Fisheries and Oceans Science
Pêches et Océans Sciences

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Research Document 2001/106

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Document de recherche 2001/106

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A proposed MPA boundary identification process for reproductive refugium establishment, using lingcod (*Ophiodon elongatus*) as an example focal species

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ISSN 1480-4883
Ottawa, 2001

ABSTRACT

The boundaries of any MPA are likely to be a function of local bathymetry, management objectives for the area, and the biological characteristics of particular focal species, if any, identified. For many MPAs, there may be an obvious bathymetric outer boundary (e.g., a bay, reefs around an isolated island, etc.) but others might be established on a section of coast of relatively homogenous bathymetry, for which recommendations of an outer boundary for the MPA may have to depend solely on the latter two criteria. Here, we consider how the boundaries of a potential MPA designed to serve as a reproductive refugium for lingcod (*Ophiodon elongatus*), a likely potential focal species in British Columbia, might be determined today from a science perspective, and consider the nature of the biological data that would be required to rationalise such a boundary.

Through our literature review for lingcod, a number of important information gaps for this species were identified. Firstly, there is no current estimate of the minimum numerical abundance of lingcod required to ensure an identified desired population reproductive potential. Secondly, to estimate the size of a no-harvest area required to sustain a specified desired lingcod population size, information is needed on the densities of individuals (male or female) by size that can be supported in different habitats, and the dispersal characteristics of individuals by size, neither of which are well described for lingcod. Due to this lack of information, we estimated MPA boundaries for such a hypothetical lingcod refugium based on the assumptions that: 1) an appropriate desired protected population size would be present along an arbitrary six km of longshore rocky shoreline, 2) that this population would be centred within the potential MPA area, and 3) that the average home range for lingcod over one year is a meaningful criterion to determine the distance the MPA's "no-harvest" boundary should be from the edge of the lingcod population desired to be fully protected.

With these assumptions, a refugium MPA for lingcod that would protect about 95% of the population would extend 34 km in any direction from the identified core lingcod habitat. Secondly, given that there is no documented history on the use of MPAs in Canada as a management tool for population rebuilding or reestablishment, if such MPAs were to be established for this purpose, appropriate follow-up monitoring will be required so that adaptive management can be implemented. Our main recommendation is that since establishing an MPA for the purpose of rebuilding depleted fish stocks requires considerable species-specific biophysical data, managers are urged to identify candidate species at the earliest possible time so that the appropriate available data can be assessed and, if deemed deficient, additional science data obtained.

RÉSUMÉ

Les limites d’une ZPM sont habituellement établies en fonction de la bathymétrie locale, des objectifs de gestion et les caractéristiques biologiques d’espèces à protéger qui auraient été relevées. Pour plusieurs ZPM, il peut exister une limite bathymétrique extérieure évidente (p. ex., une baie, des récifs autour d’une île isolée, etc.), mais d’autres ZPM peuvent être établies le long d’une portion de côte dont la bathymétrie est plutôt homogène. Dans ce cas, les limites extérieures recommandées pourraient ne dépendre que des deux derniers critères. Dans cette étude, nous examinons comment établir scientifiquement les limites d’une éventuelle ZPM qui servirait de sanctuaire de reproduction de la morue-lingue (*Ophiodon elongatus*), qui sera probablement désignée espèce à protéger en Colombie-Britannique, et nous nous penchons sur la nature des données biologiques nécessaires pour justifier ces limites.

Notre analyse bibliographique de la morue-lingue a permis de relever un certain nombre d’importantes lacunes dans les connaissances sur cette espèce. D’abord, il n’existe aucune estimation de l’abondance minimale de morues-lingues nécessaire pour assurer le potentiel de reproduction de la population qui serait désiré. Ensuite, pour estimer la superficie de la zone fermée à la pêche qui serait requise pour maintenir la population de morues-lingues à la taille désirée, il faut obtenir de l’information sur les densités par taille des individus (mâles et femelles) que peuvent soutenir différents habitats et sur les caractéristiques de dispersion des individus selon leur taille. En raison de ce manque de données, nous avons estimé les limites de ZPM pour un éventuel sanctuaire de la morue-lingue en nous fondant sur les postulats suivants : 1) la population protégée de la taille désirée serait présente le long d’un littoral rocheux sur une distance arbitraire de six km, 2) cette population serait centrée à l’intérieur de l’éventuelle ZPM et 3) le domaine vital annuel moyen de la morue-lingue constitue un critère significatif qui permet de déterminer à quelle distance de la population de morues-lingues les limites de la zone fermée à la pêche de la ZPM devraient être établies pour assurer la pleine protection de la population.

Selon ces postulats, un ZPM sanctuaire qui protégerait environ 95 % de la population de morues-lingues s’étendrait dans un rayon de 34 km à partir de l’habitat principal de l’espèce. Étant donné qu’il n’existe aucune documentation sur l’historique de l’utilisation des ZPM comme outil de gestion pour la reconstitution ou le rétablissement de populations au Canada, l’établissement de ZPM à cette fin nécessiterait un suivi adéquat pour appliquer une gestion adaptée. Voici notre principale recommandation : comme l’établissement d’une ZPM pour reconstituer des stocks de poissons appauvris nécessite beaucoup de données biophysiques sur les espèces visées, les gestionnaires devraient déterminer les espèces candidates le plus vite possible afin de permettre l’évaluation des données pertinentes disponibles et, au besoin, la collecte de données scientifiques supplémentaires.

INTRODUCTION

With the introduction of Canada's *Oceans Act* in 1997, there has been increased interest in British Columbia in legislated marine protected areas. The term "marine protected areas" (in lower case font) refers to a complex of federal and provincial legislated designations that offer different levels of protection of either habitat or species over time (Jamieson and Lessard 2000). Fisheries and Oceans Canada is responsible for the conservation and management of most renewable fishery resources in British Columbia and its regulations supersede provincial regulations. Marine protected areas (MPAs) (in upper case font, and the legislated name for Oceans Act marine protected areas) are beginning to be used as a management tool to protect, maintain, or restore natural and cultural resources in coastal and marine waters.

