelihood-importance-resampling of Ricker model (10000 samples) in Northwest quadrant. Starting abundance refers to 1927, lowest abundance usually occurs in 1991 and current abundance refers to 2003.

Northwest quadrant – Ricker model

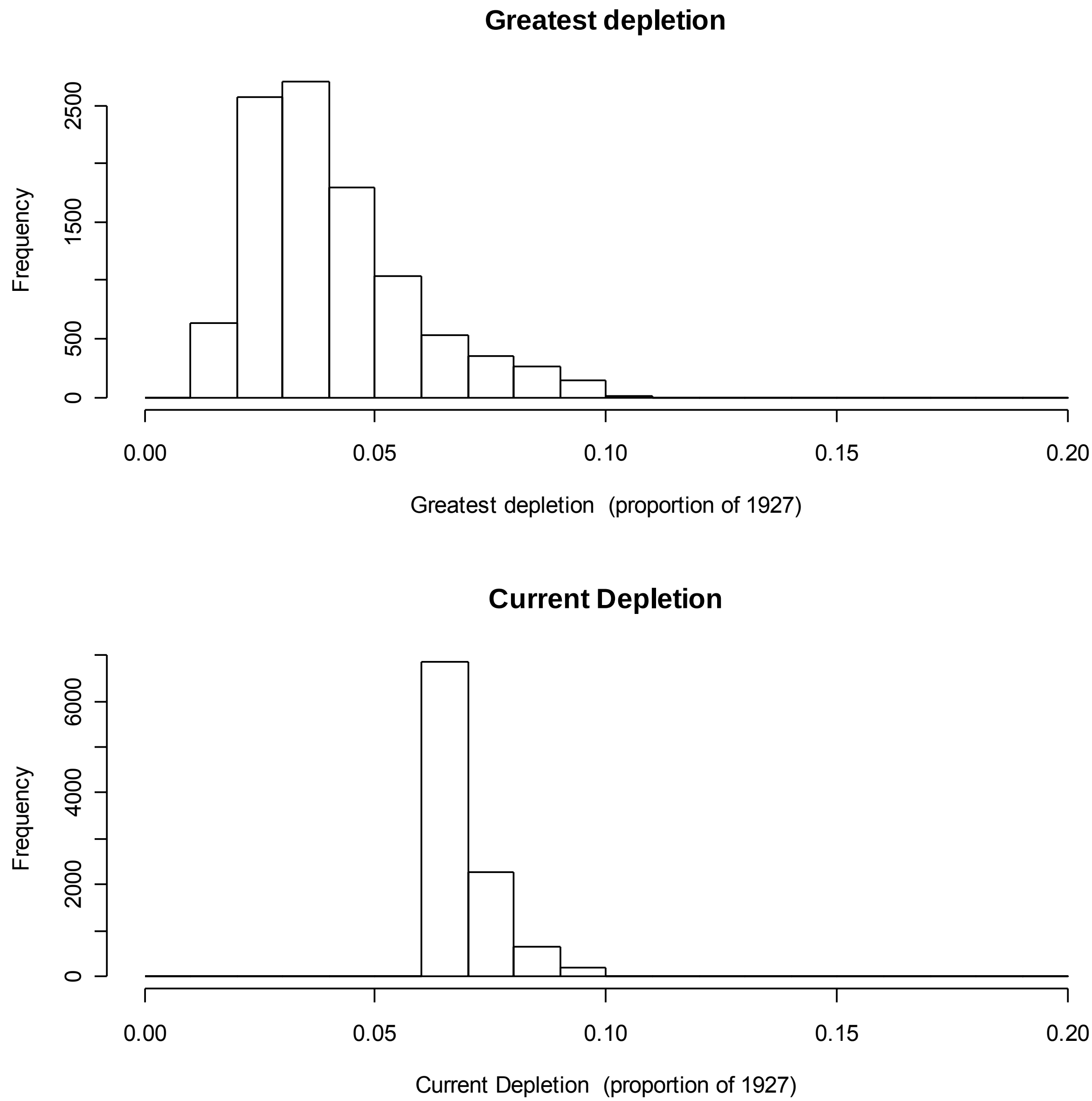


Figure E 8. Posterior distributions of depletion from likelihood-importance-resampling of Ricker model in Northwest quadrant (10000 samples). Lowest depletion usually occurs in 1991 and current depletion refers to 2003.

Southeast quadrant – Ricker model

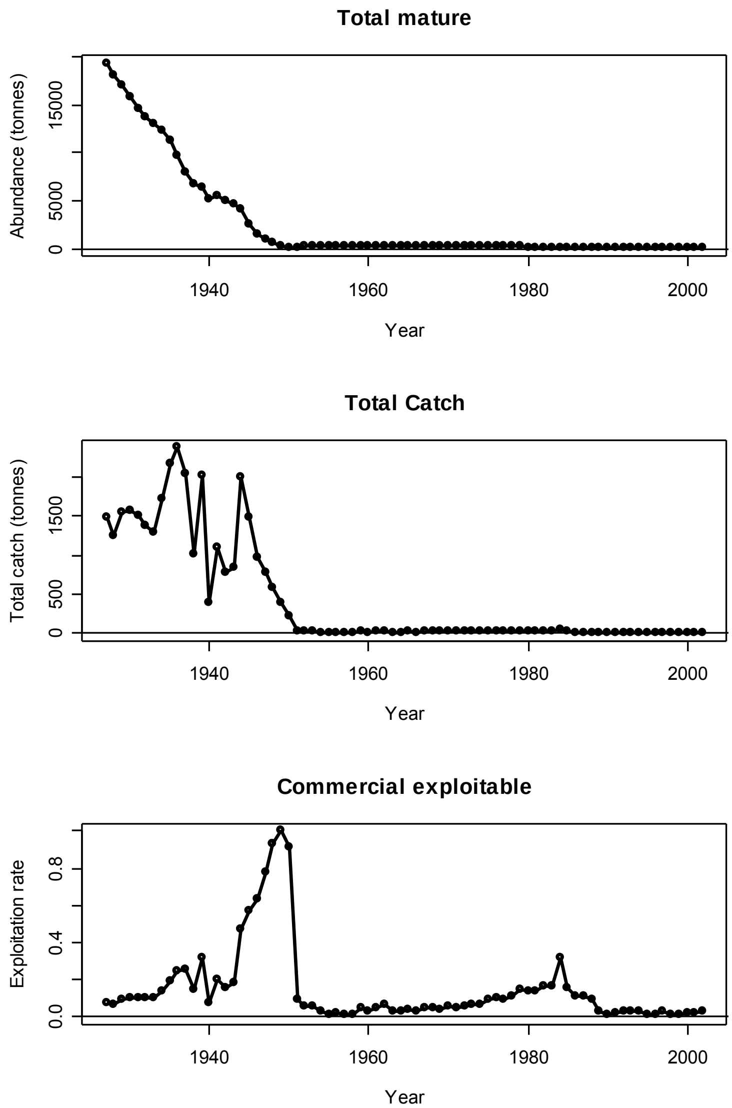


Figure E 9. Mature biomass trajectory, total catch and exploitation rate for Strait of Georgia Southeast quadrant – Ricker recruitment model.

Southeast quadrant – Ricker model

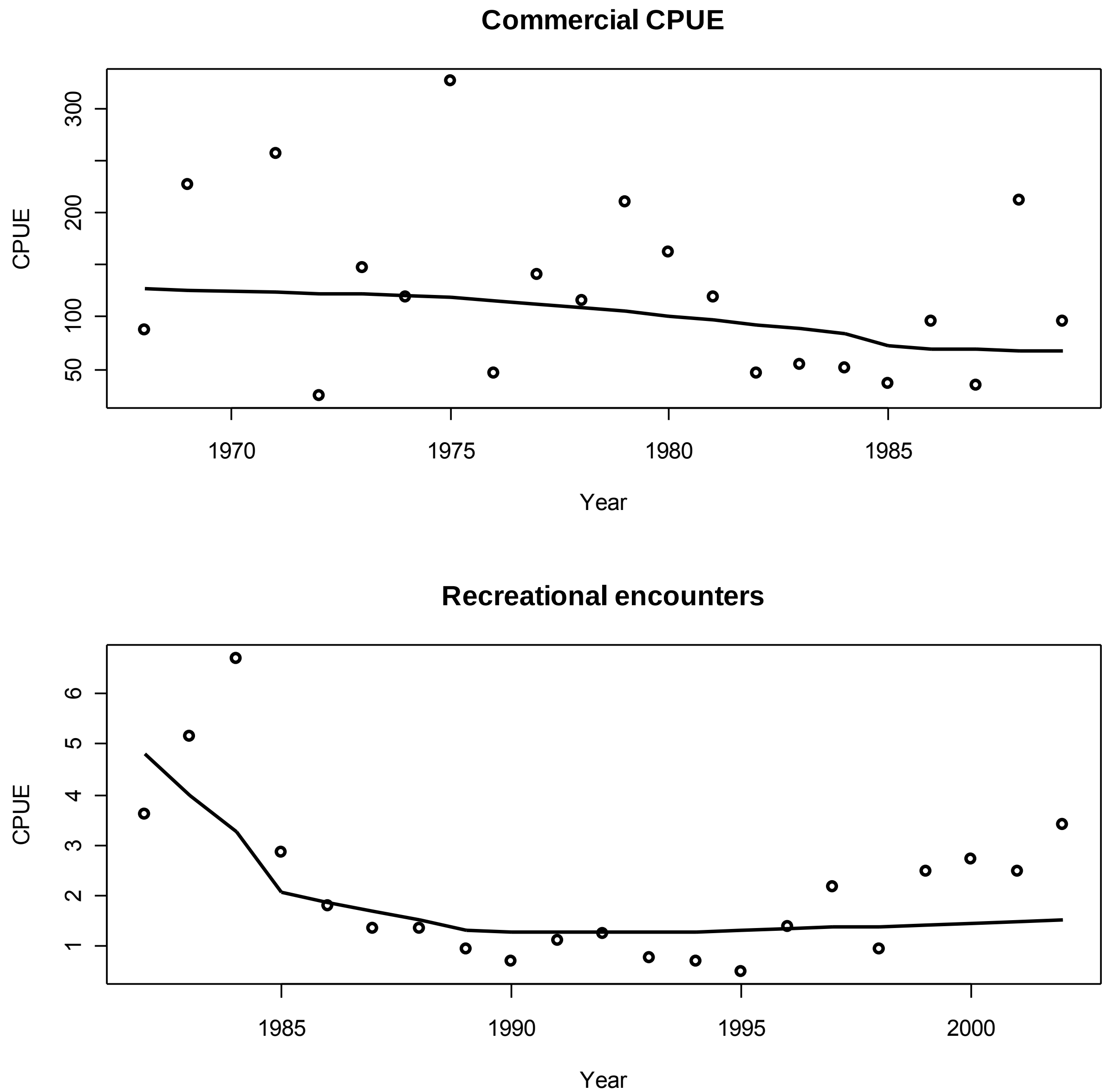


Figure E 10. Observed and expected CPUE for Ricker model fit to Southeast quadrant.

