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Update to the assessment framework for the Pink and Spiny scallop (*Chlamys rubida* and *C. hastata*) dive fishery in waters off the west coast of Canada

Mise à jour du cadre d'évaluation de la pêche en plongée au pétoncle rose et au pétoncle épineux (*Chlamys rubida*, *C. hastata*) dans les eaux du large de la côte ouest du Canada

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ABSTRACT

The framework for pink and spiny scallop assessment has been updated. Scallop biomass surveys are now conducted using a remote operated vehicle (ROV) equipped with a high resolution digital still camera in place of a video drop camera. The new methodology is documented, and the results of recent surveys using the new methodology are presented. Analytical procedures for biomass estimation have been revised, resulting in updates to previously published biomass estimates. Revised estimates are lower than those previously published, with implications for existing total allowable catch. Updated estimates of natural mortality and scallop growth rates are provided, based on revised and new data since the last assessment.

Pink and spiny scallop dive fisheries remain data limited, with no consistent time series of assessment surveys or biological data. Despite new estimates of mortality and biomass, the currently used 4% harvest rate remains consistent with best available estimates of MSY. The current assessment framework, if implemented on an annual basis, will facilitate the development of provisional reference points compliant with the DFO Precautionary Approach which can then be evaluated to test for robustness to various stock size scenarios.

RÉSUMÉ

Le cadre d’évaluation de la pêche en plongée au pétoncle rose et au pétoncle épineux a été mis à jour. Les relevés de la biomasse de pétoncles sont maintenant effectués à l’aide d’un véhicule téléguidé (VTG) muni d’une caméra fixe numérique à haute résolution au lieu d’une caméra vidéo que l’on descend dans l’eau. La nouvelle méthode est documentée, et les résultats de relevés récents utilisant la nouvelle méthode sont présentés. Les procédures analytiques de l’estimation de la biomasse ont été passées en revue, entraînant des mises à jour des estimations de la biomasse précédemment publiées. Les estimations révisées sont inférieures à celles précédemment publiées, avec des répercussions sur le total autorisé des captures. Des estimations mises à jour de la mortalité naturelle et des taux de croissance des pétoncles sont fournies, en fonction des données révisées et nouvelles depuis la dernière évaluation.

Les données sur la pêche en plongée au pétoncle rose et au pétoncle épineux demeurent limitées, sans série chronologique uniforme de relevés d’évaluation ou de données biologiques. Malgré les nouvelles estimations de la mortalité et de la biomasse, le taux de prélèvement de 4 % actuellement utilisé continue de correspondre aux meilleures estimations disponibles du rendement maximal soutenu (RMS). Le cadre d’évaluation actuel, s’il est mis en œuvre annuellement, facilitera l’élaboration de points de référence provisoires conformes à l’approche de précaution du ministère des Pêches et Océans (MPO), que l'on pourra ensuite évaluer pour vérifier la robustesse par rapport à divers scénarios relatifs à la taille des stocks.

INTRODUCTION

In 2000 the unlimited commercial dive fishery for pink and spiny scallops (*Chlamys rubida* and *C. hastata*) in British Columbia (BC), Canada was converted to a limited experimental fishery to facilitate the gathering of information for scallop stocks and the development of appropriate assessment and management strategies. A review of the biology and fisheries of pink and spiny scallops was presented to the Pacific Science Advice Review Committee (PSARC) in 1999, raising concerns regarding the sustainability and viability of the fishery given the paucity of information on scallop abundance, distribution, and life history parameters, as well as the lack of biologically based management controls and reports of localized stock depletion (Lauzier and Parker 1999). In response to these concerns, a Framework for Pink and Spiny Scallop Fisheries off the West Coast of Canada was presented to PSARC in 2000 (Lauzier et al. 2000). In 2003 a subsequent paper was presented to PSARC which analyzed two years of data from the experimental scallop fisheries and provided some preliminary biological reference points as well as recommendations for the continued assessment and management of the fisheries (Lauzier et al. 2005).

Beginning in early 2009, the Department started consultations with all stakeholders to discuss converting the licensing of the scallop dive and trawl fisheries to commercial from experimental. Fisheries and Aquaculture Management (FAM) has indicated that possible expansion (through both an increase in licenses and areas fished) of the scallop fisheries may occur if the change to a commercial fishery goes ahead.

Since the Framework was developed in 2000, advances in technology and the acquisition of new equipment have provided opportunities to update the survey methodology used to assess scallop stocks. A number of additional years of biological data have been collected, providing opportunities to update and refine analysis methods and biological reference points. This, combined with the potential for expansion of the fishery, prompted another request for science advice (RFA) to document, evaluate and review the revised assessment methodology and new data. The specific issues and questions are as follows:

1. Document, evaluate and review current protocols for the collection and analysis of scallop data;
2. Do reference points and harvest control rules need to be revised as a result of the updated assessment methodology and new biological data that has been collected since 2003?
3. What continuing and/or further research activities are required to support assessment and monitoring of scallop populations in BC?

This paper has been prepared in response to the RFA (Appendix A). We first summarize the existing framework along with the necessary background. We then document the revised survey methodology and analytical procedures which include revisions to previously published biomass estimates. Lastly, based on revised and new data since Lauzier et al. (2005) we provide updated population parameter estimates along with a recommended harvest rate.

EXISTING ASSESSMENT AND MANAGEMENT FRAMEWORK

The Framework for Pink and Spiny Scallop Fisheries in Waters off the West Coast of Canada was presented to PSARC in 2000 by Lauzier et al. (2000). The scallop framework included many of the recommendations provided by Perry et al. (1999) in their framework for providing scientific advice for the management of new and developing invertebrate fisheries. A subsequent document presented in 2003 (Lauzier et al. 2005) described progress in implementing the scallop framework and included a number of additions and updates.

The scallop assessment and management framework includes the following key requirements for the precautionary management of pink and spiny scallop dive fisheries:

1. **Redevelopment of the scallop dive fishery is to follow a phased, precautionary approach** as described in the framework for providing scientific advice for the management of new and developing invertebrate fisheries, with management options consisting of size limits, effort regulation, and total allowable catches (TACs) (Perry et al. 1999).
2. **Stakeholders are responsible for demonstrating the potential for fishery expansion** by participating and investing in collaborative research, including routine surveys that are used to provide advice for TAC management; for the harvest to be increased, further stock production must be demonstrated either by exploration into new areas or refined estimates of productivity (Perry et al. 1999).
3. **Assessment areas must be defined:**
    a. Each distinct aggregation of scallops must be assessed as a separate stock until sufficient data is obtained to delineate the degree of exchange or dispersal between scallop aggregations; historically exploited aggregations or patches that are in close proximity should be grouped into “beds” with these beds serving initially as the basic assessment and management unit (Lauzier et al. 2000) (Figure 1).
    b. Scallop populations, like many marine invertebrates, are assumed to be metapopulations – i.e. systems of populations that interact by dispersing individuals between populations; as more information is collected, assessment and management areas should be developed based on the distribution and interaction of metapopulations (Lauzier et al. 2005).

4. **The primary assessment tool is initially to be abundance trends from fishery-dependant data and from fishery independent surveys:**
    c. <u>Fishery dependant data</u>: All removals must be included in the assessment; geo-referenced harvest locations should be part of the data requirements (Lauzier et al. 2000).
    d. <u>Fishery independent surveys</u>: Scallop biomass and abundance to be determined as the product of density per unit of habitat and total habitat area (Lauzier et al. 2005):
        i. <u>Density per unit of habitat</u>: SCUBA dive surveys to determine scallop density using randomly selected 0.25 m^2 quadrats, with all scallops having at least half their body within the quadrat frame to be counted; all sampled scallops will be picked and placed in labelled mesh bags and retained for counting and biological sampling; (Lauzier et al. 2000). Survey sample size to be augmented using a video drop camera, with counts from video quadrats to be converted into legal biomass using data from the SCUBA quadrats to determine a relationship between total count and legal biomass (Lauzier et al. 2005).
        ii. <u>Total habitat area</u>: Habitat area to be defined as estimated bed size; bed size to be estimated based on consideration of fisher harvest logs and appropriate bathymetry after Hand et al. (1998); habitat data such as substrate, depth and current to be collected and analysed (Lauzier et al. 2000).

5. **Biological reference points are to be developed**:
    e. Biological sampling is to be conducted on scallop samples obtained through dive surveys as well as additional samples provided by industry to facilitate the development of estimates of growth rates, age structure of the population, mortality and recruitment (Lauzier et al. 2000).
    f. Gulland's model (Gulland 1971) is to be used as a preliminary means of estimating maximum sustainable yield (Lauzier et al. 2000). More sophisticated modelling techniques are to be developed as more data is collected. In particular, Gulland's model will be used initially to set a harvest rate as a percentage of the estimated biomass.
6. **Control (unharvested) populations are to be monitored** along with harvested populations to provide a baseline for environmental effects on scallop populations as well as to provide estimates of biological parameters for unfished populations (Lauzier et al. 2000).

BACKGROUND

DISTRIBUTION AND BIOLOGY

Pink and spiny scallops ("swimming scallops"), *Chlamys rubida* and *C. hastata* are two of 23 scallop species found in BC, and are the only scallop species to occur in sufficient abundance to have supported successful commercial fisheries in BC waters (Bourne 1987). They are smaller than other scallop species, rarely exceeding a maximum shell height of 70 mm and 80 mm, respectively, measured perpendicular to the hinge (Figure 2a, Bourne and Harbo 1987), and as such, are marketed whole, in the shell, fresh or frozen.

Pink and spiny scallops are distributed discontinuously throughout BC in small discrete beds at depths from 1 – 200 m (Bernard 1983). Scallop beds are generally located on reefs, pinnacles, and in some cases on flats and shoals, with some aggregations within close proximity of each other (within 10 km) and others in relative isolation (Lauzier et al. 2000). The distribution of scallop aggregations in BC is known only anecdotally and from commercial fishing logs and the true distribution may vary widely from what is currently known. The distribution of the two species overlaps, and a single scallop aggregation or bed often contains both species. In general pink scallops tend to be found on softer substrates than spiny scallops, and have a broader depth distribution, extending to 200 m, compared to 150 m for spiny scallops (Bernard 1983). There have been no detailed studies of natural populations of pink and spiny scallops in BC, and the degree of exchange or dispersal between and among discrete aggregations of scallops is unknown.

Pink and spiny scallops can be distinguished by the appearance of the shell, with pink scallops having numerous fine smooth ridges and spiny scallops having prominent spiny ridges (Figure 2a). However, live scallops are frequently encrusted on both valves by one of two sponges, *Myxilla incrustans* or *Mycale adhaerens* (Figure 2b), with which they share a mutualistic relationship (Bloom 1975; Burns and Bingham 2002; Farren and Donovan 2007). Sponge encrustation makes it virtually impossible to distinguish the species without first removing the sponge from the shell.