In September 1998, the Minister of Fisheries and Oceans announced the establishment of two nearshore pilot Marine Protected Area projects in BC, Race Rocks (near Victoria) and Gabriola Passage (east coast of Vancouver Island). Race Rocks will soon be declared as a Marine Protected Area under the *Oceans Act,* and will initially at least have the same bathymetric “no-harvest” boundary as the existing provincially-legislated Race Rocks Ecological Reserve, described by Jamieson and Lessard (2000). The outer boundary and internal zoning, if any, of the proposed Gabriola Pass MPA have yet to be determined. However, determining the boundary for the Gabriola Pass area, a region with no obvious bathymetric outer boundary, has raised the question as to what scientific data may be relevant or useful to resource managers in determining the boundaries of potential MPAs. How far away a MPA boundary occurs from an identified core area of interest may be both a function of the management objectives determined for the proposed MPA and the biological characteristics of a particular focal species identified, if one indeed is, as a primary rationale for that MPA’s establishment. Here, we consider how the boundaries of an MPA that is being designed to serve as a reproductive refugium for a target species, here identified as lingcod (*Ophiodon elongatus*), might proceed today from a science perspective, and consider the nature of the biological data that would ideally be required for use in such an effort. Any focal species could be chosen, but we are considering lingcod both because further conservation of this species may well be an ultimate objective for an MPA in British Columbia (BC) and because the biological data available for this species is relatively typical of the data available for any fish species in BC.

Martell (1999) used a computer model to speculate on how MPAs might conserve lingcod, and evaluated questions relating to movement rates by lingcod, spatial distribution of fishing effort, and alternate management policies. He found that rates of fish movement and the distribution of fishing effort were important in the efficacy of no-harvest areas as conservation tools, and that as expected, the sizes of no-harvest reserves were important. He concluded that while a disproportionate amount of fishing effort was likely to be distributed along no-harvest reserve area boundaries, especially at low lingcod stock sizes, in comparison to further increasing size limits or reducing fishing periods, a network of no-harvest areas would be particularly effective in lingcod stock conservation.

Wallace (1999) examined mpas as tools to rebuild marine ecosystem structure following severe depletion of selected species, and specifically considered lingcod and northern abalone (*Haliotis kamatschatkana*). He concluded that in his study areas and depth ranges surveyed, populations of both species respond positively, i.e., greater abundance and a larger average size, to the absence of human harvest in a defined area. However, he noted that because of diving limitation, he could only survey to 18 m depth, and lingcod are known to commonly inhabit depths between 10-100 m (Cass et al. 1990). He therefore could not accurately describe overall lingcod population demography at his 35 study sites in Howe Sound.

Proposed Boundary Determination Process

The application of minimum viable population size has been previously proposed (Dugan and Davis 1993) in the design of marine protected areas established to primarily conserve a focal species. The procedure typically entails three steps (Dugan and Davis 1993): 1) ascertaining a desired biomass of the target species to be conserved, perhaps to achieve a desired population larval output; 2) determining spatially relevant, achievable population densities in the overall area; and 3) estimating the geographical MPA "no-harvest" boundaries required to sustain the desired target species abundance, taking into consideration the estimated home ranges of individuals of the target species and their spatial distribution. Determining the spatial relationships of appropriate habitats within the study area in which the species would normally be expected to occur, i.e., habitat associations of the target species, and the specific spatial locations and areas of these suitable habitats, is particularly important.

Here, we undertake this exercise for lingcod in a hypothetical area within the Strait of Georgia, and from our analyses, suggest what the outer boundary of the "no-take" portion of this potential MPA might be with current knowledge, if establishment of an effective lingcod refugium was a primary desired management objective. It should be emphasised that this analysis is entirely speculative at this time, as no such determination for the purpose of any specific MPA has been stated by any resource manager to date. However, as has been recognised for years (see Martell 1999, Wallace 1999) and is shown below, the current status of the lingcod population in the Strait of Georgia is depressed, so we suggest such a purpose might well be considered for an MPA in the Strait of Georgia.

General Biology of Lingcod (Ophiodon elongatus)

Lingcod are primarily distributed in nearshore waters from California to Alaska and are abundant off the coast of British Columbia. Typically, they are found at bottom depths between 3 and 400 m, generally occupying rocky areas between 10 to 100 m (Cass et al. 1990). They are generally associated (LaRiviere 1981, Cass et al. 1990, Axys Environmental Consulting Ltd. 2000) with clean shallow waters (2 to 20 m, mostly 14 to 15 m) over rocky substrate, rocky areas or subtidal reefs, or where there is an abundance of rocky outcroppings; crevices, caves, boulders; vertical cliffs at shallow depths; and high relief bedrock at intermediate depths. They are also typically associated with 75 to 100% substrate cover by sessile invertebrates and algae and strong currents (up to 4-6 km hr^{-1}).

From seasonal catch, tagging studies, sex, and depth data, it has been determined that seasonal migrations occur in response to spawning (Cass et al. 1990; Chatwin 1956; Cass et al. 1986; Hand and Richards 1987, 1989; Matthews 1992; Smith et al. 1990). The seasonal migration from deeper offshore areas starts in October when some males, but particularly females, migrate to nearshore spawning sites (Cass et al. 1984, Gordon 1994). Spawning sites are chosen by the male, preferably in rock crevices or on ledges with strong currents to oxygenate egg masses. The depth distribution for egg masses ranges from the intertidal zone to about 100 m. However, the majority of nests have been observed between 5 to 25 m. From surveys, it has been concluded that favoured nest sites are more dependent upon suitable substrate and current velocities rather than water depth (LaRiviere et al. 1981). Once female lingcod have deposited their egg masses, typically in December to March, the fertilising male guards the nest for a six-week incubation period (Martell 1999) while the female migrates back to deeper depths (Hand and Richards 1987, 1989; Cass et al. 1990). In studies where males had been removed from their nests, new males were sometimes found to take over nest guarding. However, eggs from most nests (67%) that were unguarded were typically consumed within 2 to 22 days by predators, indicating that male presence is essential for the protection of egg masses (Cass et al. 1990). Once the eggs have safely hatched, males may also migrate to deeper waters.