Southeast quadrant – Ricker model

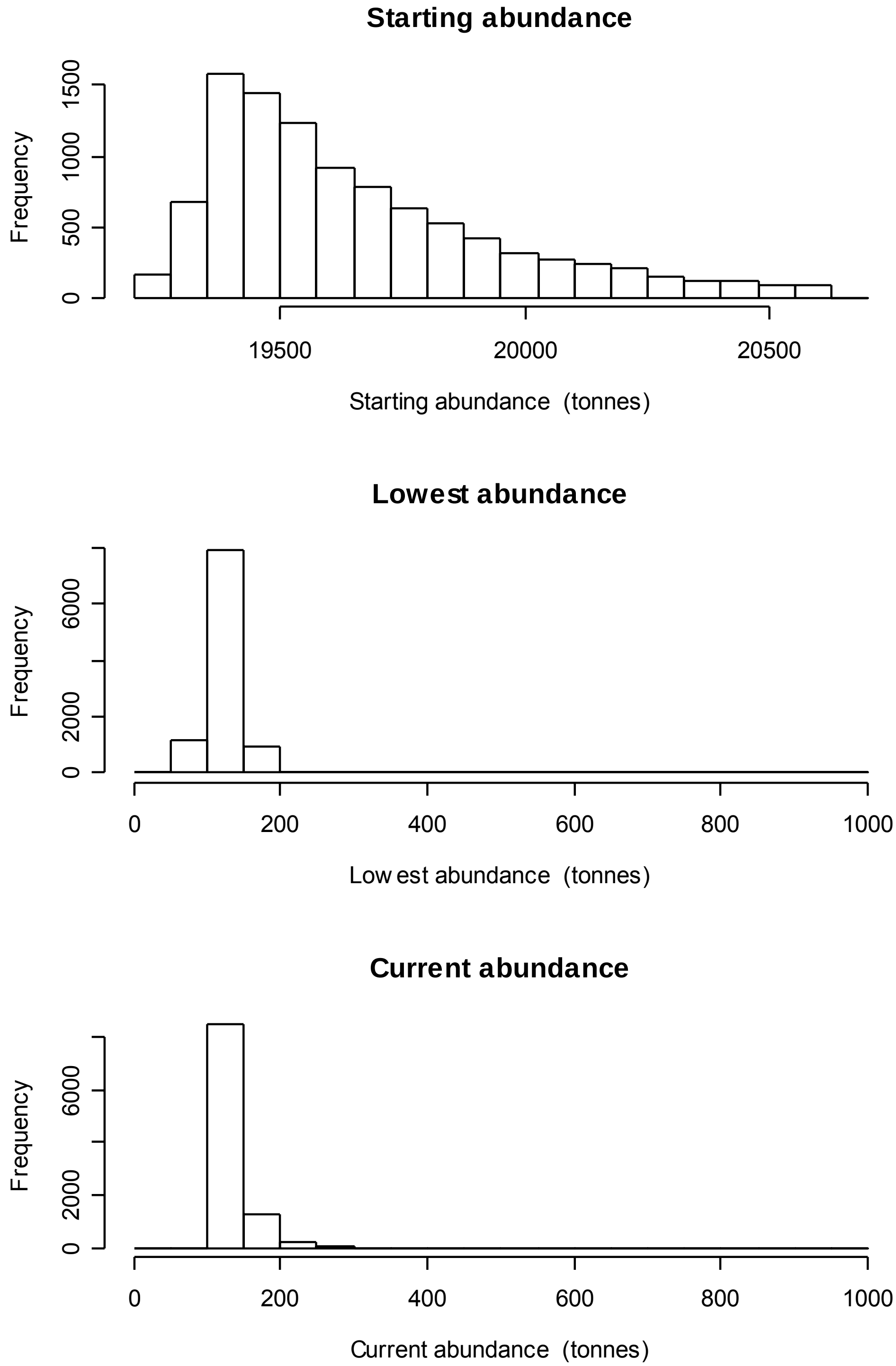


Figure E 11. Posterior distributions of abundance from likelihood-importance-resampling of Ricker model (10000 samples) in Southeast quadrant. Starting abundance refers to 1927, lowest abundance usually occurs in 1991 and current abundance refers to 2003.

Southeast quadrant – Ricker model

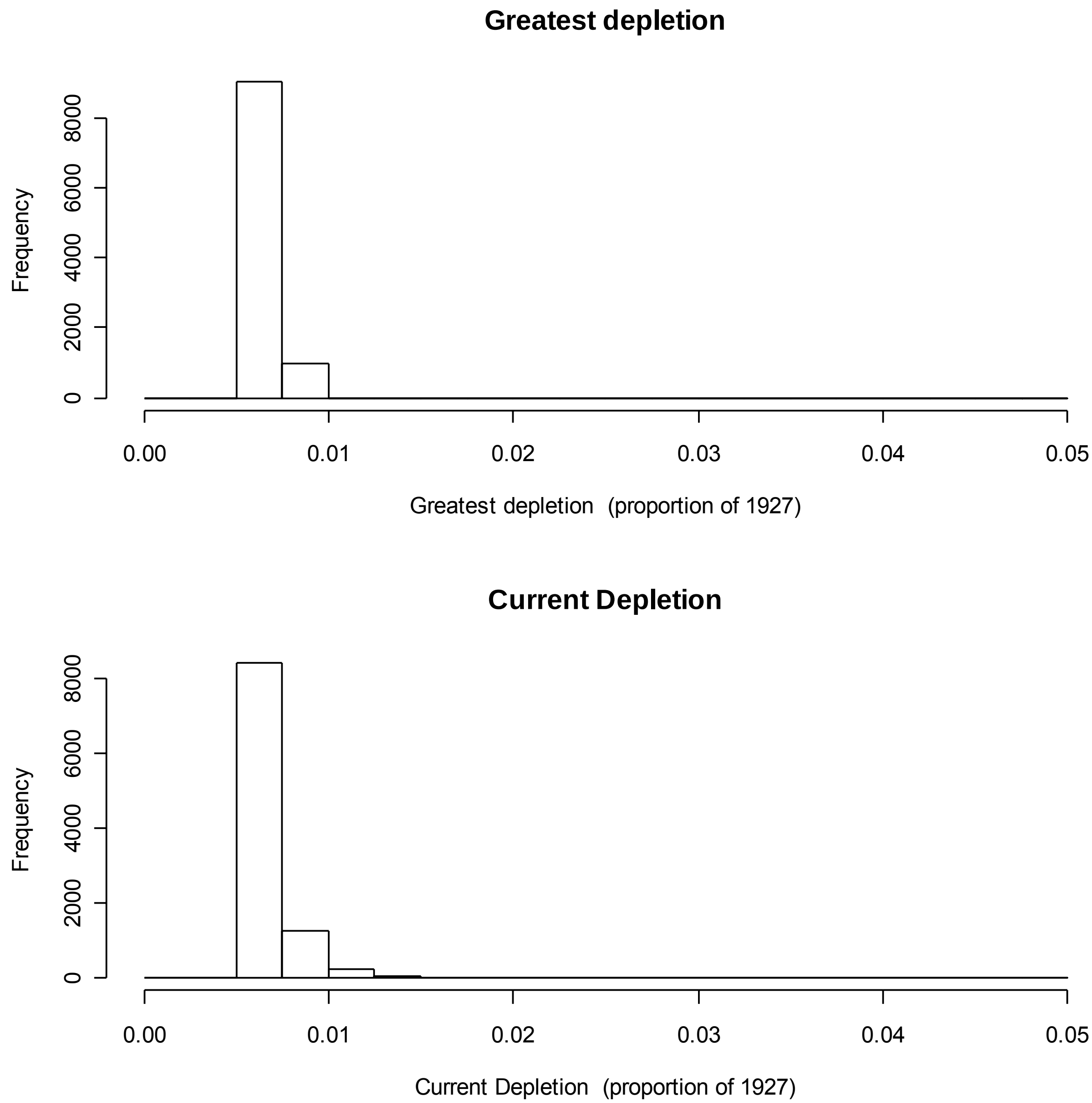


Figure E 12. Posterior distributions of depletion from likelihood-importance-resampling of Ricker model in Southeast quadrant (10000 samples). Lowest depletion usually occurs in 1991 and current depletion refers to 2003.