Sexes are separate with spawning occurring in March/April and September/October for pink scallops and in July/August for spiny scallops (MacDonald et al. 1991). Larvae are pelagic, with settlement reported for spiny scallops within 5 – 6 weeks in a laboratory setting (Cooke 1986, Hodgson and Burke 1988). Both species are sexually mature at 25-35 mm shell height or two years old (Bourne and Harbo 1987). Pink scallops grow more slowly than spiny scallops and achieve a smaller maximum shell height. Both species are 3 – 4 years old when they reach a shell height of 55 mm, the minimum legal size for the scallop dive fishery, and therefore will spawn at least twice prior to capture. While pink scallops have less shell height at age than spiny scallops after age 3, for any age they have a greater body thickness at a given shell height in comparison to spiny scallops (Lauzier et al. 2005). Maximum age for both species is six years (Bourne and Harbo 1987, MacDonald et al. 1991). However, Lauzier et al. (2000) reported a small number of 7 – 8 year old scallops, although this has not been verified. For both species, reproductive output increases with age, with annual gamete production steadily increasing in spiny scallops, exceeding somatic production after 5 years, while for pink scallops annual gamete production reaches an asymptotic maximum after 4 years and never exceeds somatic production (MacDonald et al. 1991).

ECOSYSTEM CONSIDERATIONS

Bycatch concerns

Bycatch of sublegal scallops in the pink and spiny scallop dive fishery is assumed to be nil, as divers select only the legal sized individuals. Bycatch of other species is limited to the epibionts that are encrusted on scallop valves. Most scallops carry one of the sponges *Myxilla incrustans* or *Mycale adhaerens (Bloom 1975, Burns and Bingham 2002)* . A small number of scallops carry barnacles (*Balanus sp*.) (Farren and Donovan 2007) and, less frequently, other sessile marine invertebrates.

Benthic impacts

Benthic impacts from the pink and spiny scallop dive fishery are thought to be negligible, as catch is by hand picking only.

Physical components

Habitat: Suitable habitat for pink and spiny scallops is generally hard substrate and consists of reefs and pinnacles and associated flats and shoals at depths from 1 – 200 m (Bernard 1983, Lauzier et al. 2000).

Water properties: Scallop larvae are pelagic and horizontal dispersal is therefore determined by water currents. However, the degree of exchange or dispersal between and among discrete aggregations of scallops is unknown. Water temperature is known to influence bivalve reproduction, including effects on gonad development and timing of spawning (Barber and Blake 2006). In addition, water temperature is known to influence feeding activity (MacDonald et al. 2006). Scallops are also sensitive to dissolved oxygen concentrations and levels of suspended sediment (Stewart and Arnold 1994).

Species interactions

Predator/prey interactions: Scallops are suspension feeders, feeding on single celled algae. As larvae, scallops are assumed to be vulnerable to predation from larger zooplankton and planktivorous fish. Predators of adult pink and spiny scallops are known to include sea stars, as well as octopus (Gillespie et al. 1998b) and sea otters (Wolt, C.M. unpublished data). Large fluctuations in scallop abundance would likely affect the abundance and foraging strategy of their predators as well as the structure of the benthic food web.

Mutualistic relationships: Live scallops are frequently encrusted on both valves by one of two sponges, *Myxilla incrustans* or *Mycale adhaerens* (Figure 2b), with which they share a mutualistic relationship: the sponges provide some protection for scallops from predation by sea stars (Bloom 1975, Farren and Donovan 2007), while living on scallop valves increases sponge survival by providing protection from predators such as dorid nudibranchs (Bloom 1975) and by reducing the effects of sediment accumulation (Burns and Bingham 2002).

Biotoxins: Since scallops are filter feeders they may ingest algae that are harmful to humans (e.g. “red tide”). Some algae are also toxic to scallops, and may cause hatching failure, reduced feeding activity, inhibited growth, or even death (MacDonald et al. 2006).

Possible effects of human activities

Ocean dumping: Ocean dumping may affect scallop populations by burial, increasing suspended sediment, reducing oxygen content of the water, and by exposing scallops to toxic compounds (Stewart and Arnold 1994).

Pollution: Scallops are susceptible to pollution such as heavy metals, hydrocarbons, PCBs, pesticides and sewage. Effects include kidney damage, reproductive failure, reduction or cessation of feeding activity, and death (Steward and Arnold 1994). In addition, scallops exposed to such pollutants may accumulate toxins and become themselves toxic to humans.

COMMERCIAL FISHERY (1982 – 1999)

Pink and spiny scallops have been fished commercially in BC by both dive and trawl since 1982. From1986 - 1999, fishing occurred exclusively in inshore waters of the Strait of Georgia, with the dive fishery landing about 85% of the total catch. During this time period, catches in the dive fishery ranged from approximately 35 – 95 tonnes annually, reaching a maximum of 95 t in 1996 (Table 1, Figure 3). The average price per kg increased steadily throughout the fishery, ranging from $2.78/kg ($1.26/lb) in 1984, to $5.67/kg ($2.57/lb) in 1999. The scallop dive fishery was worth on average approximately $300,000 per year, reaching a maximum of $495,000 in 1996 (Table 1, Figure 3). Historically, both the dive and trawl scallop fisheries were unlimited entry (i.e. there was no limit to the maximum number of licenses), but had a relatively low participation rate. Management controls consisted of seasonal and area closures as well as a size limit specifying a minimum shell height of 55 mm, measured perpendicular to the hinge. Little biological information was available, and the two species were managed as a single population.

EXPERIMENTAL / EXPLORATORY FISHERY (2000 – 2010)

Following the closure of the unlimited commercial dive fishery for scallops at the end of 1999, scientific licenses were issued for an experimental fishery to conduct research surveys, collect biological data, test management strategies, and develop commercial markets for scallops. Starting in 2003, scientific licenses were issued for the period August 1 – July 31, rather than for a calendar year, to allow participants time to obtain new licenses during the relatively unproductive part of the year (L. Barton Fisheries and Oceans Canada, 3190 Hammond Bay Road, Nanaimo, BC V9T 6N7, personal communication). In August 2007, because of concerns regarding the use of scientific licences for this fishery, scientific licenses were replaced by non-transferable exploratory licences. Beginning in early 2009, the Department started consultations with all stakeholders to discuss the possibility of converting to commercial licences.

Landings from the experimental/exploratory dive fishery have declined from approximately 50 t per year in 2001 – 2004 to less than 10 t per year in 2006 – 2010 (Table 2, Figure 3). The number of participants with landings has decreased from 10 in 2000 to less than three per year since 2007, with only one license holder per year making landings in 2008/09 and 2009/10 (Table 2, Figure 3). As landings have declined, the value of the fishery has also declined from $277,000 per year in 2000 to less than $60,000 per year since 2006, although the average price per kg has remained steady at around $1.27/kg ($2.80/lb). For reasons of confidentiality, some catch statistics can not be presented due to the low number of participants in the fishery. Catch rates have remained fairly constant for the duration of the experimental / exploratory fishery, with an average of 60 kg per hour of dive time (SD = 6.4 kg/h).

MANAGEMENT ACTIONS

Management actions for pink and spiny scallop commercial and experimental / exploratory fisheries are summarized in Appendix B.

Size Limits

In 1982 a minimum size limit of 60 mm shell height measured perpendicular to the hinge (Figure 2) was implemented for pink and spiny scallop fisheries to ensure sufficient spawning opportunities for scallop populations (Bourne 1984). In 1989, at the request of stakeholders and after a limited survey and market sampling, the minimum size limit was reduced to 55 mm for both the dive and trawl fisheries (Bourne and Harbo 1997, Wylie 2006). In 2001, the minimum size limit for scallop trawl fisheries was reduced to 48 mm based on the rationale that the trawl fishery targets the predominantly smaller pink scallop (E. Wylie, Fisheries and Oceans Canada, Resource Management, Nanaimo, BC, unpublished report, 2001). The minimum size limit for scallop dive fisheries remains at 55 mm shell height.

Seasonal and Area Closures

Pink and spiny scallop fisheries were open year round in approved shellfish growing waters for the duration of the commercial fishery, subject to closures due to coliform bacterial contamination, paralytic shellfish poison (PSP, red tide), or amnesic shellfish poison (ASP, domoic acid). There were numerous small area closures in park and study areas. In 1993 a number of subareas in Pacific Fishery Management Areas (PFMAs) 17, 18, 19, and 29 were closed to the scallop trawl fishery at the request of dive stakeholders, to protect the diveable habitat from perceived habitat damage and discard mortality of the trawl fishery (Wylie 2006). In 1998, a portion of subarea 29-5 was closed to all commercial scallop fishing due to reports by stakeholders of localized depletion (Lauzier and Parker 1999). In addition, the scallop trawl fishery is limited to depths greater than 20 m below chart datum to provide some separation of fishing effort between the scallop dive and trawl sectors (DFO 2004).

In 2000, the experimental dive fishery was open year round with the exception of biotoxin closures, and was limited to PFMAs 13 – 20 (Wylie 2006). A small number of experimental dive licences were restricted to PFMAs 13 and 20 because they did not meet license eligibility requirements (see below).

Effort Limitation

Historically, the pink and spiny scallop commercial dive and trawl fisheries were unlimited entry (i.e. there was no limit to the maximum number of licenses). In 2000, both scallop dive and trawl experimental fisheries were unlimited entry (Wylie 2006). Twelve scientific licenses were issued for the pink and spiny scallop dive experimental fishery.

Following the first year of the experimental fishery, dive stakeholders recommended that their scientific licence be limited subject to eligibility criteria which were developed in consultation with stakeholders (Lauzier et al. 2005, Wyllie 2006). To qualify, interested persons were required to have a minimum of 4,500 kg (10,000 lbs) of landings of scallops between 1995 and 1999, or 2,700 kg (6,000 lbs) in any one of those years. Seven scientific licenses were approved to harvest scallops in PFMAs 13 – 20. An additional three scientific licenses were issued for limited areas (PFMAs 13 and 20 only) to fishers who did not meet the eligibility requirements but who had participated in the first year of the experimental fishery.

Total Allowable Catch (TAC)

There were no catch limits for pink and spiny scallop commercial fisheries in 1982 - 1999. Beginning in 2001, the trawl experimental fishery was subject to a hail program and was allocated a total allowable catch (TAC) based on the results of biomass surveys (Wylie 2006). For the dive experimental fishery, the results of biomass surveys in 2001 – 2002 were used to establish informal catch ceilings, with catches monitored through logbooks and sales slip records (Ray Lauzier, Fisheries and Oceans Canada, 3190 Hammond Bay Road, Nanaimo, BC V9T 6N7, personal communication). Both trawl and dive experimental licences required license holders to be willing to participate in surveys and sampling activities (Wyllie 2006).

Beginning in 2006, the dive experimental fishery was subject to a hail program similar to that required for the trawl fishery and only areas scheduled for industry funded biomass surveys were open to fishing subject to a TAC (DFO 2006a). Lacking any recent biomass information, initial TACs in 2006/07 were based on the landings for the previous calendar year (2005) in PFMAs 18-1 and 29-5 (Table 3). No biomass surveys were conducted during 2006/07.

For 2007/08, scallop biomass surveys were required before areas would open for the dive exploratory fishery; a small quota was allocated to PFMA 29-5 to start the year (DFO 2007) (Table 3). This quota was issued subject to the condition that stakeholders commit to conducting a biomass survey in that area prior to March 31, 2008, with the intention that the TAC would be adjusted in-season based on survey results (DFO 2007). A scallop biomass survey funded by DFO through the Larocque program was conducted in March 2008, meeting the imposed deadline but too late for survey results to be available prior to the end of the license year.