The 50% age of maturity for female lingcod is four years and for males is three years. Females spawn annually and live for an estimated maximum 20 y, while males live to an estimated maximum 14 y (Cass et al. 1990). Determinations of fecundity were made from specimens of lingcod taken in southern British Columbia during 1937-42 (Hart 1967). From this study, Forrester (1973) determined a fish length–egg number relationship of

$$\mathrm{Log}_{10}\,\mathrm{Egg\ Number} = 3.0011 * \mathrm{Log}\ L(\mathrm{mm}) - 3.5491$$

Thus, a female lingcod 86 cm in length produces about 181,000 eggs, while a 118 cm lingcod would produce about 470,000 eggs. Egg viability is dependent on several factors: 1) mortality of guarding males because of seals, sea lions, and fisherman; 2) the depth of the egg nest (anecdotal information suggests that nests in very shallow water may have a lower egg viability (Cass et al. 1990)); 3) predation on eggs by fish (particularly kelp greenlings (*Hexagrammos decagrammus*) and striped seaperch (*Embiotoca lateralis*)) and invertebrates, such as the gastropods, Amphissa columbiana and Calliostoma ligatum; and 4) predation on newly hatched pelagic larvae (6-10 mm in length), particularly by sculpins and striped sea perch.

Lingcod larvae are found in the plankton during about 2.5 months (estimated 6-8 week pelagic period (Martell 1999)) between early March and mid-May in the Strait of Georgia (Phillips and Barraclough 1977), and are generally found in the upper 3 m of the water column (King and Surry 2000). It has not been determined whether larvae have behaviours that allow them to remain in the general area where they are hatched. When larvae are approximately 4-5 cm, they become juveniles and leave the surface to settle in inshore areas on the bottom near kelp or eelgrass beds (Cass et al. 1990) in habitats not occupied by older lingcod (Beamish et al.1995; King et al. 2000; Jeff Marliave, Vancouver Aquarium, Vancouver, BC, pers. comm., June, 2001). At an age of two years, they begin to inhabit similar habitats as do older lingcod (Cass et al. 1990).

Egg incubation by males is similar in both the Strait of Georgia and Puget Sound, with hatching success ranging from 10 to 27% in the Strait of Georgia to 90% in Puget Sound (Cass et al. 1990). Studies conducted by LaRiviere (1981) in San Juan Channel found that eggs in 40% of the 35 nests observed were successfully hatched. Within the southern Strait of Georgia, larval lingcod were found to be abundant along the eastern shoreline of the Gulf Islands, generally where adult populations were abundant (Phillips and Barraclough 1977). Egg masses may provide recruitment primarily in the immediate vicinity of the spawning area (King et al. 2000, Cass et al. 1990), meaning that areas can perhaps be recruitment overfished and that local stocks need careful management if population density is to be sustained at a desirably productive level. However, lingcod hatchings swim neustonically and are reported (J. Marliave, Vancouver Aquarium Marine Science Centre, Vancouver, BC, pers. comm.) to cross horizontal current gradients until they locate current speeds of about ten body lengths per second (i.e., since they hatch at 8 mm, of about 8 cm sec^{-1}). Rapid movement away from shore may thus be achieved, taking the larvae into areas of longshore, or tidal, current drift, and thereby achieving dispersal.

Through the use of catch curves (comparisons of the catch of a cohort at successive ages), Cass et al. (1990) reported that lingcod residing off the west coast of Vancouver Island, ranging from 6 to 12 years of age, had an annual survival rate of 0.52-0.68 for males and females combined.

History of the Lingcod (Ophiodon elongatus) Fishery in British Columbia, and specifically in the Strait of Georgia

In the following, we discuss the state of the lingcod stock in both British Columbia in general, and the Strait of Georgia in particular. These data are included to demonstrate the current depressed state of the stock and to indicate that lingcod is a species for which stock rebuilding is both warranted and justifiable.

1. British Columbia

Records for the lingcod commercial hook and line fishery started in the early 1860's and the first catch statistics from the commercial fishery were produced in 1889 (Cass et al. 1990). However, the catch of lingcod was not separated from rockfish catches until 1927, although it is known that during this period, lingcod was the primary species caught, and accounted for more than 90% of the "cod-like" species caught in British Columbian waters (Forrester 1973). Geographical areas for which landing data are compiled are shown in Figure 1.

Lingcod stocks were heavily exploited in the late 1920's and in the 1940's, with annual catches reaching over 3000 t and a peak landing in 1944 of 4023 t (Table 1) (Figure 2). The fishery stabilised during the 1950’s at an average of 2600 t year^{-1}. From the 1940's to the 1960's, it is estimated that 90% of all lingcod caught came from the Strait of Georgia handline fishery (Cass et al. 1990). During the 1960's and 1970's, catches fluctuated around an average of about 3000 t year^{-1}, with a maximum of 6423 t in 1968. Between

1980 and 1990, BC catch increased from 2200 t $year^{-1}$ to approximately 5216 t $year^{-1}$, with a peak landing of 5666 t in 1985. Since 1990, commercial catches have declined, and were 1987 t in 1999. Both Canada and the U.S. have participated in the trawl fishery in BC, with the U.S. fleet contributing 40-60% of the total trawl catch between 1954 and 1970 (DFO 2001a). In 1977, Canada's 200 mile Canadian Fishing Zone was implemented and catches from the U.S. fishery declined and finally ceased in 1980 (King and Surry 2000).

Coastwide catches were high in the early 1990's but have declined in recent years. Onboard vessel observers, bycatch limits for halibut, and the provision that all catches of quota species, including discards, would be counted against individual vessel quotas were introduced in 1996. These requirements have changed the groundfish trawl fishery in BC substantially and has resulted in reduced targeting on lingcod (DFO 2001a).