Southwest quadrant – Ricker model

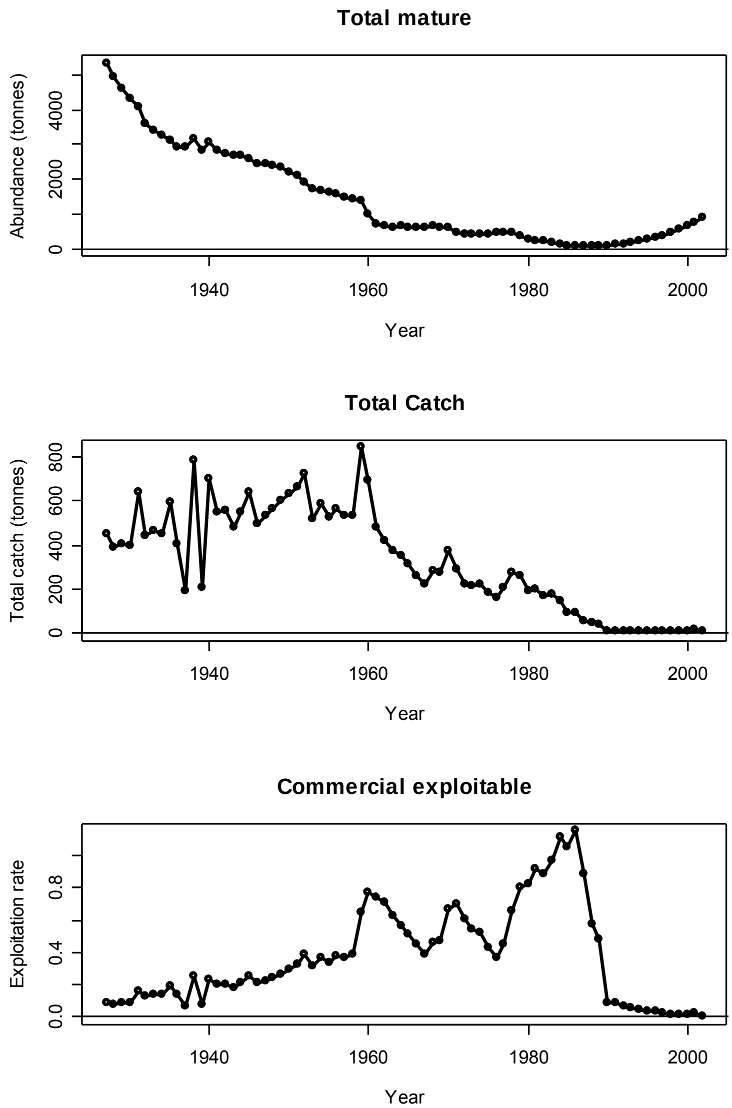


Figure E 13. Mature biomass trajectory, total catch and exploitation rate for Strait of Georgia Southwest quadrant – Ricker recruitment model.

Southwest quadrant – Ricker model

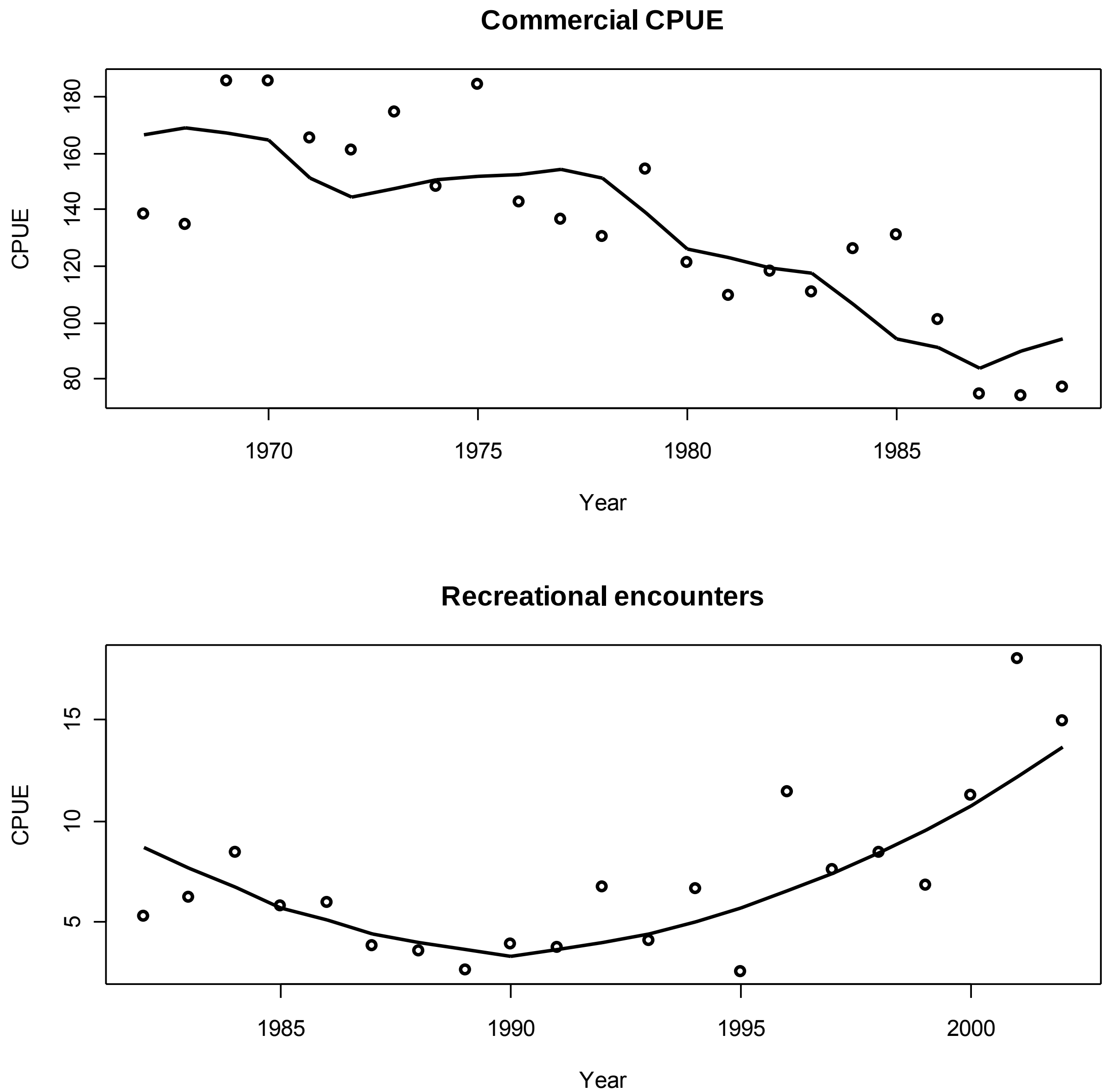


Figure E 14. Observed and expected CPUE for Ricker model fit to Southwest quadrant.

Southwest quadrant – Ricker model

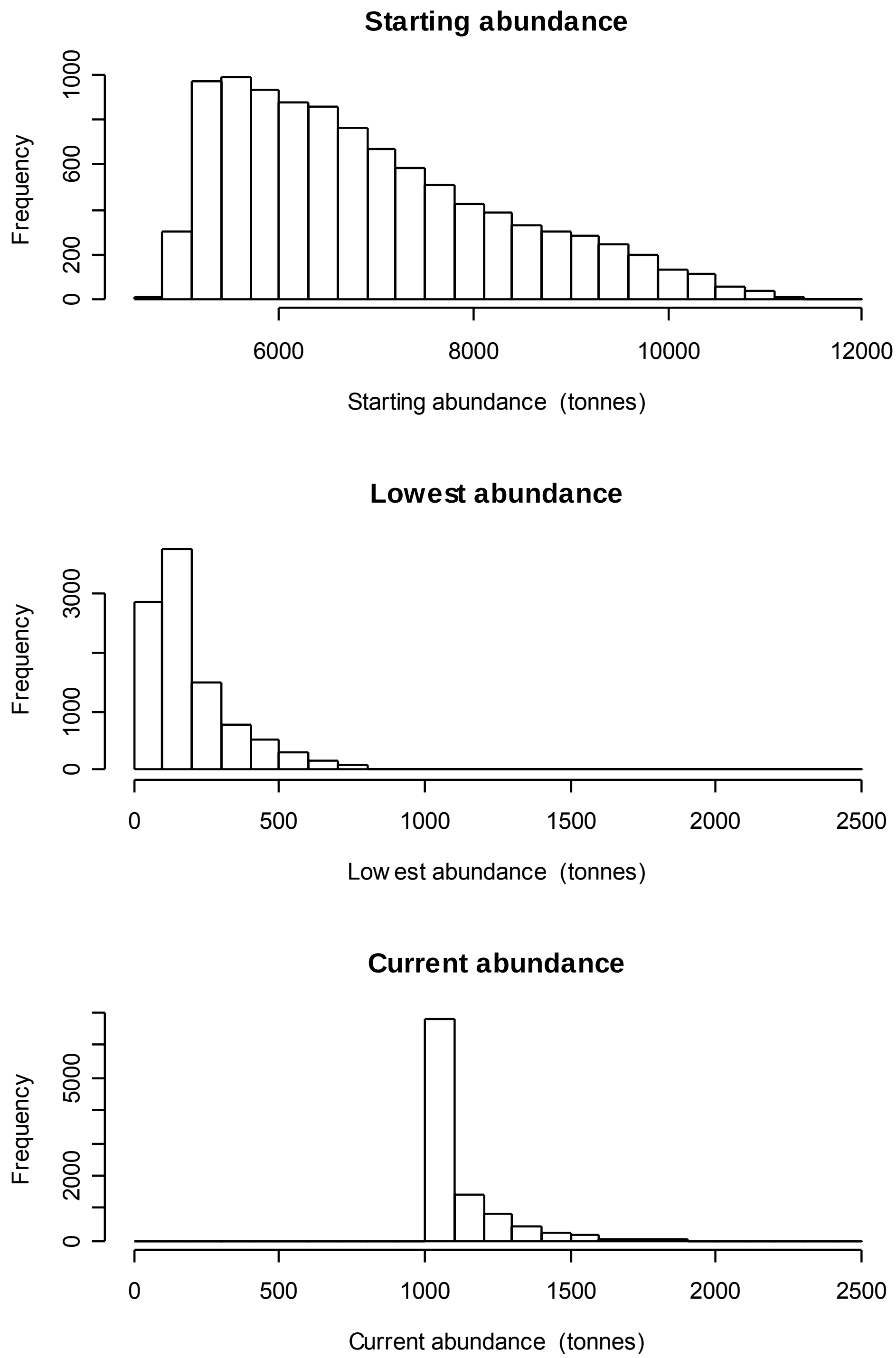
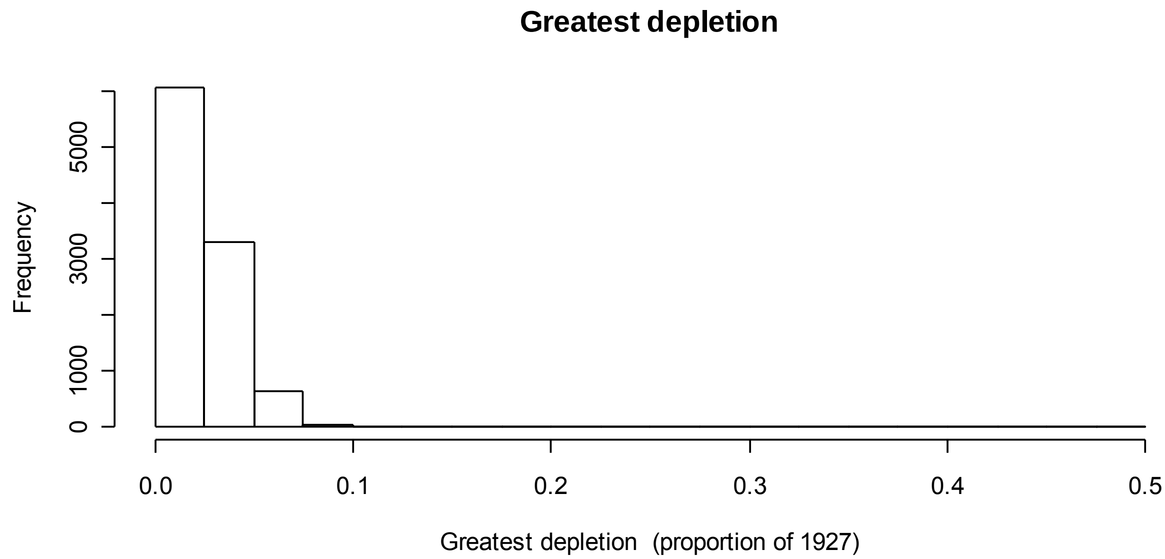