Following 2007/08, scallop dive exploratory license holders were only permitted to fish in areas where biologically-based TACs were estimated (Table 3). Once a biomass survey had occurred, a TAC based on the survey results was allocated for the surveyed beds for the following license year (August 1 – July 31), although the TAC could be adjusted in-season if a new survey occurred. Managers can carry over unused TAC into the new license year if the landings are low and a high percentage of quota is remaining (DFO 2008, 2009, and 2010). This carry-over provision is limited to one year because scallops are short-lived species. In this way TACs were allocated to the dive exploratory fishery in PFMA 29-5 in 2008/09 and 2009/10 based on the March 2008 survey, and in 2010/11 based on an October 2009 survey. TACs were allocated in PFMA 18-1 in 2009/10 and 2010/11 based on a March 2009 survey.

METHODS

DATA SOURCES

A total of nine fishery independent scallop SCUBA dive / video and SCUBA dive / ROV surveys were conducted from 2000 to 2002 and 2008 to 2009. Survey data were used for biomass estimation and estimation of population parameters such as age, growth and mortality. In addition, eight biological samples were provided by the scallop dive industry in partnership with DFO in 2000 – 2001 in order to provide initial biological information about scallop stocks. Biological and survey data are stored in the ScallopDiveBio database maintained by the Shellfish Data Unit (Fisheries and Oceans Canada, 3190 Hammond Bay Road, Nanaimo, BC V9T 6N7).

BIOMASS SURVEYS

Background

The goal of scallop biomass surveys is to estimate the total biomass of pink and spiny scallops on specific harvestable scallop beds. A range of total allowable catch (TAC) values are presented to the fishery manager based on applying a harvest rate to the estimated legal sized (≥55 mm) biomass and associated confidence intervals. The TAC is expressed as total legal biomass because scallop landings from the dive fishery are reported as the combined weight of legal sized pink and spiny scallops.

Scallop biomass surveys have been conducted in collaboration with stakeholders at Okisollo Channel (PFMA 13-8,13-10, 13-12), Sentry Shoal (PFMA 14-13), Gabriola Island / NE Valdes Island (PFMA 17-10), Mayne Island (PFMA 18-1) and Valdes Island (PFMA 29-5) (Figure 1).

Six surveys were completed in 2001 – 2002, with Mayne Island and Valdes Island surveyed in 2001, and Okisollo Channel, Sentry Shoal, Gabriola Island, and Valdes Island surveyed in 2002. The surveys followed the dive/video survey protocols as described in the scallop assessment and management framework and survey results are presented by Lauzier et al. (2005). Scallop biomass is presented as the combined biomass of pink and spiny scallops because video and photo methods preclude distinguishing the species due to the encrusting sponge on the shell. No biomass surveys were completed in 2003 – 2007.

Starting in 2006, staff at the Pacific Biological Station (PBS) began using a Deep Ocean Engineering Phantom HD2+2 Remote Operated Vehicle (ROV) deployed from Canadian Coast Guard (CCG) research vessels for a variety of underwater surveys. In 2008, the Shellfish Section at PBS acquired a digital still camera that could be mounted on the ROV. Three scallop biomass surveys have been conducted following the same survey protocol as the 2001 – 2002 surveys but using the ROV/still-camera system instead of the video drop camera. Surveys took place in 2008 and 2009 at Valdes Island and in 2009 at Mayne Island with the participation of scallop dive stakeholders (Figure 4). These new surveys have provided opportunities to update and refine the survey protocol, biomass estimation methods, and estimates of population parameters.

The new method of collecting abundance data for scallop biomass surveys using the ROV as well as updated methods for biomass estimation are documented here. Results of the three new surveys are also reported, along with a review of previous survey results using updated estimation methods.

Site Selection

Mayne Island and Valdes Island were chosen for scallop surveys in 2008 – 2009 because both sites had been previously surveyed in 2001 – 2002 and both were identified by stakeholders as being of interest for continued fishing opportunities. Mayne Island was surveyed in March 2009 while Valdes Island was surveyed in March 2008 and October 2009. Lauzier et al. (2005) consulted with stakeholders and examined commercial fishing logs to determine the likely distribution of scallops, and identified two reefs off Mayne Island at Georgina Shoal and Edith Point (Figure 4a) and four reefs off Valdes Island between Detwiller Point and Porlier Pass (Figure 4b). Survey transects for each survey were randomly located on these reefs.

Vessels and Staffing

The ROV was deployed from the research vessels *CCGS Vector* (2008 survey) and *CCGS Neocaligus* (2009 surveys). The *CCGS Vector* is a 39.74 m hydrographic survey vessel while the *CCGS Neocaligus* is a 18.8 m nearshore fishery research vessel. Both vessels are equipped with the necessary winches and electronics for deploying the ROV and both are capable of working in relatively shallow, nearshore water as required for scallop dive/ROV surveys. ROV surveys carried at least three DFO staff consisting of a pilot, a navigator, and survey biologist. Vessel crew assisted with the deployment and retrieval of the ROV.

SCUBA dive surveys were conducted by the Pacific Scallop Harvesters Association (PSHA) with funding from DFO. Surveys were conducted from the commercial dive boats the *F/V SEA DUCER* (2008 survey) and the *F/V DEVILFISH* (2009 surveys). For each survey four divers were required, consisting of three scallop industry divers and one independent third-party dive biologist contracted by the Pacific Scallop Harvesters Association (PSHA) to conduct the survey. Industry divers provided the necessary expertise in diving for scallops while the third-party biologist ensured proper adherence to survey protocols and managed the data and biological sample collection.

Transect and Quadrat Locations

ROV transects were determined prior to each survey. For the surveys in March 2008 at Valdes Island and March 2009 at Mayne Island, the first ROV transect location for each reef was determined by picking a random start location and proceeding in a direction perpendicular to the depth contours. Subsequent transects on each reef were chosen systematically and were approximately 0.1 – 0.2 n. mi apart. For the survey in October 2009 at Valdes Island, the ROV transect locations were determined by picking random start and end locations for each transect on the outer margins of the reefs. For all three surveys the number of transects completed was the maximum possible based on sea and weather conditions and available daylight. ROV "quadrats" are the photographs taken by the digital still camera. At the beginning of each transect the still camera was set up to take photos every 15 – 30 seconds depending on the length of the transect and the amount of space available on the camera memory card. The distance between photo locations was approximately 3 – 10 m for most transects, depending on currents and ROV speed.

SCUBA dive transect locations were selected by the industry divers participating in the SCUBA portion of the survey. Due to the depth of the survey locations, divers were limited to two dives of 30 minutes each per day per diver. Industry divers selected dive locations that they felt would yield large catches of scallops. SCUBA transects did not need to be randomly located, as the purpose of the SCUBA portion of the survey was to collect biological samples to provide scallop species and size composition data to apply to the ROV data. For the October 2009 survey, to ensure that the biological samples would be representative of the scallop population on the different reefs, divers were directed to select locations on each reef to be surveyed rather than concentrate their effort in a single preferred location.

For each survey, divers were required to swim side-by-side in teams of two facing into the current to avoid "herding" scallops along the transect. Each diver placed a 0.25 m^2 (0.50 x 0.50 m) quadrat frame six times, for a total of 12 quadrats per transect. Upon reaching the designated start location, divers swam 3 – 5 m before placing the first two quadrats side by side. The next quadrat was placed approximately 1 – 1.5 m away, with distance measured and a straight line maintained by placing the quadrat frames alternately a predetermined number of times.

All scallops within the quadrat frame were collected and placed in mesh bags for further processing. Each bag was labelled with transect number, quadrat number, and depth of the quadrat. Samples were retained by the third-party biologist, frozen, and returned to PBS for further processing. GPS location of the transect was recorded at the water surface. The substrate for each transect was classified and recorded by the divers according to standard substrate classifications as utilized by the Shellfish Section at PBS (Appendix C).

Biological Samples

Frozen samples were defrosted in the laboratory at PBS and cleaned of all encrusting sponge and other epibionts. For each quadrat, the total weight of cleaned legal and sublegal scallops by species was recorded. Cleaned scallops were retained for further processing for individual shell height and thickness, weight, sex, and age.

ROV Setup, Deployment, and Navigation

A Cyclops digital still-camera (C-Map Systems, Inc.) was mounted on the ROV for the duration of the ROV surveys, oriented with a viewing angle perpendicular to the substrate. Two underwater red lasers located within the camera housing were set up to provide a 10 cm reference scale in the centre of each image, while a third red laser in the camera housing provided an indication of distance from the substrate (to indicate distances greater or less than approximately 1 m). A video camera was also mounted on the ROV for the duration of the survey. While running transects, the video camera was oriented at approximately 45 degrees to the substrate, looking forward and down. Video was recorded continually; however, the main purpose of the video during the scallop surveys was to provide the ROV pilot with a visual aid to assist with navigation. Lighting for video and navigation purposes was provided by a variety of LED lights, halogen lights, and an arclight. A number of floats and small weights were attached to the ROV frame to achieve neutral buoyancy and a horizontal orientation. Exact configuration of lights, weights, and floatation differed for each survey. Lighting for the digital still images relied on the Cyclops camera's integral 200 wattsec external flash.

The ROV was deployed on the starboard side of the vessel. A 170 lb clump weight was deployed on most ROV dives using a separate steel hydrographic cable, twinned with the ROV umbilical. The ROV was tethered about 10 – 20 m from the clump weight depending on water depth. The clump weight relieves the ROV of the drag caused by current acting on the umbilical cable between the surface and the working depth, allowing the pilot greater control. Transponders were mounted on the clump weight wire and ROV frame, and a hydrophone was deployed on the port side of the vessel to detect signals from the transponders for tracking the ROV and clump weight positions relative to the ship.

A GPS was used to give the ship's position to near 1 meter accuracy and the ship's Gyrocompass or the GPS compass was used for heading information. Hypack hydrographic software (Hypack Inc.) and the Trackpoint 3 acoustic tracking system (ORE Offshore) were used both to navigate along the predetermined transects and to track the vessel, ROV, and clump weight. The ROV and ship position data were recorded in computer data files by Hypack, and the ship position was encoded in the audio track of the video recording.

ROV Still-Camera Setup

The Cyclops digital still-camera camera was controlled through the ROV umbilical cable using proprietary C-map Cyclops Controller interface software and set to take pictures every 15 – 30 seconds. Where possible, image resolution was set to 8 megapixels (3264 x 2448, normal quality jpg compression). However, the software limited the maximum number of images that could be stored on the camera to approximately 500 images. Due to the time required to download images (approximately 100 images per hour), resolution was set to 2 or 4 megapixels when necessary to conserve memory space on the camera. Because of the variable and unpredictable visibility in the photos (due to water quality, distance from substrate, light levels, scallop density) the highest resolution possible is desirable to preserve the ability to zoom images to distinguish details.

Images were periodically downloaded using the C-map software either through the ROV umbilical, or wirelessly using a USB antenna / receiver (October 2009 only). The C-map software replaced the default filename for each image with a new name consisting of the date and time. In addition, for the 2009 surveys the date and time was encoded by the camera directly into the internal metadata (EXIF data) for each image file.