2. Strait of Georgia

The commercial fishery for lingcod in the Strait of Georgia began in the mid-1800's and was prosecuted primarily by hook and line. Between 1940 and 1990, only a small portion (10% on average) of the catch was from the trawl fishery (King and Surry 2000). Commercial handline-troll and trawling landings were substantially higher during the 1950's to the early 1960's, with a peak landing of approximately 1546 t in 1957 (Table 2, Figure 3). After the early 1960's, landings steadily declined to 358 t in 1983. The majority (61%) of lingcod commercially landed by the handline and troll fisheries have come from Trawl Fishery Minor Statistical Areas (MSA) 13 and 17 (Table 1) (Tyler and McFarlane 1985). Martell (1999) calculated the estimated lingcod biomass in International Statistical Area 4B (Georgia Strait) in 1998 to range between 4600-5100 t, 9.7-12.2% of the estimated unexploited biomass. In the 1980s, he estimated the stock to be at its lowest biomass – 2175-2700 t.

Over time, different conservation measures have been implemented. A minimum size limit of 58 cm for the commercial fishery and a winter (December to February) closure to protect lingcod spawning stocks was implemented in 1940. In 1979, the seasonal closure was extended (November to April) for both commercial and sport fisheries in an attempt to improve recruitment by protecting the pre-spawning aggregation and nest-guarding males. In 1990, due to a continued decline in stocks, the commercial fishery was closed entirely in Statistical Areas 13 to 19, 28 and 29 (Figure 1), i.e. the Strait of Georgia.

Lingcod are fished by longline, sunken gillnet, trap and seine fisheries, but catches with such gear have been negligible compared to catches in the handline and trawl fisheries (Ketchen 1980). Recreational anglers and SCUBA divers also catch lingcod; however, there were no catch records until the 1980's. The most reliable estimates are based on dockside surveys to record catch data and aerial surveys to estimate the number of boats fishing. Based on these surveys, approximately 35% of the total lingcod catch was estimated to be by recreational fishers (Cass et al. 1990). Survey results also indicated that an average 13% of the total species sports catch was lingcod during 1980-1985 in the Strait of Georgia, and that an average of about 80,000 lingcod, or 125 t $year^{-1}$, was landed by recreational fisherman. Spear fishing by SCUBA divers increased during the 1960-1970's and peaked in the 1980s. In the 1990s, sport fishery landings have been less than 20% of that in the 1980s (Martell 1999).

In 1990, a 58 cm voluntary minimum size limit was implemented for the sport fishery. Subsequently, the sport fishery in Statistical Areas 13 to 19, 28, and 29, i.e. the Strait of Georgia, and Subareas 20-5 to 20-7 was restricted to June 1 to September 30, with a bag limit of 1 fish per day, and a voluntary annual limit of 10 fish. The minimum size limit was increased to 65 cm in 1991. As of 1993, an annual sport limit of 10 fish became mandatory. After these restrictions were implemented, the average size of lingcod landed increased from 58.3 cm in 1988 to 66.5 cm in 1993 (Beamish et al. 1995).

Recent Lingcod Studies in the Strait of Georgia

Specific lingcod data are included for the Gabriola Island area in the Strait of Georgia since this area has been better studied than most other areas in the Strait. Its proximity to the Pacific Biological Station in

Nanaimo has facilitated studies for logistical reasons, and because the area around Gabriola Pass has been identified as a pilot MPA area (DFO 2001b), more extensive bathymetric and overall compilation of stock assessment data are available. Data availability here demonstrates the issues that are likely to be relevant elsewhere.

1. Hook and Line Surveys

A number of recent hook and line surveys were conducted in Statistical Area 17, including Gabriola Reefs, in 1985, 1987 and 1988 (Hand and Richards 1987, 1989). During the surveys, sampling was stratified into three depth intervals (5-27, 28-45 and 46-55 m) and the number of fish caught by species and depth was recorded (Table 3). In January and February, 1987, lingcod within the upper two depth intervals represented 51% of the total catch of all species in the MPA study area. Other common species observed were spiny dogfish (21%), copper rockfish (13%) and quillback rockfish (9%). Over the two-year study period, and with each survey conducted between January and February, the mean percentages of these four species changed significantly, and were 43, 8, 15, and 27%, respectively, in year two (AXYS Environmental Consulting Ltd. 2000, Hand and Richards 1989).

In the above study, 95% of the 41 males caught were mature, and of these, 31% had developing gonads, 33% were ripe and 46% were spent. The largest immature male was 62 cm and the smallest mature male was 48 cm. Of the 113 female lingcod caught, 77% were mature, of which 28% had developing eggs, 24% were ripe, 43% were spent, and 6% were reabsorbing their eggs. The largest immature female was 86 cm and the smallest mature female was 56 cm. Lingcod CPUE was also determined to be significantly lower in 1987 and 1988 than in 1985 (Hand and Richards 1989). The results of the survey corroborated previous evidence that stocks in the Strait of Georgia had declined to a level unable to support a directed fishery.

2. Homing Ranges

Several studies (Matthews 1992, Yamanaka and Richards 1993) of lingcod homing ranges and habitat preferences have also been conducted within the Strait of Georgia and Puget Sound. Both studies indicated that transplanted fish tend to wander, whereas tagged fish that were not moved generally remained within 300 m of the tag site during the study period. Matthews (1992) conducted telemetric studies on the homing ranges and homing routes of lingcod on shallow rocky reefs in April, 1990, off the eastern portion of Gabriola Island and off Valdes Island on Valdes and Gabriola reefs (both approximately 15 to 30 m deep). Matthews (1992) determined that male lingcod were capable of homing, i.e., returning from 1 km to 2.8 km displacements, taking 33-60 h to return from 2.8 km displacements. Movement was only at night. Smith et al. (1990) estimated through recovery of tagged males and females by the rod-and-reel sport fishery and sport fishing effort data that the mean dispersal rate for male and female lingcod was 500 m day^{-1} and 1040 m day^{-1}, respectively, similar to movements determined by Matthews (1992), i.e., 1174 m day^{-1}, the average of both sexes. These transplant studies suggest lingcod have a strongly developed home site fidelity.