Figure E 15. Posterior distributions of abundance from likelihood-importance-resampling of Ricker model (10000 samples) in Southwest quadrant. Starting abundance refers to 1927, lowest abundance usually occurs in 1990 and current abundance refers to 2003.

Southwest quadrant – Ricker model



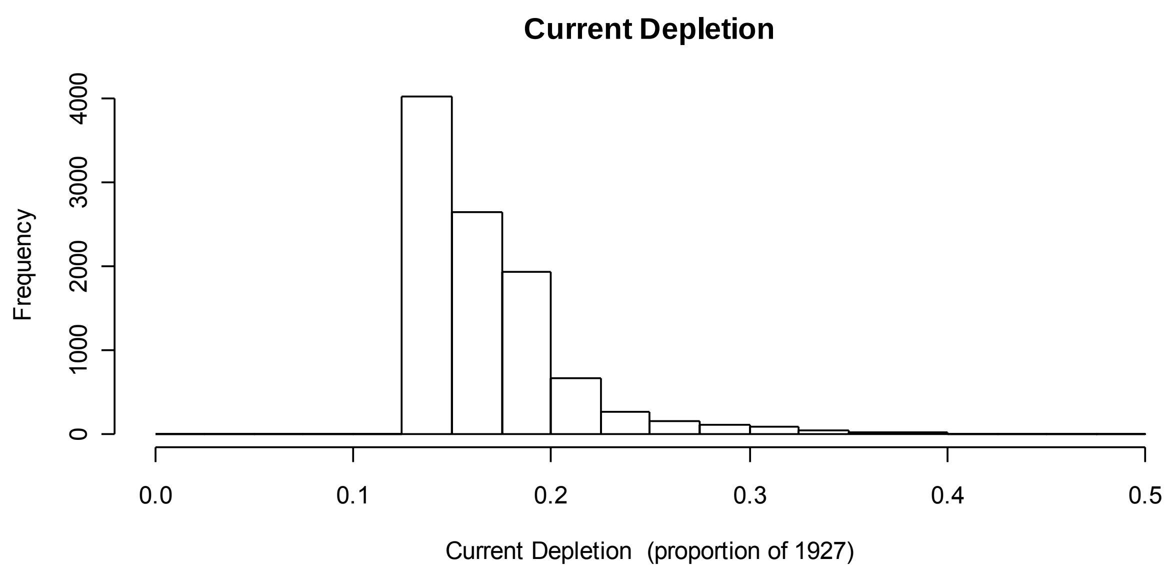


Figure E 16. Posterior distributions of depletion from likelihood-importance-resampling of Ricker model in Southwest quadrant (10000 samples). Lowest depletion usually occurs in 1990 and current depletion refers to 2003.

Appendix F. POPULATION DYNAMICS MODEL

F.1 AGE-STRUCTURED DYNAMICS

The dynamics model used for the lingcod in the Strait of Georgia is derived from a class library (Fish++) written in C++. A list of the parameters used in the model is given in Table F 1. The model includes the age structure of both sexes. The basic dynamic equations are given by:

$$N_{\bullet,a+1,t+1} = \left(N_{\bullet,a,t} - C_{\bullet,a,t}\right)S_{\bullet,a,t} \qquad \left|1 \le a < \left(a_{\max} - 1\right)\right. \tag{F.1}$$

with:

- $\bullet$ denoting *m* or *f* for males and females respectively,
- $N_{\bullet,a,t}$ number in age class *a* in year *t*,
- $C_{\bullet,a,t}$ catch in number from age class *a* in year *t*,
- $S_{\bullet,a,t}$ proportion of fish that survive after natural mortality from age *a* to *a*+1 in year *t*

$$S_{\bullet,a,t} = \mathrm{e}^{-M_{\bullet,a,t}} \tag{F.2}$$

with:

- $M_{\bullet,a,t}$ natural mortality rate at age *a* in year *t*. Natural mortality is denoted as depending in time because it can be specified as being density dependent. It can also be specified as age-dependent (future versions of the library will include the option to specify the age-dependence using a function.

There is a pooled age class (plus class) at $a = a_{\max}$. For this class:

$$N_{\bullet,a_{\max},t+1} = \left(N_{\bullet,a_{\max},t} - C_{\bullet,a_{\max},t}\right)S_{\bullet,a_{\max},t} + \left(N_{\bullet,a_{\max}-1,t} - C_{\bullet,a_{\max}-1,t}\right)S_{\bullet,a_{\max}-1,t} \tag{F.3}$$

For Strait of Georgia lingcod, catch data are not differentiated by age, and so:

$$C_{\bullet,a,t} = H_{\bullet,t}\, s_{\bullet,a} N_{\bullet,a,t} \tag{F.4}$$

with:

- $s_{\bullet,a}$ age-specific selectivity, i.e. the proportion of age class *a* vulnerable to the fishery. The model also allows for catches from different gear types with different age-specific selectivities.

- $H_{\bullet,t}$ is the proportional harvest rate in year *t*, specifically:

$$H_{\bullet,t} = \frac{C_{\bullet t}}{\sum_{a=1}^{a_{\max}} N_{\bullet,a,t} s_{\bullet,a} w_{\bullet,a,t}} \tag{F.5}$$

with:

$C_{\bullet,t}$ catch in mass (kg) over all ages in year t

$w_{\bullet,a,t}$ mean mass (kg) of fish aged a in year t. Mass at age can depend on t because growth can be specified to be density dependent.

In other catch series, the catch is available in numbers of fish, so that:

$$H_{\bullet,t} = \frac{C_{\bullet t}}{\sum_{a=1}^{a_{\max}} N_{\bullet,a,t} s_{\bullet,a}} \tag{F.6}$$

In this case with $C_{\bullet,t}$ the catch in numbers over all ages in year t.

The model is coded so that time can be advanced in arbitrary increments, including zero. Catches can be removed at any time step and at as many time steps as required. Different catch series can be removed from the population at the same time step, or at different times if required. For the lingcod model the time step used is one year.

The age-specific selectivity can be specified arbitrarily. A logistic function is available if required:

$$s_{\bullet,a} = \frac{1}{1+e^{-g_{\bullet}\left(a-a_{\bullet s50}\right)}} \tag{F.7}$$

with:

$a_{\bullet s50}$ age at which 50% of a cohort is vulnerable to the fishing gear, and

$g_{\bullet}$ a constant which determines the rate at which selectivity changes with age. Specifically:

$$g_{\bullet} = \frac{\ln(19)}{\left(a_{\bullet s95} - a_{\bullet s50}\right)} \tag{F.8}$$

with:

$a_{\bullet s95}$ age at which 95% of a cohort is vulnerable to the fishing gear.

Masses at age are calculated using a growth curve and a mass length relationship, that is:

$$w_{\bullet,a,t} = AL_{\bullet,a,t}{}^{B} + 0.5 \cdot AB(B-1)L_{\bullet,a,t}{}^{B-2}\,\mathrm{V}[L_{\bullet,a,t}] \qquad \text{(F.9)}$$

with:

constants A and B

$L_{\bullet,a,t}$	length at age from the growth curve. This can depend on t because the growth curve can be specified to be density dependent
$\mathrm{V}\lfloor L_{\bullet,a,t} \rfloor$	variance of length at age a in year t.

We assume that $\mathrm{V}\lfloor L_{\bullet,a,t} \rfloor$ is well approximated by $\left(L_{\bullet,a,t}\xi_L\right)^2$, where ξ_L is a constant coefficient of variation applicable to the variability of length at age for all ages. Consequently:

$$w_{\bullet,a,t} = AL_{\bullet,a,t}{}^{B}\left(1 + 0.5 \cdot B(B-1)\xi_L{}^{2}\right) \qquad \text{(F.10)}$$

The second terms in equations F.9 and F.10 are a "delta method" corrections required because a fish of mean length (i.e. from a growth curve) is not a fish whose mass is equal to the mean mass at age. However, application to the lingcod model is in accordance with the common practice that $\mathrm{V}[L_{\bullet,a,t}]$ is assumed to be zero.

Length at age is given by a von Bertalanffy growth curve:

$$L_{\bullet,a} = L_{\bullet\infty}\left(1 - \mathrm{e}^{-k_{\bullet}(a-a_{\bullet 0})}\right) \qquad \text{(F.11)}$$

with:

$L_{\bullet\infty}$	asymptotic mean length at age
$k_{\bullet}$	rate constant
$a_{\bullet 0}$	intercept

The formulation when growth is density dependent is given later.