Position Data

Following each survey, position data were reviewed in Hypack. Deviations of the course from a perfectly smooth, straight line are expected due to both tracking imprecision and the difficulty in piloting the ROV in a straight line. Tracking imprecision varies from less than a meter to many meters due to factors such as depth, bottom type, and surface conditions. The ability of the ROV to travel in a straight line depends on the precision of the tracking system, and factors such as weather, currents, visibility, and bottom type as well as the combined skill of the pilot, vessel skipper, and deck crew. Prior to using the tracking data for image georeferencing, it often needs to be edited to better reflect the actual path of the ROV. Editing is a two step process that consists of manually removing obviously incorrect positions, followed by smoothing performed by the software. The smoothing level can be adjusted to remove errors created by the tracking system without removing actual ROV course changes. If there is any doubt about whether the edited track line reflects the actual path of the ROV, the video can be reviewed to see if the behaviour of the ROV matches the course changes seen in the edited track lines. Reviewed (and edited, if necessary) track lines for each survey were exported from Hypack and saved as comma-delimited (CSV) and GPS eXchange Format (GPX) files.

Image Georeferencing

The free, open-source Perl library ExifTool was used to read, manipulate, and extract EXIF data from the photos. The free, open source software GPicSync (http://sourceforge.net/projects/gpicsync/files/ downloaded on January 15, 2009) was used to insert the correct latitude, longitude, and depth into the EXIF data of each photo, by matching the embedded time stamp for the photo with the time in the position data. For photos in 2008 that had the time stamp in the filename only, a Perl script was written to extract the date and time information from the filename and embed it in the EXIF data (Appendix D) so that the photos could be processed by GPicSync. A Perl script was written to export the filename, date, time, and georeferencing information to a CSV file that could be imported into a database (Appendix D).

Image Processing

Following each survey, photos were examined using image processing software. The criteria for selecting suitable software were that it be either already available or easily obtainable, that it be capable of handling large file sizes, and that it provide the ability to annotate and measure objects in the images. PhotoShop CS4 Professional was the preferred software, but ArcView 3.2 was also utilized successfully. A number of other software packages were deemed unsuitable due to file handling capabilities or high cost.

Each photo was treated as a quadrat. Quadrat size was determined by measuring the reference scale provided by the red lasers and calculating the area of the photo:

$$a = r\left(\frac{s}{l}\right)^2$$

where:

a = area of photo (m^2)
r = photo resolution in pixels
s = reference scale provided by lasers, usually 0.1 m (10 cm)
l = length of reference scale as measured in the image in pixels

Previous scallop video surveys using the video drop camera had a 0.25 m^2 quadrat frame mounted to the camera frame so that it was visible in the video.

Image quality was recorded as unusable, poor, moderate, good, or high quality, with approximately 90% (or more) of the images usable. Unusable images were those where scallops could not easily be distinguished, or where the size of the field of view could not be estimated. The following types of images were excluded from the analysis:

- Images too close to the substrate (calculated image size < 0.25 m^2);
- Images where scallops can not be easily distinguished from substrate features, because of distance from substrate, water clarity, or obstructions in the field of view;
- Images where substrate slopes steeply or where relief changes suddenly;
- Blurred images due to the ROV moving too quickly.

In the same way as for the SCUBA quadrats, all scallops within each image (quadrat), as well as those with at least half their body within the image were counted. Scallops were not identified to species, because sponge encrustation makes it virtually impossible to distinguish the species without first cleaning the shell. The substrate was classified according to standard substrate classifications as utilized by the Shellfish Section at PBS (Appendix C). Where time permitted, all fish and invertebrates observed within the image were identified to the lowest taxonomic level possible and recorded.

Biomass estimation

To estimate scallop biomass for each survey, a relationship is derived between the biomass and number of scallops per SCUBA quadrat, and that relationship is then applied to the number of scallops counted per ROV quadrat. All quadrats are standardized to the same size, generally 0.25 m^2 for consistency with previous surveys. Lauzier et al. (2005) found that the best fit for this relationship was a linear regression of the log-transformed biomass and log-transformed total count. Logarithmic transformations are well accepted for linear regressions involving biological size or weight data, due to the multiplicative nature of growth models (eg. Bolker 2008, Zar 1999). The original regression model was implemented in S-Plus, but the model has been updated to run in R 2.10.0 (Appendix E). The relationship between biomass (*B*) and number of scallops or population size (*P*) in a standardized quadrat is defined as follows:

$$B = e^{x_0 + x_1 \ln P + \varepsilon}$$

$$\varepsilon \sim N\left(0, \sigma^2\right)$$

where for some standard quadrat size,

B = Biomass, or weight in grams
P = Population size, or number of scallops counted
x_0 and x_1 are the regression coefficients to be estimated for each survey
ε is a normally distributed error term with mean 0 and variance σ^2

Once the regression coefficients have been estimated, they are used to estimate biomass from the counts in each ROV quadrat. When using the regression model derived from the SCUBA data to estimate mean biomass from the ROV data, an additional term is required to correct the bias introduced by the back-transformation and is equivalent to the back-transformed error term from the original model (Newman 1993). The mean biomass ($\overline{B}$) per quadrat is then given by the following:

$$\overline{B} = \frac{1}{n}\left(\sum_i^n e^{x_0 + x_1 \ln P_i}\right) e^{\sigma^2/2}$$

where for some standard quadrat size,

n is the number of surveyed quadrats
i is an index for the surveyed quadrats
$e^{\sigma^2/2}$ is the estimate of bias from the back-transformation.

Non parametric bootstrapping was used to calculate confidence intervals for $\overline{B}$ following the percentile or naïve method (Davison and Hinkley 1997). Both the SCUBA data and the ROV data are resampled for the boostrap.

Lauzier et al. (2005) stated that the regression model estimated legal biomass (i.e. the weight of scallops with greater than 55 mm shell height). In the original model, zeros in the legal biomass, which arise when all the scallops in a quadrat are sublegal, were replaced by the arbitrary value of 50 g so that logs could be taken. However, upon close examination of the original S-Plus code used to run the model, it was determined that the model was in fact estimating total biomass, likely due to a coding error or misinterpretation of database field names. Furthermore, instead of replacing the zeros with the arbitrary value of 50 g, the code replaced all legal weights that were less than 50 g, thereby artificially inflating the legal biomass. Therefore, the legal biomass estimates reported for 2001 – 2002 surveys (Lauzier et al. 2005), as well as those utilized for recommending TACs based on survey results from 2008 – 2009, were over estimates.

In preparing this update to the scallop by dive assessment framework, biomass estimates for all the dive/video and dive/ROV surveys conducted to date have been revised. Three types of biomass estimates were evaluated. Total biomass was calculated using the log-transformed regression model. Legal biomass was calculated directly, using the log-transformed regression model, and indirectly using a ratio estimator. For the log-transformation of legal biomass, a constant (1) was added to all the biomass values and then subtracted in the back-transformation (Zar 1999). The ratio estimator, equivalent to the ratio between legal and total biomass from the SCUBA samples, was estimated using linear regression through the origin (Thompson 1992).

To obtain an estimate of total legal biomass for the scallop bed, estimated mean scallop biomass per quadrat (0.25 m^2) is multiplied by the total area of the scallop bed. Lauzier et al. (2005) used bed areas that were a combination of a digitization of historical fishing areas from logbook records and the area of depth contours that were between 10 m and 30 m. However, ROV photos and video provide georeferenced information about scallop distribution and habitat, and detailed multi-beam bathymetry information is now available from Natural Resources Canada (NRCAN) for many areas of the Strait of Georgia. Therefore scallop bed areas may be redefined based on actual distribution and habitat type.

For Mayne Island in 2009 the boundaries of the scallop bed were redrawn prior to the survey to be consistent with the 10 m and 30 m contours. In addition, industry divers requested that an additional transect be added beyond the northern boundary of the previously defined scallop bed. Therefore the bed area for Mayne Island was increased for that year. The new bed area for Mayne Island is 158.1 ha (42% increase) as measured in ArcGIS 9.2, compared to the previous area of 111.2 ha, and applies only to the 2009 survey (Figure 4a).

At Valdes Island, prior to the preparation of this paper and for consistency with previous results, recent surveys continued to use the bed area as originally defined by Lauzier et al. (2005). However, survey transects have been concentrated on only a few sites (reefs) within the bed and some portions of the bed have never been surveyed. Moreover, some of the unsurveyed areas are suspected to be unsuitable habitat for scallops, such that the bed area for Valdes Island is overestimated. For this reason, new area estimates are provided for Valdes Island and revised biomass estimates will therefore be provided for both the original and revised bed area.

The new bed area for Valdes Island is 133.6 ha (54% reduction), as measured in ArcGis 9.2, compared to the previous area of 289.3 ha, and applies to all the surveys that have been conducted at Valdes Island (2001, 2002, 2008, 2009) (Figure 4b).

POPULATION PARAMETERS

Background

One of the goals of the Assessment and Management Framework was to develop biological reference points which could be used to assess stock status and develop harvest control rules (Lauzier et al. 2005, Lauzier et al. 2000). Large biological samples were collected by the scallop dive industry in partnership with DFO in 2000 – 2001 ("industry" samples), and biological samples have continued to be collected during biomass surveys in 2001 – 2002 and 2008 – 2009 ("survey" samples). Biological samples are used to provide information on scallop population parameters such as age, growth, and mortality which are required for the development of a biologically based harvest strategy.

Biological Sampling

Target sample sizes were 1500 scallops for each Pacific Fishery Management Area (PFMA) sampled for the industry samples in 2000 - 2001. In addition, biological sampes were also collected during each biomass survey from 2001 – 2002 and 2008 – 2009 with a target sample size of 200 scallops. Data on shell height, sex, and age were collected from all samples. Data on weight, and some cases, shell thickness were collected from the biomass samples.

Scallops were cleaned of all encrusting sponge and other epibionts prior to biological sampling. Shell height was measured as the maximum distance between the hinge and the ventral margin of the shell. Shell thickness was measured as the maximum body thickness (through both valves, with the valves closed). In 2008 - 2009, shell height was measured with vernier calipers to the nearest 0.1 mm and weight was measured to the nearest 0.1 gram. However, for most samples in 2000 – 2002, shell height and weight were measured to the nearest 1 mm or nearest 1 gram, respectively. Shell thickness was measured to the nearest 0.1 mm, but the field database recorded the data to the nearest 1 mm. Shells were opened to determine sex by examining gonad colouration. The testes are white or cream coloured while the ovaries are orange or red.

For age determination, all scallop tissue was discarded and the shells carefully washed and dried. Ages were determined by counting growth bands on the hinge ligament and on the shell surface (MacDonald et al. 1991). The growth bands are visible in the form of light and dark bands and are interpreted as annuli. This method of aging pink and spiny scallops is based on methods described by Stevenson and Dickie (1954) and Merrill (1965), and has been validated for a number of scallop species (e.g. Merrill et al. 1965, Hart and Chute 2009, Lomovasky et al. 2007). Although not validated for pink and spiny scallops, the method has been expertly verified by a detailed examination of the shell microstructure (A.V. Silina correspondence to N. Bourne July 1983). Age determination from the shell surface alone is considered less reliable due to the presence of numerous visible lines from growth layers that do not constitute a full year's growth.