3. Home Ranges

There have been a number of tagging studies of lingcod in the Strait of Georgia that have tried to quantify rates of movement or document migration in the stock (Hart 1943; Chatwin 1956; Cass et al. 1983, 1984, 1986; Smith et al. 1990, Martell 1999). In each of these studies, a small proportion (4-38%) of the tagged population was recovered at distances greater than 10 km from the release site. Smith et al. (1990) conducted mark and recapture studies from 1982 to 1985 within Strait of Georgia MSAs 13, 14, and 16. A total of 4658 males and 5635 females were tagged and released at nine locations. Lengths ranged between 32.9-90.8 cm (males) and 31.7-120.2 cm (females). Analyses concluded that females dispersed at a much faster rate than males and it was estimated that after one year of dispersing from their release locations, 95% of tagged males and females would be within 17 km and 34 km, respectively, of their release locations. Females were found to have a greater dispersal rate due to their life history pattern. Large females tend to occur in greatest abundance in deeper water where there is a spacious and relatively uniform habitat (Chatwin 1956, Cass et al. 1986). Males prefer rarer habitats consisting of shallow waters along reefs. Due to the scarcity of this latter habitat, males often resided permanently in preferred areas, resulting in their more limited dispersal movements.

Additional tagging studies have also been conducted offshore of the west coast of Vancouver Island (Mathews and LaRiviere 1987). These studies indicated that the vast majority (95% of recoveries in the first and second year after tagging) of lingcod stayed within 10 km of their home site, with only very slight movement beyond 50 km. Exceptions included an individual that travelled 385 km.

Lingcod Abundance Indices

Before the closure of the commercial fishery in the Strait of Georgia, a CPUE index based on commercial catch rates was used as an indicator of stock abundance trends. However, with the closure of the fishery, this catch index is no longer available as an indicator of lingcod abundance (Haist 1995). An index of catch rates for the sport fishery was also used in the past to assess stock trends. However, this index was based only on the recorded lingcod caught and retained by anglers. In addition, due to changes in the sport fishing regulations, i.e. minimum size and retention limits, sport fishing abundance indices are also no longer as useful because they now reflect only the number of lingcod landed.

As a consequence of the confounding of fishery statistics, numerous studies including nest counts, creel surveys and hook and line surveys have been conducted to determine the best method of estimating lingcod abundances. Surveys concluded that the relationship between nest density and numbers of lingcod was not clear (Yamanaka and Richards 1995). Hook and line surveys by Yamanaka and Murie (1995) suggested that a CPUE-based analysis may be meaningful, but further analysis is required. A review of the creel survey interview database (different from the sport fishing abundance index) determined that the lingcod catch rate index may possibly reflect stock abundance fluctuations (Haist 1995). As a result of these studies, the creel survey index is currently being used to assess relative abundance trends in the Strait of Georgia. Lingcod creel survey data, and lingcod nest density estimates, will be discussed at the fall 2001 Groundfish PSARC meeting, though, so this issue is not yet fully resolved. In conclusion, the above indices provide at best only information on abundance trends. Consequently there is no current methodology that provides acceptably accurate estimates of lingcod abundance.

Population Fecundity Estimation

Lingcod population fecundity is a function of both the number of individuals (in this case, both males and females; females to produce eggs and males to guard the eggs) by size and the fecundities of individuals by size. The specific optimum population size structure to maximize lingcod population fecundity is not known, but like most fish, it would likely consist of a relatively large proportion of large, and presumably older, individuals. With an estimated typical 12 year life span for male lingcod (A. Cass, DFO, Nanaimo, BC, pers. comm.) and regular annual recruitment, we hypothesise that a maximum population fecundity would likely be achieved in a protected population after about 15-25 years. This assumes that current recruitment rates are depressed because population fecundity is presently low, and that it may take about a decade for local recruitment to begin to approach an average pre-fishery level. However, we have no data to confirm this, i.e., no age structure information to estimate recruitment rate and no current estimates of stock size.

Given the above state of our understanding of lingcod biology, one can only speculate as to how large an optimal refugium lingcod population should be. Larval dispersal distances are unknown, and so benefits to adjacent fished lingcod populations may arise from both the spillover of adult individuals into them (see Martell 1999) and increased larval settlements in fished areas because of greater overall population fecundity in the nearby protected area. With no operational MPA examples to indicate the extent to which either event might occur, an optimal “protected” lingcod population size is not known at this time.

Estimation of MPA Boundaries for a Lingcod Refugium

Given that neither an optimal lingcod population size nor current lingcod spatial patterns of occurrence or densities are known, the optimal core area (the geographical area from which resident lingcod should experience no fishing mortality) size for a protected lingcod population can only be hypothesised at this time. However, if it is assumed that such a population could be contained within a 6 km long-shore rocky shoreline, and assuming that it is centred at the middle of the hypothetical MPA area, an estimate of where the outer boundary of an MPA to protect most lingcod in this core area might be can at least be suggested from the limited data available on lingcod home ranges. To achieve effective protection with an MPA for both sexes, then the average home range value used should be that for the most wide-ranging sex, i.e., for lingcod, the female. With an average home range of 34 km, then the outer boundary of a continuous rocky area should be about 37 km [34 + 3 (the core area radius) km] in each direction. This distance, however, does not reflect possible site-specific variation in average home range distance, so this estimation is simply to give managers a general estimate of the scale of protection that might be required along a continuous rocky shoreline.

Some potential MPA sites may include one or more unique identifiable reef areas, with the rocky habitat preferred by males discretely located spatially. If the MPA is of sufficient size to contain a desired non-ranging male lingcod population, designating only the reef area a “no-harvest” area might then fully protect the males. If the females in a larger zone outside this protected area were protected via a lingcod-specific *Fisheries Act* regulation, then protection of a male lingcod population might be achievable with a smaller “no-harvest” MPA area . In this case, the “no-harvest” MPA boundary would be determined by the spatial characteristics of the reef area, and the no-harvest zone for female lingcod only would be determined by their average home range, in the context of the local bathymetry.

For any specific site, the spatial pattern of suitable lingcod habitat is obviously important, and any specific suggestions for boundaries should involve a range of boundary options, with estimated risks relating to achieving identified objectives associated with the different options.

DISCUSSION

Lingcod have supported significant fisheries in BC for over a century, including a major fishery in the Strait of Georgia, and are still extensively exploited in BC. Nevertheless, there is still a great deal not known about the biology of the species, particularly as it relates to reproduction, recruitment and larval dispersal. Spatial data on specific fishing locations from commercial and recreational fishing is largely unavailable for the Strait of Georgia, with data compiled into Statistical Areas totals that do not permit meaningful analyses on the relative importance of particular sites within them. The intent of making these points is not to suggest inadequacies in previous research, but rather to point out that much relevant research still remains to be done on this important species. These data deficiencies apply to most, if not all, the exploited species in British Columbia.