F.1.1 Setting up the model

The model can be initialised in equilibrium at a specified harvest rate (including zero for the case of stocks at the beginning of exploitation). The age structures for each sex are set up using equations F.1 and F.3 after assigning an arbitrary number of animals in the first age class, but with t fixed at 0. The numbers at age are then scaled to obtain a specified biomass in any one of: total (1+) biomass, exploitable biomass or spawning biomass. The appropriate multiplier is:

$$\nu = \frac{B}{\sum_{a=1}^{a_{\max}} \left(\phi_{f,a} w_{f,a} n_{f,a} + \phi_{m,a} w_{f,q} n_{m,a} \right)} \tag{F.12}$$

where B is the required biomass in a specified segment of the population, $n_{\bullet,a}$ is the number at age set using the arbitrary number at age 1, and $\phi_{\bullet,a}$ is a vector giving the proportion of each age class that is a member of the specified segment. Obviously, if the specified biomass is for the total population $\phi_{\bullet,a} = 1$ for all a. Otherwise $\phi_{\bullet,a}$ is a maturity or selectivity function as required. The specified biomass is obtained by:

$$N_{\bullet,a,0} = \nu \cdot n_{\bullet,a} \tag{F.13}$$

The fertility per unit biomass of females in the unexploited population is found by setting up the population age structure without exploitation. Unexploited fertility is then given by:

$$f_K = \frac{N_{f,1,0} + N_{m,1,0}}{\sum_{a=1}^{a_{\max}} m_{f,a} w_{f,a} N_{f,a,0}} \tag{F.14}$$

where $m_{f,a}$ is the proportion of females that spawn at age a. The proportion mature at age for either sex is given by a logistic function:

$$m_{\bullet,a} = \frac{1}{1 + e^{-h_\bullet (a - a_{\bullet m50})}} \tag{F.15}$$

with:

$a_{\bullet m50}$ age at which 50% of a cohort is sexually mature, and

$h_\bullet$ a constant which determines the rate at which maturity changes with age. Specifically:

$$h_\bullet = \frac{\ln(19)}{\left(a_{\bullet m95} - a_{\bullet m50} \right)} \tag{F.16}$$

with:

$a_{\bullet m95}$ is the age at which 95% of a cohort is mature.

When required, the effects of recruitment variability can be included by multiplying the numbers in each age class by a random lognormal number. However, this feature is not used in fitting the model to the lingcod data, and so is not described here.

F.2 STOCK RECRUITMENT RELATIONSHIPS

The model can be specified with a choice of three commonly used stock recruitment relationships (SRRs); Beverton and Holt, Ricker and Pella-Tomlinson. An additional SRR is available that allows depensation in the Beverton and Holt model.

F.2.1 Beverton and Holt

The basic relationship for the number of recruits at age 1 in year t+1 is:

$$R_{1,t+1} = \frac{a\left(B_{f,t} + B_{m,t}\right)}{b + B_{f,t} + B_{m,t}} \tag{F.17}$$

with:

$B_{\bullet,t}$ mature biomass of males or females in year t

a and b constants

We determine the parameters a and b by specifying the SRR in terms of the ratio of the fertility (recruitment per unit mature biomass) at negligible stock size to the fertility when the stock is at the unexploited equilibrium. At unexploited equilibrium let:

$$R_{1,0} = N_{f,1,0} + N_{m,1,0} \tag{F.18}$$

thus, we can define fertility at un-fished equilibrium as:

$$f_K = \frac{R_{1,0}}{B_{f,0}} \tag{F.19}$$

let the fertility at negligible stock size be:

$$f_0 = \kappa f_K \qquad \Big| \kappa > 1 \tag{F.20}$$

i.e. fertility increases when the stock is depleted, it follows from F.17 that:

$$a = f_0 b \tag{F.21}$$

and therefore that:

$$b = \left(\frac{f_0}{R_{1,0}} - \frac{1}{B_{f,0} + B_{m,0}} \right)^{-1} \tag{F.22}$$

Thus, a and b are determined from f_K, the number of recruits in the un-fished population and the recruitment compensation multiplier κ. f_K is known from setting up the initial unexploited age structure. Thus, the additional parameter κ is sufficient to fully determine this SRR. The compensation multiplier (κ) is related to productivity. The parameter κ can be estimated by fitting the model to data.

F.2.2 Ricker Model

The basic relationship for the Ricker model is:

$$R_{1,t+1} = a\left(B_{f,t} + B_{m,t}\right)\mathrm{e}^{-b\left(B_{f,t}+B_{m,t}\right)} \tag{F.23}$$

where a and b are constants (but not with the same values as for the Beverton and Holt model). We use the same approach of defining the parameters by applying a compensation multiplier to the fertility of the unfished equilibrium population. In the Ricker case this leads directly to:

$$a = \kappa f_K \qquad \Big| \kappa > 1 \tag{F.24}$$

and

$$b = \frac{\ln\left(\dfrac{a\left(B_{f,t} + B_{m,t}\right)}{f_K} \right)}{B_{f,t} + B_{m,t}} \tag{F.25}$$

The parameter κ can be estimated by fitting the model to data.

F.2.3 Beverton and Holt model with depensation

The Beverton and Holt model, defined above (equation F.17), is multiplied by a logistic function to allow for fertility to decline at low abundance. The multiplier is given by:

$$d_R = \frac{1}{1 + \mathrm{e}^{-\varphi(B - B_{50})}} \tag{F.26}$$

with:

d_R is the proportion of recruits given by the SRR at biomass B that are produced after depensation

B_{50} is the biomass where depensation results in 50% of recruitment being lost relative to the non-depensatory SRR

φ is a rate constant that determines the range of biomasses over which depensation occurs

F.2.4 Allocation of recruits to each sex

We assume that the sex ratio of recruits is independent of population abundance, and so:

$$N_{f,1,t} = R_{1,t}(1-\phi) \tag{F.27}$$

$$N_{m,1,t} = R_{1,t}\phi \tag{F.28}$$

where ϕ is the proportion of recruits that are males

$$\phi = \frac{N_{m,1,0}}{N_{f,1,0} + N_{m,1,0}} \tag{F.29}$$

If random recruitment is specified, $R_{1,t}$ is multiplied by a random number before partitioning recruits to the two sexes.

F.2.5 Variability in recruitment

When required, the effects of recruitment variability can be included by multiplying the numbers of recruits by a random lognormal number ρ with an expected value of 1.0 and a specified coefficient of variation (ξ_R). The same random multiplier is used for both males and females at the same age, so that the total recruitment is variable but the sex ratio at each age is not. The multiplier is given by:

$$\rho = \mathrm{e}^{\mathrm{rnorm}(0,1)\sigma - \frac{\sigma^2}{2}} \tag{F.30}$$

Where rnorm(0,1) is a function that returns an instance of a standard random normal variable and

$$\sigma = \sqrt{\ln\left(1+\xi_R^{\ 2}\right)} \tag{F.31}$$

F.3 MODEL VARIANTS

F.3.1 Density dependent growth

Density dependent growth is modelled by allowing the parameters of the von Bertalanffy growth curve (equation F.11) to depend on stock abundance, so that, for example, the growth rates of fish in a depleted stock are greater than those for a stock in the un-fished state. In the lingcod model growth is made density dependent by resetting the parameters of the growth curve as follows:

$$L_{\infty,t} = L_K + (L_0 - L_K)\left(1 - \frac{B_t}{K}\right) \qquad \text{(F.32)}$$

where:

- $L_{\infty,t}$ is the asymptotic length in the growth curve at stock biomass B_t,
- L_K is the asymptotic length at carrying capacity K
- L_0 is the asymptotic length at negligible stock size

and

$$k_t = k_K + (k_0 - k_K)\left(1 - \frac{B_t}{K}\right) \qquad \text{(F.33)}$$

where:

- k_t is the rate in the growth curve at stock biomass B_t,
- k_K is the rate at carrying capacity K
- k_0 is the rate at negligible stock size

The intercept, t_0, is assumed to be independent of density. Separate growth models can be defined for each sex.

Recruits lie on the new growth curve. However, older animals cannot instantly move to a new growth curve, even though they will also experience a density dependent change in growth rate. This is modelled by applying to older animals the growth increment from the current growth curve that corresponds to their length, rather than their age (see Figure F 1). Thus, there is a time lag from a change in the growth curve to the population attaining the age-length structure consistent with that growth curve. This is illustrated in Figure F 2. If the current growth curve is below the previous growth curve older animals are not assumed to shrink, but to experience the lower growth rates that apply in the next step, which may mean that they grow no further.

Figure F 1 shows the key features of the growth model. In this case the previous growth curve lies below the current growth curve; the distance between the two growth curves have been made large in the figure to enable the model to be more easily visualised. A fish of age 10 has a length of around 310 mm. On the current growth curve a fish of 310 mm has an age of just less than 5, and experiences a growth increment as shown by the arrow, and grows to approximately 330 mm by age 6. The same growth increment is applied to the 10 year old fish so that it too grows approximately 20mm in one year to reach 330 mm by age 11. Thus, older fish grow above the previous growth curve, but do not approach lengths on the current growth curve until at least several years have elapsed (see Figure F 2). This means that the length structure of the population at any given time does not correspond to the growth curve unless the population is in equilibrium.

The relative increase in length at a given age on the current growth curve is:

$$\gamma_{\bullet,a'} = \frac{1-e^{-k_\bullet(a'+\Delta t-t_0)}}{1-e^{-k_\bullet(a'-t_0)}} \qquad \text{(F.34)}$$

where a' is derived from the current length of each age-class using:

$$a'_\bullet = t_0 - \frac{1}{k_\bullet \ln\left(1-\frac{L_\bullet}{L_\infty}\right)} \qquad \text{(F.35)}$$

F.3.2 Density dependent mortality

Natural mortality can also be made density dependent:

$$M = M_K + (M_0 - M_K)\left(1-\frac{B_t}{K}\right) \qquad \text{(F.36)}$$

where:

M_t natural mortality at stock biomass B_t,

M_K natural mortality at carrying capacity K

M_0 natural mortality at negligible stock size

F.3.3 Density dependent growth and mortality

Density dependence in both natural mortality and growth can be modelled simultaneously.

F.3.4 Time dependent variation in carrying capacity

Carrying capacity can be altered in any year to reflect possible effects of regime shifts.