Growth Rates

The average growth rate of individuals in a population is obtained by comparing the average size of surviving individuals at successive ages, and may be different from the true growth rate of an individual obtained by back-calculating length at age (Ricker 1975). Growth rates for pink and spiny scallops were previously examined by Bourne and Harbo (1987) and MacDonald et al. (1991). Bourne and Harbo (1987) collected samples from the commercial trawl fishery and back-calculated shell height at age by measuring the distance between the midpoints of successive annuli on pink and spiny scallop shells; they fitted sigmoidal growth curves by eye, by plotting the average shell height at age. MacDonald et al. (1991) collected SCUBA dive samples and fitted pink and spiny scallop shell height and age at capture to a von Bertalanffy growth model. The growth rates presented in this paper are average growth rates based on the shell height and age at capture.

The most commonly applied growth model is the von Bertalanffy growth model (von Bertalanffy 1938). The following parameterization of the von Bertalanffy growth model was used to describe growth of pink and spiny scallops, with the length parameter in the model represented by shell height measured as the maximum distance between the hinge and the ventral margin of the shell:

$$H_t = H_\infty\left(1 - e^{-K(t-t_0)}\right)$$

where:

H_t = shell height at time t
H_∞= mean asymptotic shell height
K = Brody growth coefficient
t_0 = time when shell height equals zero

The parameter estimates H_∞, K, and t_0 were derived by the least squares method using the Solver function in MS Excel 2002 with no constraints on possible values. Initial parameter values were determined by Ford-Walford plots (Ogle 2010a). Parameter estimates were confirmed and standard errors and 95% confidence intervals were obtained in R 2.10.0 using the packages FSA (Ogle 2010b), NCStats (Ogle 2010c), and nlstools (Baty and Delignette-Muller, 2009), following the methodology of Ogle (2010a).

Natural mortality

There are few published estimates of mortality for any scallop species. Lauzier et al. (2005) presented preliminary estimates of total and natural mortality for pink and spiny scallops based on the results of Ricker catch curve analysis (Ricker 1975) of scallop samples collected between 2000 - 2002. New estimates of mortality are presented based on revised and new data since Lauzier et al. (2005).

Mortality estimates from catch curves

Mortality was estimated from catch at age data from the same biological samples used for the growth analysis.

Ricker catch curves (Ricker 1975, Ogle 2010d) plot the natural log of catch against age, and the total instantaneous mortality (*Z*) is the slope of the descending limb of the curve. Total annual survival (*S*) or mortality (*A*) are derived from *Z* by the following relationships:

$$S = e^{-Z} \text{ and } A = 1 - S$$

In addition, instantaneous total mortality (*Z*) is the sum of the instantaneous rates of fishing mortality (*F*) and natural mortality (*M*), so that if fishing mortality is nil, *M* is equivalent to *Z*.

Ricker's catch curve analysis assumes that survival is constant at all ages under consideration, that there has been no change in mortality rate with time (either natural mortality or fishing mortality), that the sample is taken randomly from all age groups involved, and that year-classes involved were recruited at the same abundance (Ricker 1975). However, Ricker catch curves may not be robust to violations of these assumptions (Dunn et al. 2002).

The Chapman-Robson method (Chapman and Robson 1960, Ogle 2010d) calculates total annual survival (S) by deriving a maximum likelihood estimator from the geometric probability distribution of the catches at each age on the descending limb of the curve. Total instantaneous mortality (*Z*) and total annual mortality (*A*) can then be derived from survivial (*S*). Dunn et al. (2002) suggest that the Chapman and Robson method may be a more robust method when some of Ricker's (1975) assumptions are violated, especially when there are errors in aging or random variability in the true recruitment or mortality parameters which may bias the results of classical catch curve analyis. The FSA (Ogle 2010b) and NCStats (Ogle 2010c) packages in R 2.10.0 were used for both the Ricker and Chapman-Robson catch curve analysis.

Both the Ricker method and the Chapman-Robson method provide estimates of total mortality (*Z* or *A*). However, since there was no commercial catch of scallops for three years prior to the 2001 survey at Valdes Island or for the year prior to the 2009 survey at Mayne Island, and since the commercial catch for the year prior to the 2009 survey at Valdes Island was virtually nil, it was possible to estimate natural mortality (*M*) for Valdes Island in 2001 and 2009 and for Mayne Island in 2009.

Mortality estimates from life history parameters

In data limited fisheries, reliable estimates of natural mortality are often difficult to obtain. In such situations, many authors have utilized mortality estimates derived from empirical relationships among life history parameters (e.g. Beddington and Kirkwood 2005, Cope and Punt 2009, Gillespie et al. 1998a, Hewitt et al. 2007). Some authors (e.g. Pascual and Iribarne 1993) caution that empirical estimates of mortality, such as those obtained from life history parameters, may contain substantial prediction errors; however, such estimates provide an inexpensive means of describing mortality for data-poor fisheries. In particular, estimates from life history parameters reduce the uncertainty about a mortality rate from the range of all possible values to a range of likely values (Pascual and Iribarne 1993).

Following the methodology of Hewitt et al. (2007) and Gillespie et al. (1998a), a number of methods were used to estimate natural mortality from life history parameters. With one exception, the methods were derived from fish data, and all methods were derived from data on many species. Hewitt et al. (2007) point out that the use of multiple methods, even those not specifically derived for invertebrates, would reduce the bias imposed by any one method. Corroboration from different methods may alleviate some of the uncertainty associated with possible violations of the assumptions of catch curve analysis or due to aging errors.

Methods derived for molluscs

Method 1: Hoenig (1983) derived relationships between mortality and the maximum observed age for fish, cetaceans, and molluscs. Hoenig (1983) provided coefficients specifically for molluscs, based on a dataset that included clams, cockles, gastropods, oysters, and two scallop species, *Chlamys tehuelcha* and *C. varia* (Hoenig 1982). The relationship is given by

$$\ln(M) = 1.23 - 0.832\ln(t_{\max})$$

where *M* is the instantaneous natural mortality and t_{max} is the maximum observed age. A maximum of age of 6 was assumed for pink and spiny scallops.

Methods derived for fish

Method 2: Charnov and Berrigan (1990), Charnov (1993),and Jensen (1996) proposed a number of relationships between mortality and parameters that can be derived from the Von Bertalanffy growth model. These are as follows:

$$M = XK$$

$$M = \frac{X}{t_m}$$

where M is the instantaneous natural mortality, X is a constant, given as 1.65 by Charnov (1993) and 1.5 by Jensen (1996), K is the Brody growth coefficient, and t_m is the age at maturity which, if not already known, can be estimated from the growth curve by the following:

$$H(t_m) = 0.67H_\infty$$

where $H(t_m)$ is the shell height at maturity and H_∞ is the asymptotic shell height from the von Bertalanffy growth model.

Method 3: Alverson and Carney (1975) derived a relationship between mortality, maximum age, and parameters from the Von Bertalanffy growth curve:

$$M = \frac{3K}{e^{0.38Kt_{\max}} - 1}$$

where M is the instantaneous natural mortality, K is the Brody growth coefficient and t_{max} is the maximum observed age.

Method 4: Roff (1984) derived a relationship between mortality, age at maturity, and parameters from the Von Bertalanffy growth curve:

$$M = \frac{3K}{e^{Kt_m} - 1}$$

where M is the instantaneous natural mortality, K is the Brody growth coefficient, and t_m is the is the age at maturity, as obtained from method 2.

HARVEST RATES

Lauzier et al. (2005) recommended establishing total allowable catches (TACs) based on harvest rates determined from estimates of maximum sustainable yield (MSY) as a management option for pink and spiny scallop fisheries. They provided a preliminary estimate of MSY using the Gulland (1971) model because it had very few data requirements, and expressed the hope that in future more complex models could be used as the fishery developed and more data was collected. Unfortunately, the scallop dive fishery remains data limited, and estimates for many of the population parameters required by other models are not available.

The Gulland model is given by

$$MSY = XMB_0$$

where MSY is the maximum sustainable yield, X is a constant, M is the natural mortality, and B_0 is the unexploited or virgin biomass. Lauzier et al. (2005) followed Boutillier et al. (1998) and others and used X = 0.2.

The Gulland model is frequently used to provide preliminary estimates of MSY for developing fisheries for which little data is available, as it requires only estimates of natural mortality and virgin biomass (B_0). However, the model is not applicable when significant exploitation is already ongoing and B_0 can not be estimated (Garcia et al. 1989). For scallop dive fisheries, the initial biomass estimate at Valdes Island in 2001 was proposed as a proxy for B_0, as there had been no landings in this area for three years due to the partial closure in PFMA 29-5 (Lauzier et al. 2005). However, Lauzier et al. (2005) did note that the population could at best be considered to be recovering, and they applied an additional factor of 0.5 to the yield estimates to account for the fact that the population had been previously exploited.

Gillespie et al. (1998a) utilized the method of Garcia et al. (1989) to calculate preliminary estimates of MSY for Manila clams. Garcia et al. (1989) developed estimators for yield for use in developing fisheries based on the Schaefer (1954) and Fox (1970) surplus production models that require only an estimate of annual natural mortality and a single year of biomass and catch data. Unlike the Gulland model, the MSY estimators of Garcia et al. (1989) are valid when B_0 is not known and stocks are undergoing exploitation. Although Garcia et al. (1989) characterize yield estimates obtained from a single year of biomass and catch data in this manner as "adventurous" and Gillespie et al. (1998a) concur, they do provide a first rough estimate of MSY that would not otherwise be available.

Garcia et al. (1989) define the relationship between annual fishing mortality rate, F_{MSY} and annual mortality rate, M_a, by the following:

$$F_{MSY} = XM_a$$

where X is a constant that depends on stock parameters (Gillespie et al. 1998a). The notation of Garcia et al. (1989) uses M for annual mortality, but this has been subscripted as M_a to avoid confusion with the standard definition of M as an instantaneous rather than annual rate.

For the Schaefer model, given one year of Biomass estimates (B_c) and catch (Y_c), MSY is given by the following:

$$MSY = \frac{(F_{MSY}B_c)^2}{2F_{MSY}B_c - Y_c}$$

Similarly, for the Fox model, MSY is given by the following:

$$MSY = F_{MSY}B_c\, e^{\left(\frac{Y_C}{F_{MSY}B_c} - 1\right)}$$

The biomass estimate B_c is the exploited average biomass, and both the catch and biomass referred to should have the same age or size structure (Garcia et al. 1989). Thus, since Y_c is by definition legal-sized catch, B_c is legal-sized biomass.

MSY was estimated using the Schaefer and Fox models. Since MSY increases with increasing estimates of natural mortality, the minimum estimate of the annual mortality rate (M_a) was selected for each species. A variety of scaling factors (X) were applied to the natural mortality to select values for F_{MSY}. The combined legal biomass estimates and catch for Valdes and Mayne Island in 2001 were used for B_c and Y_c. For calculations involving the Valdes Island biomass, both the biomass estimate obtained by applying the updated bed area and the estimate obtained by applying the original bed area from Lauzier et al. (2005) were used . A factor of 0.5 was applied to all MSY estimates from the Schaefer and Fox models, following the recommendation of Perry et al. (2002) to ensure that MSY is not exceeded when determining appropriate harvest rates.