If MPAs are to be based on the micro-management of specific species’ populations to achieve desired population outcomes, then the appropriate science data to likely achieve this, and to know that this has indeed be achieved, will be required. Here, we suggest what some of these data may be, and hopefully demonstrate what some of the difficulties may be in utilising existing limited relevant data. In the process of our analysis, we suggest what data types may be most useful to obtain in future research in support of MPA establishment for the rebuilding of depleted fished populations.

Analyses of lingcod populations in the Strait of Georgia discussed above suggest that attempting to rebuild lingcod stocks now may be timely. Relatively spatially-persistent groundfish species should be considered in contemplating the potential boundaries of MPAs. Since it may take many years to realise the benefits of protection of relatively long-lived species, there would seem to be little to be gained by procrastination in initiating the establishment of effective “no-harvest” areas for depleted stock rebuilding.

Our analyses indicate that for lingcod at least, effective no-harvest MPA reproductive refugia will be perhaps larger than might initially have been assumed by those uninformed with lingcod biology, being potentially upwards of 70 km or so in length along a continuous rocky shoreline. An alternative to a large no-harvest MPA to protect both lingcod sexes in some areas may be the use of linked no-harvest MPAs and conventional Fisheries Act closures, i.e. an adaptive management approach. Alternatively, there could still be a large MPA, but only smaller “no-harvest” zones around isolated reefs within it to ensure protection of male lingcod. In these two latter scenarios, a network of smaller no-harvest areas to protect males may achieve the same objective as a single large no-harvest area. The most appropriate approach could perhaps be modelled for a specific area of interest, utilising the area’s exact spatial pattern of suitable lingcod habitats.

RECOMMENDATIONS

1. While not perfect, sufficient data appears to exist to rationalise the manner by which DFO oceans and fisheries managers can work together to rebuild depleted populations for some species, including lingcod, in selected areas.

2. When DFO resource managers are considering the establishment of MPAs for the rebuilding of depleted fished stocks, managers are urged to identify relevant candidate species at the earliest possible time and to give direction and support to researchers so that the appropriate species-specific biophysical data will be available when needed.

3. Given that there is no documented history on the use of MPAs as a management tool in the rebuilding of depleted fished populations, MPAs established for this purpose will be an exercise in adaptive management. Resources will therefore need to be made available to effectively document the longer-term consequences of MPA establishment so that possible improvements, if necessary, can be recommended.

ACKNOWLEDGEMENTS

We thank the two PSARC reviewers and PSARC Habitat Subcommittee members for their constructive comments. Drs. J. Marliave and J. King in particular provided useful comments. Avrael Spigelman helped with the bibliography.

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Table 1: Lingcod commercial line, trawl, and total catches (tonnes) for British Columbia, 1927 - 1999 (King and Surry 2000).

	Line	Trawl Catch (t)			Total
Year	Catch (t)	Canada	U.S.	Total	Catch (t)
1927	--	--	--	--	2349
1928	--	--	--	--	2399
1929	--	--	--	--	2265
1930	--	--	--	--	2268
1931	--	--	--	--	2343
1932	--	--	--	--	1837
1933	--	--	--	--	1853
1934	--	--	--	--	2203
1935	--	--	--	--	2920
1936	--	--	--	--	3195
1937	--	--	--	--	1957
1938	--	--	--	--	2179
1939	--	--	--	--	2201
1940	--	--	--	--	2321
1941	--	--	--	--	1933
1942	--	--	--	--	2027
1943	--	--	--	--	2981
1944	--	--	--	--	4023
1945	3278	630	--	630	3908
1946	3070	659	--	659	3729
1947	3632	243	--	243	3875
1948	6135	451	--	451	6586
1949	6526	737	--	737	7263
1950	3851	787	--	787	4638
1951	1808	850	--	850	2658
1952	1980	507	--	507	2487
1953	1377	370	--	370	1748
1954	1874	597	652	1249	3123
1955	1525	776	1150	1926	3451
1956	1856	1115	936	2051	3907
1957	2008	985	973	1958	3966
1958	1749	961	902	1863	3612
1959	1495	1132	1730	2862	4356
1960	1659	1078	1834	2912	4571
1961	1545	1308	1772	3080	4625
1962	1761	950	1353	2303	4064
1963	1440	648	941	1589	3028
1964	1151	1280	1121	2401	3552
1965	1104	1741	1899	2641	4744
1966	1212	2000	2489	4489	5701
1967	1320	1889	2392	4280	5600
1968	1125	2920	2378	5298	6423
1969	1323	1818	1327	3145	4467
1970	1483	1439	983	2422	3905
1971	1158	1554	727	2281	3439
1972	1235	1038	504	1542	2777
1973	844	1204	567	1771	2615
1974	938	1506	820	2326	3264
1975	873	1894	836	2730	3603
1976	856	1367	828	2195	3051
1977	961	1175	357	1532	2493
1978	895	907	33	941	1836
1979	977	1159	86	1245	2222
1980	831	1315	56	1370	2202
1981	821	1739	12	1751	2572
1982	957	2878	0	2878	3834
1983	787	2992	--	2992	3779
1984	724	2971	--	2971	3695
1985	813	4853	--	4853	5666
1986	900	2925	--	2925	3825
1987	1184	2400	--	2400	3584
1988	936	2521	--	2521	3457
1989	921	3059	--	3059	3980
1990	1167	4048	--	4048	5216
1991	1171	4211	--	4211	5381
1992	1125	3248	--	3248	4373
1993	1462	3764	--	3764	5226
1994	1223	3431	--	3431	4654
1995	1097	3110	--	3110	4207
1996	688	1761	0	1761	2449
1997	756	1038	0	1038	1794
1998	876	1151	0	1151	2027
1999	1027	960	0	960	1987

Table 2: Lingcod handline-troll and longline catch (t) from International Statistical Area 4B by statistical area, 1951-1993 (see Figure 1) (Beamish et al. 1995).