F.4 FITTING THE MODEL TO DATA

The variants of the model are fitted to the catch per unit effort (CPUE) data using a log-likelihood function based on the assumption that CPUE has a log-normal distribution. The log-likelihood is given by:

$$LL = -n\ln(\hat{s}) - \frac{1}{2\hat{s}^2}\left(\sum_{t=1}^{n}\left[\ln\left(\frac{\varsigma_t}{\eta_t^{\lambda}}\right)\right]^2 - \frac{1}{n}\left[\sum_{t=1}^{n}\ln\left(\frac{\varsigma_t}{\eta_t^{\lambda}}\right)\right]^2\right) \qquad \text{(F.37)}$$

where:

n	number of CPUE data points in the series
$\hat{s}$	standard deviation of the residuals of the log-transformed CPUE data
ς_t	observed value of CPUE in year t
η_t	expected abundance of the exploitable segment of the population in year t (from the population model being fitted to the data)
λ	non-linearity exponent in the relationship between CPUE and abundance

The parameters $\hat{s}$, η_t and λ are estimated by maximising the log likelihood function using the simplex non-linear minimisation algorithm of Nelder and Mead (1965). Although a closed form estimator for $\hat{s}$ is available (de la Mare, 1986) this is not used here because better control of the search for the maximum likelihood was obtained by including $\hat{s}$ as a constrained parameter during minimisation. The catchability coefficient (q) is estimated implicitly in F.37.

The population trajectory is derived from the model as a function of initial population size (K) and the κ multiplier used in the stock recruitment relationship. Given that we have only CPUE data, all deviations are assumed to arise from observation error and the model fitted to the data is assumed to have no variability in recruitment. Thus, the fitted population trajectory corresponds with the median of a distribution of population abundances in each year. It is the median rather than the mean because the data are not corrected for the difference between the mean and the median when fitting occurs in the log domain.

To describe the uncertainty in the estimates of initial and current abundance I combine the likelihood function with priors on the parameters to give Bayes' posterior distributions. The following uniform prior is used when calculating the Bayes' posterior density of initial (and derived) abundance:

$$K = \mathrm{U}\left[\mathrm{Sup}(C_t), \textstyle\sum_t C_t\right] \quad ; \quad t \in \{1:n\} \qquad \text{..(F.38)}$$

where U[a,b] denotes a uniform probability density function with range a,b and C_t is the total catch in year t. Thus the prior probability of initial abundance is bounded below by the largest catch in any year and above by the total catch over all years. K will fall between these limits for a persistent population that has been highly depleted at some time. The other parameters have the following uniform priors:

Parameter	min	max
κ	1.0	10.0
$\hat{s}$	0.12	0.25
λ	0.3	2.0

In the lingcod application there are two independent sets of CPUE data, and so the combined log-likelihood function is the sum of the log-likelihoods for each series separately. Values for the parameters $\hat{s}$ and λ are estimated separately for each series, and since each CPUE series applies to a different segment of the population, the model trajectories are derived using different age-specific selection functions.

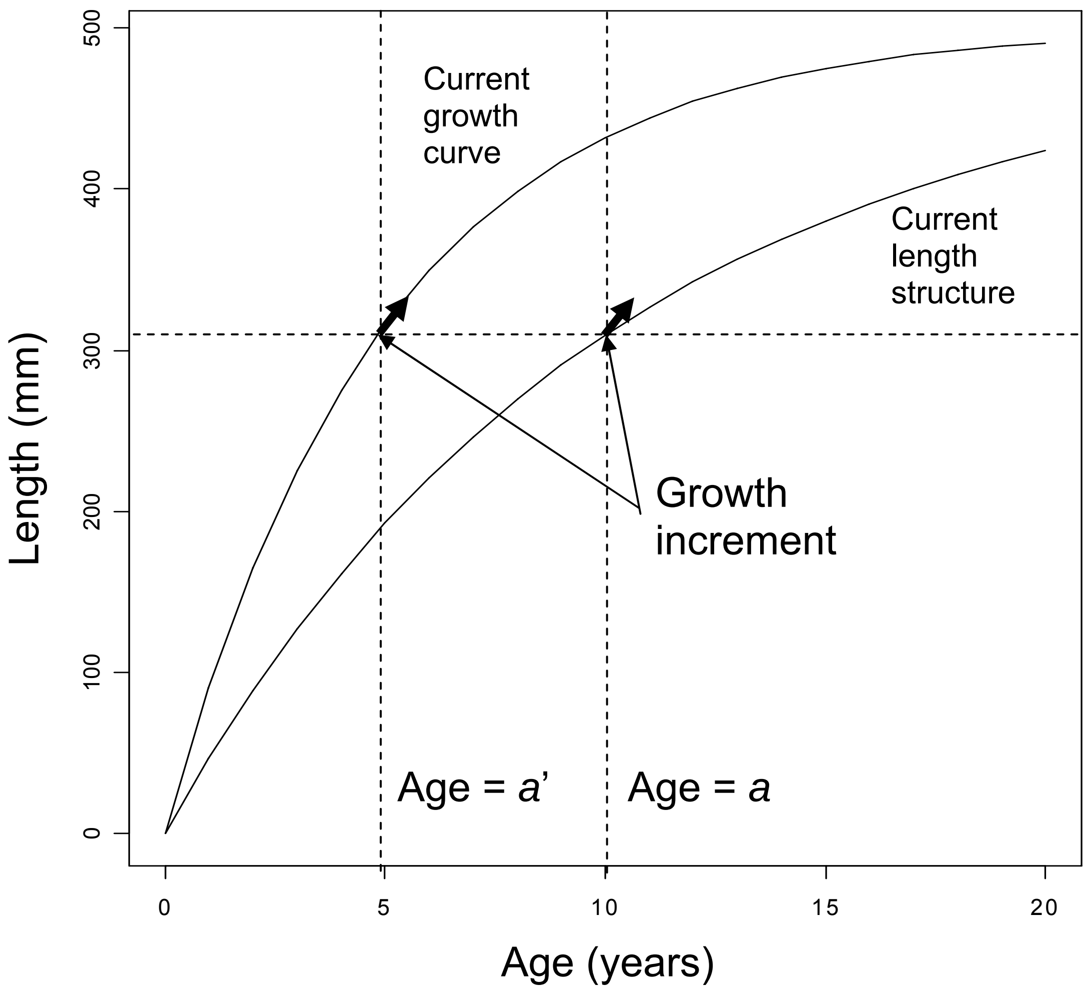


Figure F 1. This figure depicts the method of applying density-dependence in growth. We suppose that in a given year the population has the 'current length structure'. However, due to density dependence, the growth curve that the population would have in equilibrium is the curve labelled 'current growth curve'. In this case, the current length structure lies below the current growth curve. It is assumed that all animals of the same length will grow according to the growth increment at that length on the current growth curve.

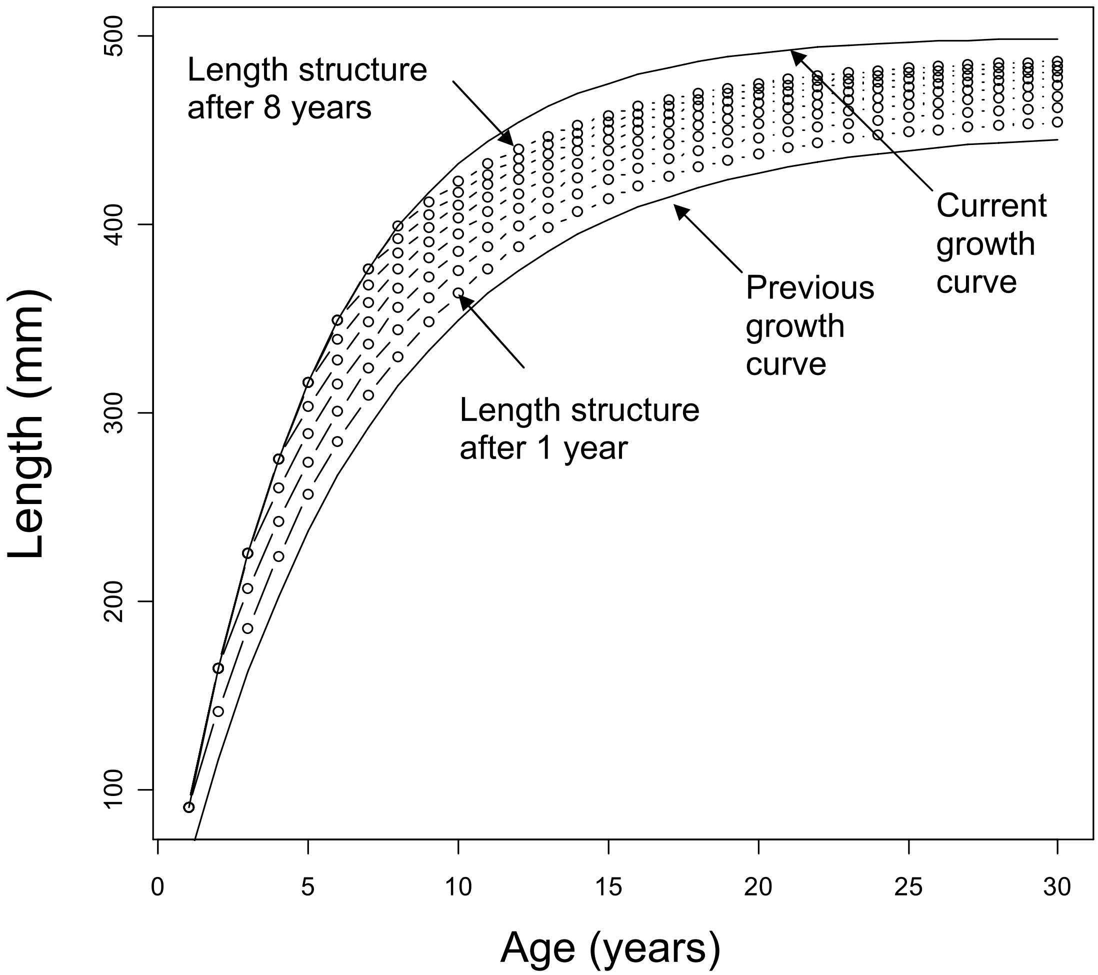


Figure F 2. Yearly changes in length structure of the population given by the density dependent growth model by supposing the growth curve changes from the ‘previous growth curve’ to the ‘current growth curve’ in one year. Each year the length structure of the older animals moves closer to the current growth curve, while younger animals follow the current curve.

Table F 1. List of parameters used in the model.