To allow comparison with the existing harvest rate, MSY was also estimated with the Gulland model (1971), making the same assumptions as Lauzier et al. (2005) and using the 2001 Valdes biomass as B_0.

RESULTS

BIOMASS SURVEYS

Surveys and Samples

Three scallop dive/ROV surveys were conducted in 2008 – 2009 (Figure 4). On March 1, 2008, a dive/ROV survey was conducted at Valdes Island, with 379 scallops collected from four SCUBA transects, and 479 photo quadrats collected from 10 ROV transects. On March 22 – 25, 2009, a dive/ROV survey was conducted at Mayne Island, with 410 scallops collected from eight SCUBA transects, and 762 photo quadrats collected from 14 ROV transects. In October 2009, a dive/ROV survey was conducted at Valdes Island, with 171 scallops collected from six SCUBA transects on October 24 – 25, and 969 photo quadrats collected from 17 ROV transects on October 2 and 10. Detailed descriptions of biological samples collected and video/ROV surveys completed are included in Table 4 and Table 5. Summary statistics for biological samples are included in Appendix F.

Information from surveys conducted in 2001 – 2002 was presented by Lauzier et al. (2005) but is also included in Table 4, Table 5, and Appendix F for comparison purposes. A small number of records (12 quadrats), representing a single SCUBA dive event and identified in the database as “S Gabriola Reef,” were excluded from the 2001 biological data collected during the dive/video survey at Valdes Island in 2001 because the position data recorded for the dive indicate that the location was outside the survey area.

Model Selection

The log-transformed regression models were significant for both total and legal biomass ($p < 0.05$). However, the models with legal biomass appeared to provide unreliable estimates. In some cases the transformation bias term was sufficiently large that the legal biomass estimates were greater than the total biomass estimates, and in all cases the fit to the data was poor (r^2 = 0.06 – 0.51) (Table 6). For all surveys, the r^2 value for the model containing total biomass was larger than the corresponding model containing legal biomass (r^2 = 0.41 – 0 89). The log-transformed regression model was therefore only appropriate for estimating total biomass (Figure 5 - Figure 7).

The SCUBA biological samples were used to calculate the ratio of legal biomass to total biomass using linear regression through the origin (Thompson 1992). The resultant ratio estimator (the slope of the line) was applied to the total biomass estimates from the log-transformed regression model to obtain indirect estimates of legal biomass (Figure 5). The r^2 value for the ratio estimator was greater than 0.65 for all surveys, and the ratio of legal biomass to total biomass ranged from 0.37 to 0.94 (Table 7).

Density Estimates for all Surveys: 2001 – 2002 and 2008 – 2009

Revised scallop density estimates (g/m^2) are presented for all surveys using the updated estimation methods (Table 8). In addition, the previously reported density estimates are presented for comparison (Table 8).

In 2001 surveys took place at Mayne and Valdes Islands, and in 2002 surveys took place at Mayne, Valdes, and Gabriola Islands, Sentry Shoal and Okisollo Channel. Valdes Island was the only site surveyed in both years. Total densities over this time period ranged from 224 – 360 g/m^2 while legal densities ranged from 105 – 327 g/m^2. Previously reported legal densities ranged from 207.7 – 446.1 g/m^2 (Lauzier et al. 2005).

In 2008 a survey took place at Valdes Island, and in 2009 surveys took place at both Mayne and Valdes Islands. Total densities over this time period ranged from 43 – 71 g/m^2 while legal densities ranged from 37 – 62 g/m^2, an order of magnitude less than the range of densities for 2001 – 2002. For Valdes Island in 2008 and 2009, legal densities were virtually identical between years at 39 g/m^2 and 37 g/m^2, respectively. Previously reported legal densities for this time period ranged from 69.6 – 98.4 g/m^2 (M. Surry and K. Fong, unpublished data).

Biomass Estimates for Mayne and Valdes Islands: 2001 – 2002 and 2008 – 2009

Revised total and legal biomass estimates are presented for Mayne and Valdes Islands using the updated estimation methods and both the original and revised bed area where applicable (Figure 4 and Table 9). For Valdes Island, note that the biomass estimates for the original bed area of 289.3 ha are 116% larger than the estimates when the revised bed area of 133.5 ha is used.

For Mayne Island in 2001, the revised biomass estimates and 95 % confidence intervals (C.I.) are 335,559 kg (95% C.I. = 304,666 – 366,934 kg) for total biomass, and 191,001 (95% C.I. = 173,417 – 208,860 kg) for legal biomass using a bed area of 111.2 ha. The previously reported legal biomass estimate in 2001 was 331,981 kg for the same bed area (Lauzier et al. 2005).

For Valdes Island in 2001, the revised biomass estimates are 374,100 kg (95% C.I. = 333,067 – 414,033 kg) for total biomass and 213,753 kg (95% C.I = 190,307 – 236,570 kg) for legal biomass using a bed area of 133.5 ha. The previously reported legal biomass estimate in 2001 was 1,179,873 kg for a bed area of 289.3 ha (Lauzier et al. 2005).

For Valdes Island in 2002, the revised biomass estimates are 289,370 kg (95% C.I. = 274,127 – 323,606 kg) for total biomass and 281,942 kg (94% C.I. = 259,034 – 305,789 kg) for legal biomass using a bed area of 133.5 ha. The previously reported legal biomass in 2002 estimate was 760,418 kg for a bed area of 289.3 ha (Lauzier et al. 2005).

For Mayne Island in 2009, the revised biomass estimates are 111,785 kg (95% C.I. = 87,615 – 141,117 kg) for total biomass and 97,884 kg (95% C.I. = 76,719 – 123,569 kg) for legal biomass using a bed area of 156.1 ha. The previously reported legal biomass estimate in 2009 was 132,042 kg for the same bed area.

For Valdes Island in 2008, the revised biomass estimates are 72,923 kg (95% C.I = 60,918 – 84,523 kg) for total biomass and 52,738 kg (95% C.I. = 44,056 – 61,127 kg) for legal biomass using a bed area of 133.5 ha. The previously reported legal biomass estimate in 2008 was 284,497 kg for a bed area of 289.3 ha.

For Valdes Island in 2009, the revised biomass estimates are 58,027 kg (95% C.I. = 48,450 – 67,909 kg) for total biomass and 49,453 kg (95% C.I. = 41,291 – 57,876 kg) for legal biomass for a bed area of 133.5 ha. The previously reported legal biomass estimate in 2009 was 223,068 kg for a bed area of 289.3 ha.

POPULATION PARAMETERS

Industry biological samples were collected from Pacific Fishery Management Areas (PFMAs) 14, 15, 17, 18, 19, and 20 in 2000 – 2001. Survey biological samples were collected during biomass surveys at Okisollo Channel (PFMA 13), Sentry Shoal (PFMA 14), Gabriola Island (PFMA 17), Mayne Island (PFMA 18), and Valdes Island (PFMA 29) in 2001 – 2002 and at Mayne and Valdes Islands in 2008 – 2009. Unfortunately the samples from 2008 are unavailable. To date, the total sample size is approximately 9800 spiny scallops and 1300 pink scallops (Table 4).

Growth Rates

The maximum reported age for pink and spiny scallops is six years (Bourne and Harbo 1987; MacDonald et al. 1991) and ages in excess of six years are considered unlikely (N. Bourne, Fisheries and Oceans Canada, 3190 Hammond Bay Road, Nanaimo, BC V9T 6N7, personal communication). However, Lauzier et al. (2000) observed a number of scallops aged 7 and 8 years in the initial samples. A preliminary examination of samples collected in 2001 – 2002 revealed that all the initial samples and some of the biomass samples contained scallops aged 7 or 8 years and that it was primarily one sampler that performed the age determination. Although the number of 7 or 8 year old scallops in each sample was small (less than 2% of the total number of scallops), the wide variation in shell height at age for these samples suggests that there may have been some inconsistency in aging and that aging errors may be present. Since the older ages found in these samples were not expertly verified and exceed the maximum age reported in the literature (Bourne and Harbo 1987; MacDonald et al. 1991), all samples that contained scallops aged 7 or 8 years were excluded from the growth analysis. The resulting sample size was 1677 spiny scallops and 389 pink scallops.

The von Bertalanffy growth model was used to describe growth of pink and spiny scallops (Figure 8). Model parameters, standard errors, 95% confidence intervals (C.I.), and p-values are included in Table 10. Previously reported results (MacDonald et al. 1991) are included for comparison.

For pink scallops in 2001 – 2009, observed maximum shell height was 61.3 mm, similar to that reported by MacDonald et al. (1991) and Bourne and Harbo (1987), at 67.0 mm and approximately 63 mm, respectively. Von Bertalanffy parameter estimates for pink scallops in 2001 – 2009 were very similar to those reported by MacDonald et al. (1991), with predicted asymptotic shell height (H_∞) at 68.0 mm (95% C.I = 62.3 – 78.0 mm) and 67.0 mm (95% C.I. = 64.6 – 69.4 mm), respectively, while for both data sets, the value of the Brody growth coefficient (K) was 0.41 and the value of t_0 (theoretical time at which shell height = 0) was not significantly different from 0 ($p > 0.05$).

For spiny scallops in 2001 – 2009, observed maximum shell height was 78.3 mm, similar to that reported by MacDonald et al (1991) and Bourne and Harbo (1987), at 80.5 mm and approximately 75 mm, respectively. Von Bertalanffy parameter estimates for spiny scallops in 2001 – 2009 were different from those reported by MacDonald et al. (1991), although they noted that the von Bertalanffy model fit the data for spiny scallops less well than it did for other species, citing low sample sizes for older age classes as a possible reason. For spiny scallops in 2001 – 2009, H_∞ was 72.4 mm (95% C.I. = 70.6 – 74.2 mm), while MacDonald et al (1991) reported a much larger value for H_∞, at 93.7 mm (95% C.I. = 88.5 – 98.9 mm). Values for K and t_0 in 2001 – 2009 were also different from those previously reported, with $K = 0.44$ and t_0 not significantly different from 0 ($p > 0.05$) for the 2001 – 2009 data, while MacDonald et al. (1991) reported $K = 0.32$ and $t_0 = 0.46$.

Natural Mortality

Estimates of total instantaneous mortality derived from Ricker's (1975) catch curves appeared poor, with very broad confidence intervals, and p-values for most samples greater than 0.05. In addition, a number of samples had an age range of only two years for the descending limb of the catch curve, so no standard errors, p-values, or confidence intervals could be calculated. Therefore, Ricker catch curves did not appear to provide usable mortality estimates for pink and spiny scallops and thus are not presented.

In contrast, estimates from the Chapman-Robson (1960) method were not limited by the number of years in the descending limb of the catch curve, and confidence intervals were narrower than those produced by the Ricker method (Table 11). Therefore the Chapman-Robson estimates of total mortality were used to estimate natural mortality for Valdes Island in 2001 and 2009 and for Mayne Island in 2009. For 2001, estimates of instantaneous natural mortality (M) were 0.8 for spiny scallops and 1.2 for pink scallops, while estimates of annual natural mortality (M_a) were 0.5 and 0.7, respectively, based on the sample from Valdes Island. For 2009, estimates of instantaneous natural mortality (M) were 1.9 – 2.0 for spiny scallops and 1.2 – 1.3 for pink scallops, while estimates of annual natural mortality (M_a) were 0.9 and 0.7, respectively, based on the samples from Mayne and Valdes Islands. Note that the 2009 estimates were very similar for the two survey areas.