	Statistical Area											
Year	12	13	14	15	16	17	18	19	20	28	29	Total
1951	23.3	397.9	88.5	46.3	99.3	357.9	253.2	32.2	17.3	1.8	0.4	1318.1
1952	11.8	440.3	83.6	73.2	169.3	438.0	235.7	28.6	25.2	7.0	0.0	1512.7
1953	5.7	345.8	84.4	46.1	166.2	289.0	179.0	38.9	28.2	4.4	0.1	1187.8
1954	16.0	437.3	157.6	21.5	244.9	362.5	169.1	33.7	13.2	4.8	1.9	1462.5
1955	6.5	330.0	84.4	64.7	243.0	338.9	112.3	44.1	8.0	0.0	0.0	1231.9
1956	17.2	564.7	96.3	60.6	235.0	396.8	106.9	44.1	2.1	1.2	0.8	1512.3
1957	7.0	542.4	82.4	107.2	288.4	364.7	96.9	54.0	2.3	0.3	0.8	1546.4
1958	16.5	497.2	105.6	79.3	229.7	350.2	93.5	73.8	4.5	0.6	0.0	1450.9
1959	16.1	338.3	86.7	31.4	167.8	345.3	85.3	104.7	0.8	0.6	15.4	1192.4
1960	24.3	337.9	110.7	47.1	173.9	378.0	97.0	82.8	23.1	1.3	3.5	1279.6
1961	32.1	393.1	92.1	45.6	183.7	285.7	64.3	63.6	29.6	7.7	2.4	1199.9
1962	160.2	412.0	114.1	60.4	139.0	241.2	57.2	76.4	19.4	8.9	4.1	1293.0
1963	68.0	301.4	63.1	30.5	159.6	250.6	44.7	63.5	20.7	0.1	0.1	1002.3
1964	36.3	289.8	43.3	18.8	170.0	191.5	53.8	52.6	21.4	0.1	0.4	878.0
1965	30.3	303.2	52.4	6.6	135.8	155.3	50.1	39.3	11.2	0.0	4.6	788.8
1966	44.4	299.5	61.7	28.7	125.7	131.4	61.2	33.0	17.6	1.1	0.0	804.3
1967	49.3	332.8	55.7	19.8	133.3	109.6	69.9	17.8	7.0	0.0	0.4	795.6
1968	50.7	273.6	54.2	22.0	104.7	157.7	53.3	14.8	10.5	0.0	0.7	769.2
1969	61.9	227.7	81.9	56.0	109.5	143.5	52.3	31.7	13.8	0.0	0.1	778.4
1970	46.4	225.5	40.8	84.7	85.7	272.1	37.4	23.7	6.5	0.0	0.6	823.4
1971	50.1	119.2	30.0	66.5	89.7	199.9	22.7	18.9	2.2	0.1	0.1	599.4
1972	39.5	152.3	25.1	43.6	81.3	129.9	19.6	38.5	2.4	0.0	0.5	532.7
1973	22.2	85.9	8.4	62.0	38.2	123.7	34.4	27.7	1.1	0.6	0.2	404.4
1974	11.2	129.6	13.3	25.2	23.3	127.6	22.2	16.7	2.9	0.0	0.3	372.3
1975	8.6	93.9	15.1	76.0	26.5	123.0	10.9	8.9	5.0	0.0	0.9	368.8
1976	10.4	96.0	12.9	74.9	17.2	82.5	13.4	9.8	7.8	5.7	0.4	331.0
1977	25.7	128.0	31.4	63.4	19.0	104.1	40.6	15.7	2.6	2.2	0.3	433.0
1978	13.8	158.0	25.3	48.3	18.4	145.3	36.1	42.2	5.7	0.2	2.0	495.3
1979	29.2	215.5	36.8	28.7	15.6	157.4	26.9	30.2	13.7	7.1	1.5	562.6
1980	14.7	131.6	14.2	25.8	6.6	103.3	23.9	23.0	5.3	4.5	0.7	353.3
1981	17.5	137.4	28.9	34.6	12.9	83.6	16.4	16.3	3.3	0.1	0.5	351.5
1982	20.1	177.8	14.9	48.0	7.7	59.6	20.3	17.5	2.1	0.5	1.1	369.6
1983	16.8	112.3	17.9	32.9	13.2	56.5	18.0	14.1	4.6	0.3	0.3	286.9
1984	18.7	65.6	7.0	4.0	5.2	46.5	30.1	13.0	2.5	0.0	0.2	192.8
1985	20.1	46.0	8.2	4.0	0.3	29.8	15.9	10.5	2.6	0.0	0.3	137.7
1986	21.0	20.2	16.0	0.5	2.4	17.2	12.9	13.7	1.8	0.0	0.5	106.2
1987	15.6	22.6	2.2	0.9	0.1	10.0	8.0	8.4	5.9	6.7	0.0	80.4
1988	43.6	12.1	2.5	0.1	0.2	7.1	4.4	8.4	2.4	1.6	1.1	83.5
1989	33.6	12.9	5.0	0.3	0.9	4.7	5.1	12.2	2.6	0.0	0.0	77.3
1990	40.3	0.0	2.3	0.0	0.0	0.1	0.0	0.1	1.3	0.3	0.0	44.4
1991	15.6	9.6	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	25.3
1992	12.1	0.5	0.3	0.1	0.0	0.0	0.3	0.0	0.2	0.0	0.0	13.4
1993	12.3	0.1	0.0	0.0	0.0	0.6	0.0	0.0	0.6	1.1	0.0	14.7

Table 3: Percent species composition (number of individuals) by depth stratum for all-gear catch at Gabriola reefs during January and February for 1987 and 1988 (Hand and Richards 1987, 1989).