$\varsigma_{i,t}$	CPUE in series *i* and year *t*
q_i	catchability coefficient for data series *i*
$\eta_{i,t}$	exploitable abundance of population component *i* in year *t*
λ_i	exponent determining degree of linearity between CPUE series *i* and abundance
$\bullet$	denoting *m* or *f* for males and females respectively,
$N_{\bullet,a,t}$	number in age class *a* in year *t*,
$C_{\bullet,a,t}$	catch in number from age class *a* in year *t*,
$S_{\bullet,a,t}$	proportion of fish that survive after natural mortality from age *a* to *a*+1 in year *t*
$M_{\bullet,a,t}$	natural mortality rate at age *a* in year *t*.
$s_{\bullet,a}$	age-specific selectivity, i.e. the proportion of age class *a* vulnerable to the fishery
$H_{\bullet,t}$	is the proportional harvest rate in year *t*
$a_{\bullet s50}$	age at which 50% of a cohort is vulnerable to the fishing gear, and
$a_{\bullet s95}$	age at which 95% of a cohort is vulnerable to the fishing gear.
$g_\bullet$	a constant which determines the rate at which selectivity changes with age.
$w_{\bullet,a,t}$	mass at age *a* at time of year *t*
A	constant in mass at age relationship
B	exponent in mass at age relationship
$L_{\bullet,a}$	length at age
$L_{\bullet\infty}$	asymptotic mean length at age
$k_\bullet$	von Bertalanffy rate constant
$a_{\bullet 0}$	von Bertalanffy intercept
$B_{\bullet,t}$	mature biomass of males or females in year *t*
a	constant in a stock-recruitment relationship
b	constant in a stock-recruitment relationship
f_K	fertility (1 year old fish per unit female spawning biomass) at *K*
K	Carrying capacity
f_0	fertility at negligible stock size
$B_{f,t}$	Spawning biomass of females in year *t*
$B_{m,t}$	Spawning biomass of males in year *t*
d_R	proportion of recruits given by the SRR that are produced after depensation
B_{50}	biomass where depensation results in 50% of recruitment being lost relative to the non-depensatory SRR
φ	rate constant that determines the range of biomasses over which depensation occurs

ϕ	proportion of recruits that are males
$L_{\infty,t}$	asymptotic length in the growth curve at stock biomass B_t,
L_K	asymptotic length at carrying capacity K
L_0	asymptotic length at negligible stock size
k_t	von Bertalanffy rate in the growth curve at stock biomass B_t,
k_K	von Bertalanffy rate at carrying capacity K
k_0	von Bertalanffy rate at negligible stock size
$\gamma_{\bullet,a'}$	growth increment at apparent age a'
M_t	natural mortality at stock biomass B_t,
M_K	natural mortality at carrying capacity K
M_0	natural mortality at negligible stock size
n_i	number of CPUE data points in series i
$\hat{s}_i$	standard deviation of the residuals of the log-transformed CPUE data in series i

Appendix G. COMPARISON OF THE TWO METHODS OF RESAMPLING THE POSTERIOR DISTRIBUTION.

The figures in this section compare posterior distributions of abundance and depletion based on the marginal distribution of abundance and the corresponding conditional estimate of the productivity multiplier with those based on the joint distribution of abundance and productivity multiplier. Table G 1 shows the differences between the projected recovery times for the two resampling methods. The effect of the improved joint resampling method is noticeable in the estimates of current stock size and depletion where it spreads the sharp cut-off on the lower level of depletion into a longer tail. However, Table G 1 shows that the improved method has not had a substantial effect on the stock projection estimates of recovery time.

Table G 1. Monte Carlo recovery time statistics (recovery year percentiles) using projections based on marginal abundance posterior compared with those from the joint abundance-resilience posterior distribution. K = estimated equilibrium unexploited spawning biomass.

	Marginal abundance method			Joint abundance-resilience method		
Recovery Criterion	5%ile	50%ile	95%ile	5%ile	50%ile	95%ile
>0.1K	2004	2005	2005	2004	2004	2008
>0.2K	2009	2016	2026	2008	2015	2025
>0.3K	2012	2023	2038	2012	2022	2038
>0.4K	2015	2028	2050	2014	2027	2047
>0.5K	2017	2034	2058	2016	2032	2057

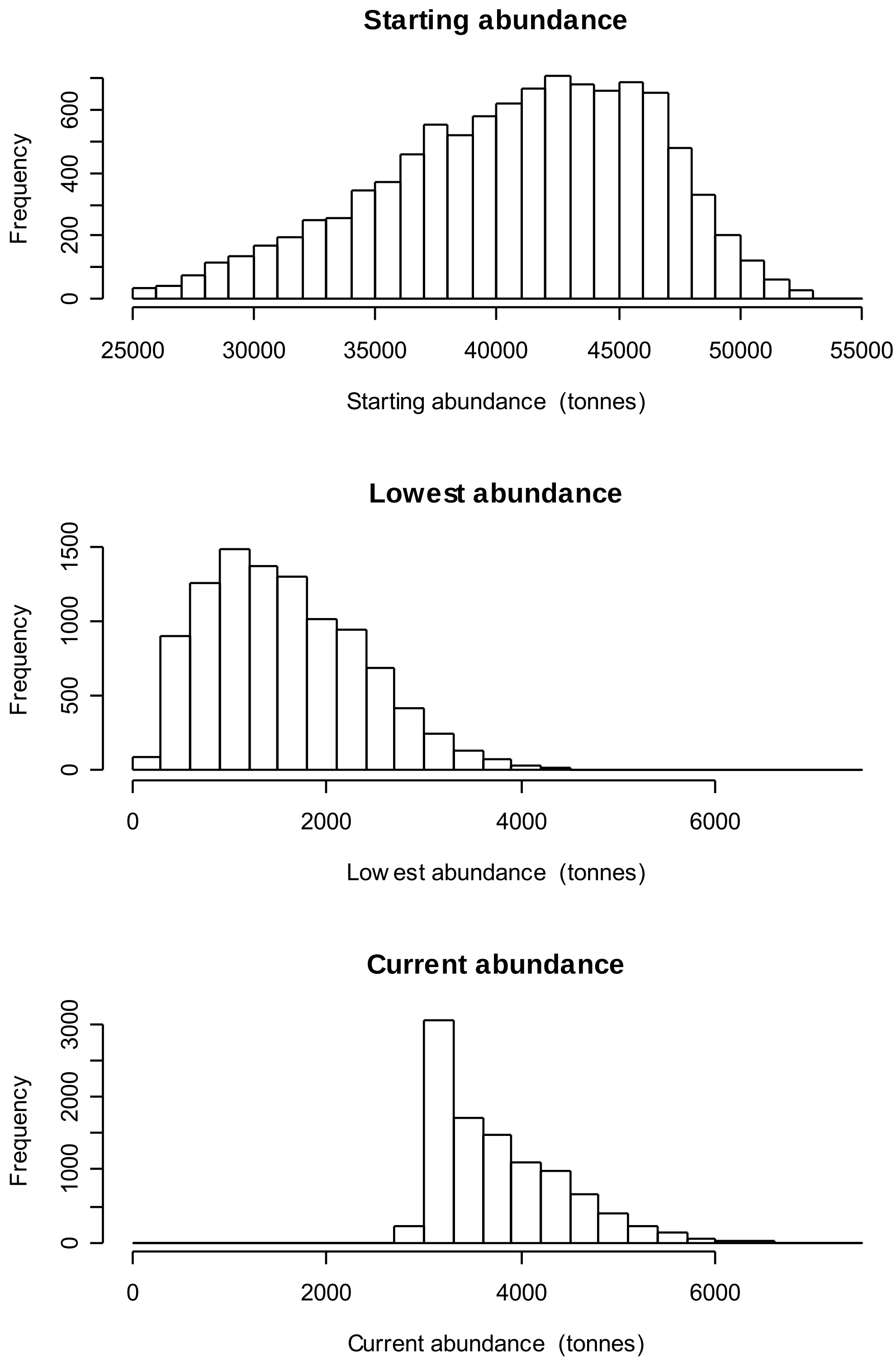


Figure G 1. Monte Carlo posterior distributions of abundance derived from the marginal posterior distribution of initial abundance from the Ricker model (based on 10000 projections).