Mortality estimates from life history parameters are summarized in Table 12. For spiny scallops, estimates of instantaneous natural mortality (M) based on parameters estimated from the 2001 and 2009 samples ranged from 0.7 – 1.3 (annual natural mortality M_a = 0.5 – 0.7). For pink scallops, estimates of instantaneous natural mortality (M) based on parameters from the 2001 and 2009 surveys ranged from 0.6 – 1.3 (annual natural mortality M_a = 0.5 – 0.7).

HARVEST RATES

The range of annual natural mortality estimates was similar for both species, and legal biomass estimates and reported catch are for the combined species. The combined pink and spiny scallop biomass was therefore used for all maximum sustainable yield (MSY) calculations, and the results are presented as such.

Values of MSY were lowest for the estimator based on the Fox (1970) model using the lowest estimate of annual natural mortality, M_a = 0.5 (M = 0.7). Higher estimates of annual natural mortality result in higher estimates of MSY; therefore since mortality is uncertain, the lowest rate was selected. Estimated values for MSY, MSY adjusted by a factor of 0.5 (Perry et al. 2002), and the hypothetical exploitation rate as a percentage of the 2001 combined biomass at Valdes and Mayne Islands are presented in Table 13 for a range of possible F_{MSY} scaling factors (X). For presentation purposes, values of X were selected to illustrate the range of results, with X = 0.2 representing the scaling factor commonly used in the Gulland model, X = 1.0 representing the condition where $F = M_a$, and X = 0.5 representing an intermediate value where $F = 0.5M_a$. For X = 0.2, X = 0.5, and X = 1.0, the adjusted MSY was 12,442 kg, 27,339 kg, and 52,557 kg, respectively, representing 3.07%, 6.75%, and 12.98% of the 2001 combined biomass from Mayne and Valdes Islands (revised bed area).

MSY from the Gulland model using X = 0.2 and applying a factor of 0.5 (Perry et al. 2002) was 22,446 kg, or 6% of the 2001 biomass from Valdes Island (revised bed area). The current harvest rate is set at 4% of a biomass estimate for a given area (Lauzier et al. 2005). Despite updates to biomass estimates and utilizing additional estimators for MSY, a 4% harvest rate remains consistent with the best available estimates of MSY.

DISCUSSION

BIOMASS SURVEYS

In 2003, Lauzier et al. (2005) presented a methodology for conducting scallop biomass surveys which incorporated dive surveys in conjunction with a video drop-camera. Since that time, advances in technology and the acquisition of new equipment have provided opportunities to update the survey methodology used to assess scallop stocks. Recent (2008 – 2009) biomass surveys have used a remote operated vehicle (ROV) equipped with a digital still camera in place of the video drop-camera, and the original survey methodology has been adapted accordingly.

Benefits and Disadvantages

High resolution digital still photos from the ROV have replaced the video quadrats from the original drop-camera, providing a number of benefits for scallop assessment. The ability to navigate the ROV allowed quadrats to be collected along pre-determined random transects independent of tide and current, allowing a more rigorous statistical design. Since the ROV is set up to take photos at predetermined intervals, the human tendency to sample high density areas is eliminated by using photo quadrats, thereby reducing the likelihood of overestimating scallop density. Since photos can be georeferenced with the ROV navigational data, scallop distribution and information about the substrate type (i.e. bedrock, boulders, mud, etc.) can be visualized and mapped in relation to bottom topography, providing improved scallop bed delineation and information about scallop habitat. Higher resolution images from the digital still camera (a maximum of 8.0 megapixels compared to 0.3 megapixels from the video drop camera) allow live scallops to be more easily identified and counted, and small or cryptic scallops are more likely to be detected. Counts from video quadrats were likely underestimates due to the low resolution of the images (Ray Lauzier, Fisheries and Oceans Canada, 3190 Hammond Bay Road, Nanaimo, BC V9T 6N7, personal communication). Higher resolution images and a larger field of view allow fish and other invertebrates to be identified, providing information about community structure and species interactions. As noted by Lauzier et al. (2005), augmenting the survey sample size with video or photographic quadrats instead of relying strictly on diver quadrats greatly increases the sampling intensity that is possible, because divers are restricted by time and depth. For example, due to the depth of the scallop survey locations (10 – 30 m), divers are limited to two dives of 30 minutes each per day per diver, and can therefore collect approximately 50 quadrats in a day of diving, compared to hundreds of video or photo quadrats per day (Table 5). Using video or photo quadrats in conjunction with a dive survey greatly reduces the collection and removal of scallops from their habitat since only a small number of dive quadrats are required to provide species and size composition.

Improvements to the quality and usefulness of the data come at a cost, however, as the ROV is a sophisticated and expensive piece of equipment that requires considerable expertise to utilize. ROV surveys using a still camera as described in this document are necessarily limited to being conducted “in-house” from a Coast Guard vessel. Academic institutions or private companies may be a source of alternative ROV equipment for charter, but a still camera may be unavailable, and chartering may entail significant cost. Although the data collection time is greatly reduced, the post-processing of survey data collected with an ROV can be time consuming, as scallops are counted manually from each photo quadrat. For example, it takes approximately four weeks to process 1000 photos. Image recognition technology for scallops is still in development (Fearn et al. 2007, Rosenkranz et al. 2008), and it is unknown whether existing techniques will be applicable in the complex habitat inhabited by pink and spiny scallops in BC.

Revised Estimates

A review of the analytical procedures used to estimate scallop biomass revealed that previously reported results were overestimating the legal biomass. The estimation methodology was therefore revised, and new estimates for total and legal scallop biomass were provided for both the original (2001 – 2002) and recent (2008 – 2009) biomass surveys. The revised and now smaller estimates for 2008 – 2009 at Mayne and Valdes Islands have implications for the total allowable catch (TAC) set for these areas (Table 3 and Table 9). TACs were based on a harvest rate that was 4% of the estimated legal biomass. The revised estimate of 97,884 kg legal biomass for Mayne Island in 2009 results in the 2009/10 TAC (5,000 kg) being 5% of the legal biomass instead of 4%. If the revised bed area estimate for Valdes Island is used to calculate biomass, the revised estimate of approximately 50,000 kg legal biomass in 2008 and 2009 results in the 2008/09 TAC (11,000 kg) and 2009/10 TAC (9,000 kg) being over 18% of the estimated legal biomass instead of 4%. However, the exploitation rate has been low, at less than 2% of the revised estimates.

When revised scallop density estimates from surveys conducted in 2001 – 2002 are compared to surveys conducted in 2008 – 2009, the difference in densities is notable, with the early surveys yielding estimates of approximately 100 – 300 g/m^2 of legal biomass compared to 40 – 60 g/m^2 for surveys in 2008 – 2009. Although the survey methodology has changed, it is unlikely that the original video surveys overestimated the number of scallops per quadrat, as the ROV methodology provides higher resolution images and therefore more accurate counting of small or cryptic scallops that would have been missed in the lower resolution video images. It is also unlikely that scallop counts from video quadrats could have been biased high due to placing the quadrat deliberately on high density areas, as the geographic coordinates of the survey vessel were approximate, and the operators had little control over the position of the quadrats (Ray Lauzier, Fisheries and Oceans Canada, 3190 Hammond Bay Road, Nanaimo, BC V9T 6N7, personal communication). Lacking any information on scallop density for 2003 – 2007, it is unknown whether the change in abundance represents a declining trend, a change in distribution, or a natural fluctuation in population size. No similar decline has been observed in the scallop trawl fishery in the northern Strait of Georgia. Ongoing overfishing is unlikely, as reported commercial landings are very low and most pink and spiny scallops are distributed deeper than recreational diving depths at these locations. A change in oceanographic conditions, predator abundance, or increased incidence of toxic algal blooms are possible factors that could influence scallop distribution and abundance.

Sources of Uncertainty for Biomass Estimates

An inherent difficulty in surveying a mobile species such as scallops using quadrats is that individuals can “escape” when disturbed by a sampling device such as a quadrat frame. However, the absolute number of scallops in the estimation methodology is based on counting scallops in the ROV photos, and scallops are only rarely observed swimming in the forward-facing video or still images obtained during ROV operations. The ROV is generally approximately 1 m from the substrate, and the swimming response of scallops to an ROV survey is therefore assumed to be negligible.

Diver samples are assumed to be representative of the size composition of the population, but bias could be introduced into the estimation if divers fail to collect the full size range of scallops. Scallops smaller than approximately 25 mm appear rare in the samples, and it is suspected that some size selectivity in the sample collection may have occurred, either because small scallops were lost through the mesh of the collection bag, or divers were unable to locate or pick up the smallest scallops. Biasing the sample collection towards larger scallops could cause the legal biomass to be overestimated, as the counts from the ROV photos include all sizes, but the legal to total biomass ratio comes from the diver samples. Smaller mesh size for the collection bags and increased training for the divers may alleviate the apparent selectivity of the samples.

The quadrat size for the ROV portion of the biomass surveys is calculated from the size of the field of view of the still camera, based on a 10 cm reference scale provided by two lasers integral to the camera system. Distance of the ROV from the substrate, the slope and relief of the substrate, and distortion from the camera lens all contribute to inaccuracies in the estimation of the size of the field of view. However, the reference scale is centred in the images, and images with grossly sloped substrate, sudden changes in relief, or obstructions in the centre of the image are excluded from the analysis; therefore it is assumed that the mean of the errors in estimation of the size of the field of view would be close to zero, leading to little bias in the estimation. Distortion from the lens is assumed to overestimate the size of the field of view; therefore, biomass estimates may be biased low. A 0.25 m^2 quadrat “frame” using four lasers similar to the existing 10 cm reference scale has been investigated, and would potentially eliminate some of the variability in measuring quadrat size in ROV photos. However, the increased weight and drag on the ROV, as well as the difficulty in maintaining proper alignment of the lasers has made this difficult to implement. In addition, the problems of substrate slope and relief would remain. In addition, a brief investigation of quadrat size suggested that the larger effective quadrat size obtained by using the full field of view of the ROV photos reduces the variability in the number of scallops counted per quadrat, due to the patchy distribution of scallops even on a very small scale.

Future Improvements

As scallop bed areas are redefined based on georeferenced distribution and habitat information, future surveys can partition the sampling effort among the available scallop habitat and take advantage of stratified random sampling designs, thereby improving the statistical robustness of the biomass estimates.

Scallop biomass estimates continue to be the combined total of pink and spiny scallop biomass because video and photo methods preclude distinguishing the species due to the encrusting sponge on the shell, and because a species-specific TAC would be meaningless when scallop landings continue to be reported as a combined total. Should managers wish to consider species-specific TACs in the future, the species composition of the biomass can be estimated from the biological samples in the same manner as legal biomass is estimated, i.e. by the ratio of pink and spiny scallops in the samples. This ratio could only be applied if the biological samples are collected from the same depths as the ROV quadrats, as the relative density of pink scallops is known to increase with depth,.