	1987			1988		
	5-27 m	28-45 m	46-55 m	5-27 m	28-45 m	46-55 m
Lingcod (*Ophiodon elongatus*)	60% (27)	89% (17)	-	57% (17)	12% (2)	17% (1)
Quillback rockfish (*Sebastes maliger*)	16% (7)	5% (1)	11% (1)	3% (1)	6% (1)	-
Copper rockfish (*Sebastes caurinus*)	24% (11)	5% (1)	-	13% (4)	-	-
Yelloweye rockfish (*Sebastes ruberrimus*)	-	-	-	-	12% (2)	33% (2)
Spiny dogfish (*Squalus acanthias*)	-	-	67% (6)	20% (6)	71% (12)	50% (3)
Rock sole (*Epidopsetta bilineata*)	-	-	11% (1)	-	-	-
Speckled sandab (*Citharichthys stigmaeus*)	-	-	11% (1)	-	-	-
Kelp greenling (*Hexagrammos decagrammus*)	-	-		7% (2)	-	-

Figure 1: Major and minor statistical areas for the British Columbian groundfish trawl fishery.

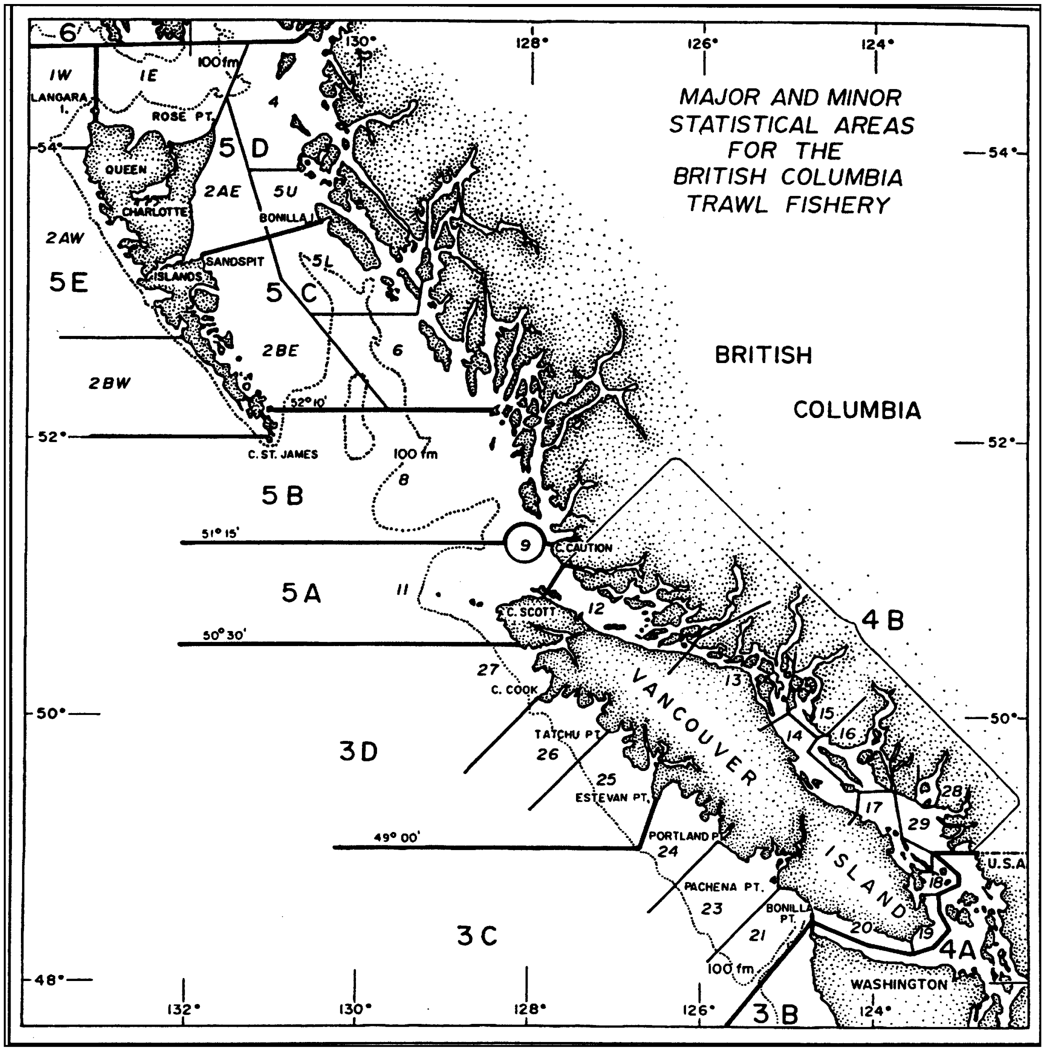

Figure 2: Recorded commercial landings of Lingcod (*Ophiodon elongatus*) off the West Coast of British Columbia and within the Strait of Georgia (MSA 12,13 and 17-19) (Cass et al. 1990).

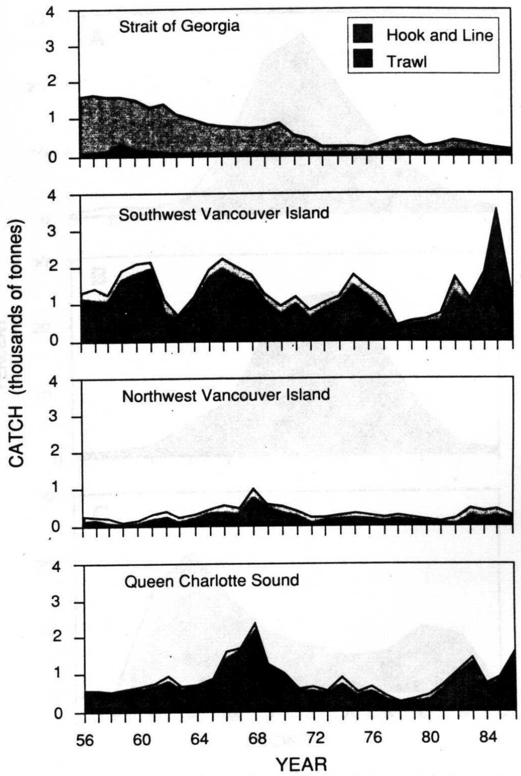

FIG. 7. Canadian catches of lingcod by area and fishing method off the west coast of Canada.

Figure 3: Commercial handline-troll landings of lingcod, showing the total landings from the Area 4B (Figure 1) and from the main areas of the fishery (MSA 13 and 17), 1951-1983 (Tyler and McFarlane 1985).