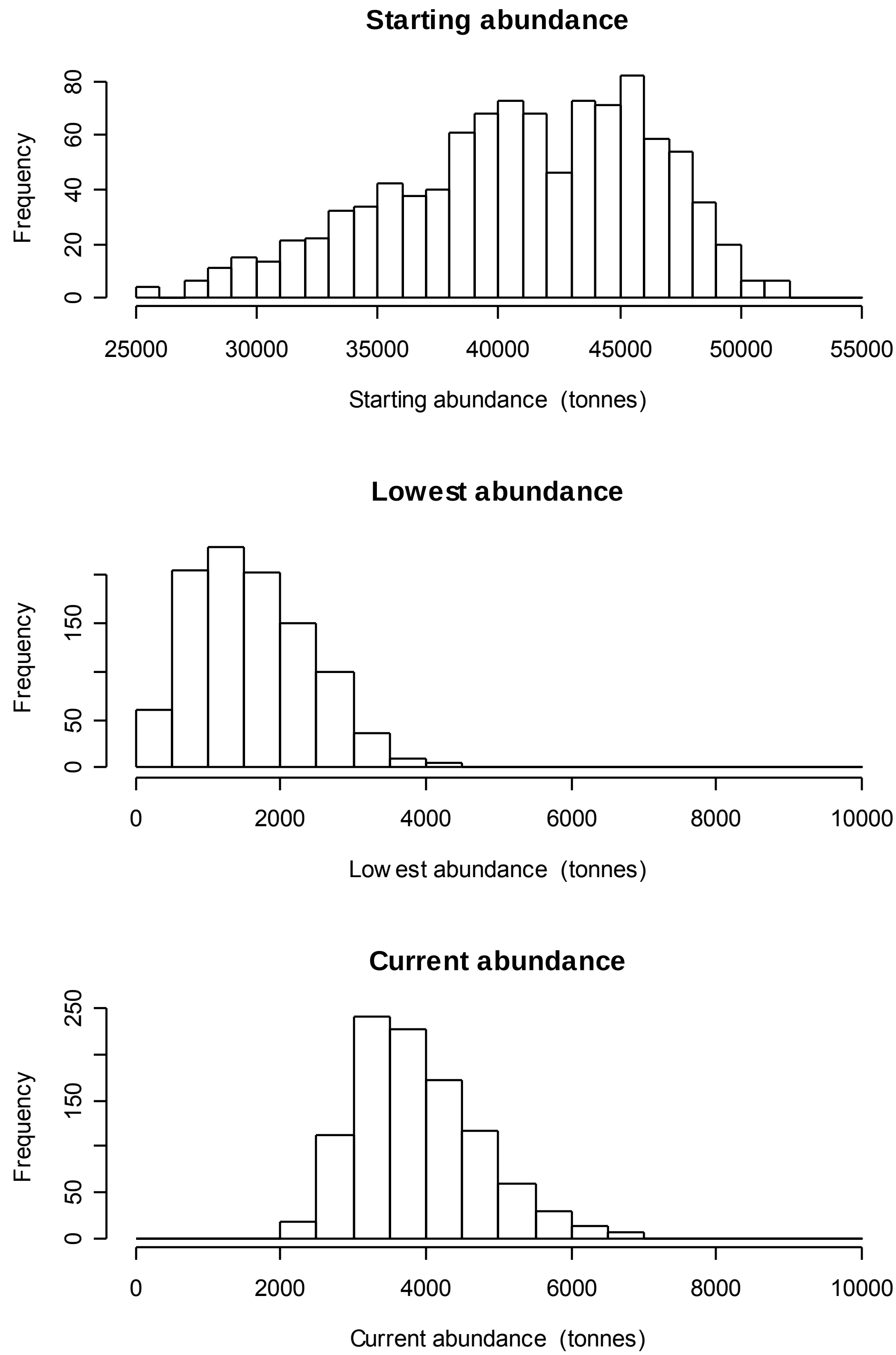
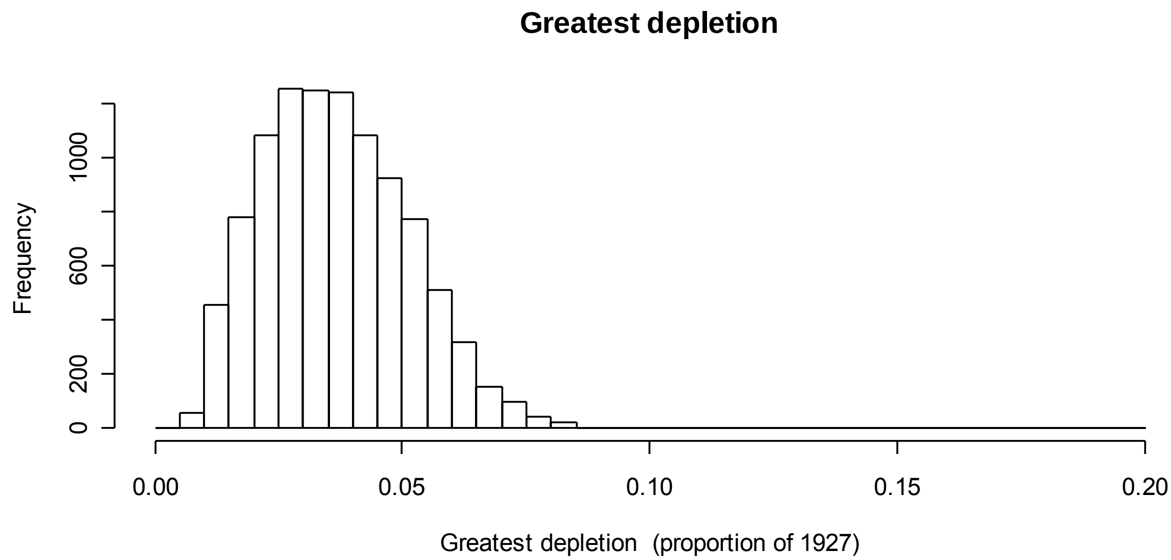


Figure G 2. Monte Carlo posterior distributions of abundance derived from the joint posterior distribution of initial abundance and resilience (using marginal-conditional sampling) from the Ricker model (based on 1000 projections).



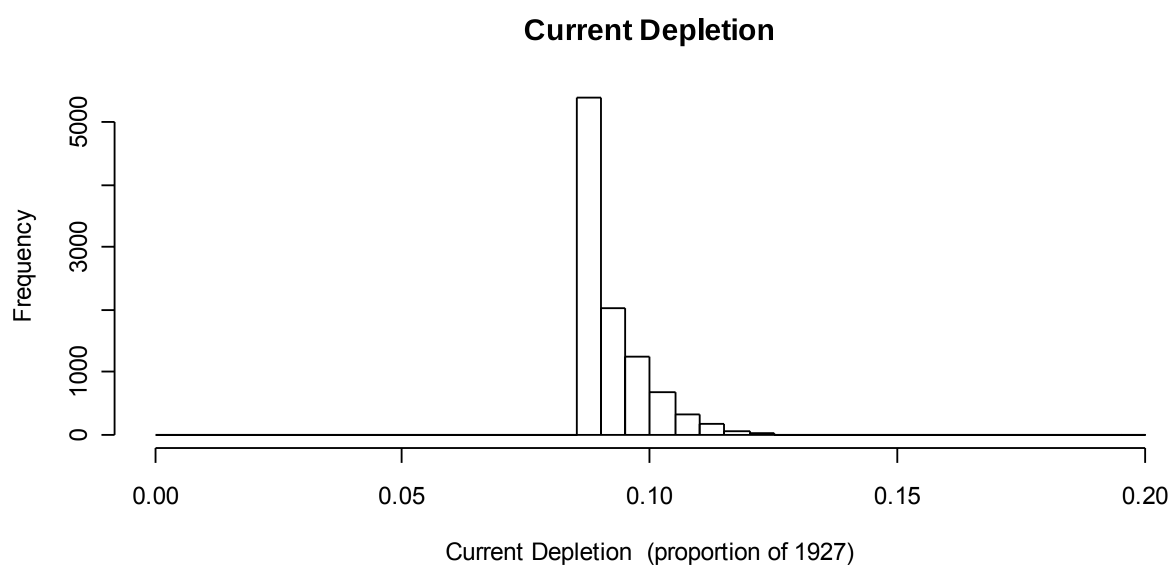


Figure G 3. Monte Carlo posterior distributions of depletion derived from the marginal posterior distribution of initial abundance from the Ricker model (based on 10000 projections).

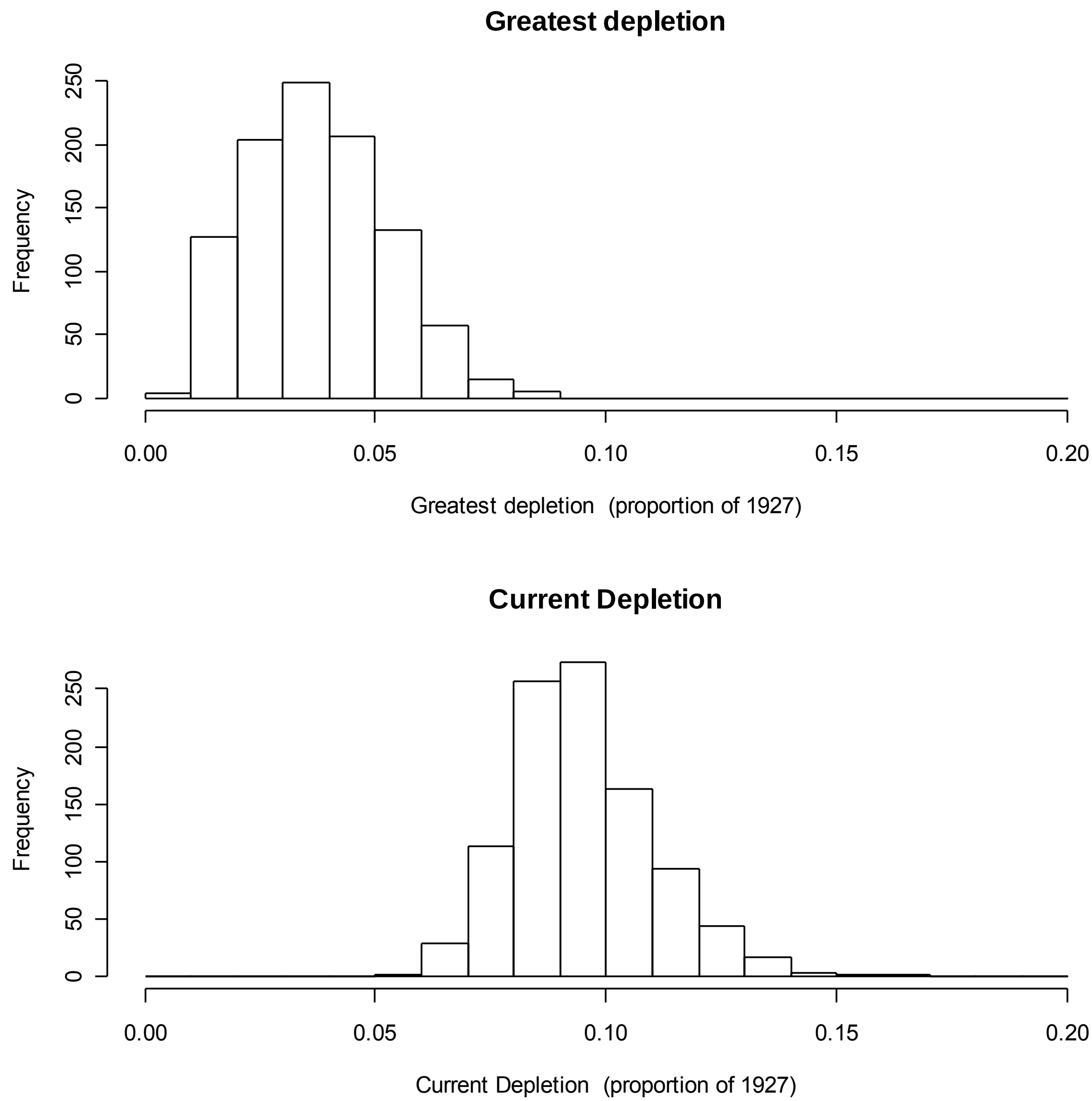


Figure G 4. Monte Carlo posterior distributions of depletion derived from the joint posterior distribution of initial abundance and resilience (using marginal-conditional sampling) from the Ricker model (based on 1000 projections).