Biomass estimates are currently conducted on an individual bed-by-bed basis. Lauzier et al. (2000) noted that each distinct aggregation of scallops must be assessed as a separate stock until sufficient data is obtained to delineate the degree of exchange or dispersal between scallop aggregations. Although assessment and management on a larger scale is desirable due to the limited resources available for estimating biomass and administering TACs, there continues to be insufficient data to move forwards on implementing a larger scale approach as recommended by Lauzier et al. (2005). At a minimum, a consistent time series of biomass surveys and biological data from a variety of areas would be required to investigate whether changes in biomass and populations dynamics appear correlated between different areas.

Stock assessment of weathervane scallops (*Placopecten caurinus*) in Alaska and sea scallops (*P. magellanicus*) on the east coast of North America is based primarily on counting scallops in video or continuous still images from equipment deployed on towed sleds (Rosenkranz and Byersdorfer 2004, Gallager et al. 2005). The high relief substrate preferred as habitat by pink and spiny scallops in BC precludes the use of towed sled methodology. Methods are being developed elsewhere for automated habitat classification and detection of scallop abundance from video and still images (Fearn et al. 2007, Rosenkranz et al. 2008) but it is unknown whether such methods are applicable to the complex habitat inhabited by pink and spiny scallops in BC.

POPULATION PARAMETERS

Growth

A new analysis of pink and spiny growth was conducted by fitting the von Bertanlanffy growth model to shell height at age for each species. The average asymptotic shell height was found to be 68.0 mm for pink scallops and 72.4 for spiny scallops, and the maximum observed shell height in the samples was 65.0 mm and 78.3 mm, respectively. The results were similar to those previously reported (MacDonald et al. 1991) for pink scallops only, although the results for spiny scallops may not be comparable, as MacDonald et al. (1991) reported a poor fit, citing low sample sizes for older age classes as a possible reason.

Although the maximum shell height reported in the literature for pink and spiny scallops is approximately 70 mm and 80 mm, respectively, scallops of this size appear rare, and the growth curves suggest that most scallops die before achieving their theoretical asymptotic shell height.

In reviewing the available data, a large proportion of the age data was suspected to contain aging errors and was therefore excluded from the analysis. This exclusion represents the loss of a significant investment of resources, and highlights the need for ongoing assessment of sampling methodology and quality control, especially when conducting a subjective activity such as age determination.

Mortality

New estimates of natural mortality were provided for pink and spiny scallops, based on catch curve analysis and corroborated by estimates from life history parameters. The new estimates of instantaneous natural mortality (M) range from 0.6 – 2.0 for spiny scallops and 0.6 – 1.3 (corresponding annual mortality estimates M_a range from 0.5 – 0.8) for pink scallops and are within the range of published estimates for *Chlamys* species with similar life history (Orensanz et al. 1991).

Sources of Uncertainty for Population Parameters

The variation in shell height at age for pink and spiny scallops, as well as documented concerns regarding age determination during certain years, suggests that aging errors may be present. Samples were collected at different times of year, so variance in the size of the last annulus is expected. Pink scallops are known to spawn twice per year, so two size classes may be present for pink scallops at least in the first few years of life. Lauzier at al. (2000) reported scallops aged 7 and 8, and although these samples have been excluded from the present analysis, further investigation into the maximum age of pink and spiny scallops may be required.

Uncertainty in estimates of natural mortality arises when the samples utilized may contain aging errors, when the maximum age is not reliably known, and when the samples utilized are from exploited populations.

Uncertainty in age determination, estimates of maximum age, and estimates of natural mortality could be reduced in future by analysing samples collected from unexploited populations.

HARVEST RATES

Preliminary estimates of MSY were calculated using a method based on the Fox (1970) surplus production model (Garcia et al. 1989) that uses a single year of biomass and catch data, and is valid for a population that is undergoing exploitation where virgin biomass is not known. Estimates of MSY from the Gulland (1971) model as used by Lauzier et al. (2005) were also examined and found to be within the same range as the Fox model. Despite the new estimates of mortality and biomass, the currently used 4% harvest rate remains consistent with best available estimates of MSY.

Uncertainty in Harvest Rates

A high degree of uncertainty exists in the estimation of maximum sustainable yield and associated harvest rates for the pink and spiny scallop dive fishery given the paucity of available biological and time series data. Such estimates must be considered as preliminary estimates only.

PRECAUTIONARY APPROACH

The development of a harvest strategy compliant with the Precautionary Approach (PA) is required for scallops. The minimum elements of the harvest strategy component of the DFO PA include a removal reference for three stock status zones delineated by a Limit Reference Point (LRP) and an Upper Stock Reference (USR) (DFO 2006b).

Unfortunately, for British Columbia scallops stocks, there are a paucity of biological and time series data so moving forward on this requirement will need to take place over several years. The current assessment framework, if implemented on an annual basis will facilitate the development of PA compliant provisional reference points which can then be evaluated to test for robustness to various stock size scenarios.

SCALLOP REFUGIA

Scallop refugia, or areas protected from exploitation, were identified as part of the original assessment framework (Lauzier et al. 2000), and a portion of the Valdes Island bed has remained closed for this reason. Refugia could serve as sources of new recruitment for exploited populations and would provide opportunities to assess population dynamics and biology of unexploited populations, as well as to compare the effects of different exploitation rates. However, no work has been conducted to date to examine the effects of scallop refugia. The low participation in the scallop fishery, as well as the limitations of the dive fishery by depth and the trawl fishery by substrate continues to provide inherent refuges for scallops and potential sources of unexploited populations for research.

PHASED APPROACH

The pink and spiny scallop dive fishery is one of three previously commercial invertebrate fisheries in BC to which the phased approach for new and developing fisheries has been applied. The scallop dive fishery is illustrative of the difficulty in obtaining buy-in from stakeholders in a former commercial fishery who feel they have lost economic opportunities, compared to stakeholders in a genuinely new and developing fishery where assessment capacity can be built up as economic capacity increases. The assessment costs for the scallop fishery are considerable, and progress towards redevelopment has therefore been much slower than was originally anticipated.

RECOMMENDATIONS

1. Endorse the updated survey methodology and biomass estimation methods, including new estimates of scallop bed area.
2. Given the continuing paucity of time series of assessment surveys and biological time series, maintain the harvest rate at the existing level of 4% of biomass estimates for the areas to be fished.
3. Update harvest options in light of updated biomass estimates based on recent surveys (2008 – 2009).
4. As Mayne Island (PFMA 18-1) and Valdes Island (PFMA 29-5) represent the only areas with any time series of biomass surveys, continue to conduct assessment surveys and collect biological samples at these locations annually or biannually.
5. Collect biological samples from unexploited areas to address the questions of maximum size and age of these species.

6. Prior to any survey of additional locations other than Mayne Island or Valdes Island, as a first step in a new area, scallop distribution and bed area needs to be delineated by the best available techniques.

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TABLES

Table 1. Landings[1], catch per unit of effort (CPUE)[1], and value[2] for commercial dive fisheries for pink and spiny scallops in British Columbia, 1982 – 1999. Catch and CPUE in 1982 are left blank to protect participants' privacy.

Year	Landings (t)	CPUE (kg/h)	Value	Average price per kilogram	Participants
1982	--	--	--	--	2
1983	8.0	40.7	--	--	4
1984	15.6	78.8	$28,973	$2.78	5
1985	10.8	248.4	$124,181	$2.60	5
1986	35.7	66.0	$209,178	$3.17	8
1987	69.1	52.5	$241,213	$3.72	9
1988	48.9	75.9	$261,010	$4.34	10
1989	32.4	84.9	$315,642	$4.20	8
1990	64.4	171.2	$316,769	$4.65	9
1991	47.6	49.3	$287,016	$4.87	7
1992	38.4	60.1	$341,047	$4.77	7
1993	77.3	104.4	$391,534	$4.75	9
1994	73.4	95.8	$469,067	$4.77	16
1995	76.1	116.7	$427,419	$5.02	14
1996	94.5	88.1	$495,014	$5.19	15
1997	73.6	59.3	$390,341	$5.19	10
1998	54.6	49.5	$273,468	$5.39	6
1999	36.7	44.6	$191,403	$5.67	9

[1] Data from fisher logbooks (Shellfish Data Unit, Fisheries and Oceans Canada, 3190 Hammond Bay Road, Nanaimo, BC V9T 6N7)
[2] Data from sales slips (Regional Data Services Unit, Fisheries and Oceans Canada, 200 – 401 Burrard Street, Vancouver, BC V6C 3S4)

Table 2. Landings[1], catch per unit of effort (CPUE)[1], value[2] and number of participants[1] for experimental / exploratory dive fisheries for pink and spiny scallops in British Columbia, 2000 – 2009. Note that some values are left blank to protect participants' privacy.

Year	Landings (t)	CPUE (kg/h)	Value	Average price per kilogram	Participants
2000	53.2	48.6	$277,020.61	$5.99	9
2001	43.5	61.3	$208,528.63	$6.48	6
2002	50.0	62.2	$235,436.46	$6.21	8
2003	45.7	66.1	$180,939.76	$6.18	6
2004	26.9	60.6	$138,249.97	$6.02	6
2005	12.0	63.9	$77,782.56	$6.23	4
2006	8.7	53.7	$55,141.60	$6.38	3
2007	--	53.8	--	$6.53	2
2008	--	64.3	--	$6.17	1
2009	--	69.1	--	$6.06	1

[1] Data from fisher logbooks (Shellfish Data Unit, Fisheries and Oceans Canada, 3190 Hammond Bay Road, Nanaimo, BC V9T 6N7)
[2] Data from sales slips (Regional Data Services Unit, Fisheries and Oceans Canada, 200 – 401 Burrard Street, Vancouver, BC V6C 3S4)

Table 3. Total Allowable Catches (TACs) allocated to the experimental / exploratory dive fisheries for pink and spiny scallops in British Columbia, 2006 – 2011. The basis for the TAC (biological or otherwise) is indicted in brackets.

License Year (August 1 – July 31)	TAC (kg)		Total (kg)
	PFMA 18-1	PFMA 29-5	
2006/07	4545 (Previous Year's Catch)	6818 (Previous Year's Catch)	11363
2007/08	0	900 (Arbitrary)	900
2008/09	0	11000 (Survey-based)	11000
2009/10	5000 (Survey-based)	9000 (Carried-over)	14000
2010/11	3300 (Carried over)	8923 (Survey-based)	12223

Table 4. List of samples and sample sizes for pink and spiny scallop biological samples collected by the scallop industry (I) or as part of scallop dive/video or dive/ROV surveys (S) in 2000 – 2009. For summary statistics, see Appendix F.

Pink Scallops

Location (PFMA)	Type	Date	N	Shell Height	Sex	Weight	Shell Thickness	Usable Ages
Area 15	I	2000	14	14	14	--	--	--
Gabriola Is. (17-10)	I	Apr 2000	66	66	66	--	--	--
Mayne Is. (18-1)	I	Mar 2000	136	136	136	--	--	--
Shelter Pt. (14-13)	I	Mar 2000	9	9	--	--	--	--
Valdes Is. (29-5)	I	Jun 2000	281	281	281	--	--	--
J. de F. (20)*	I	Mar 2001	47	47	47	--	--	--
Mayne Is. (18-1)	S	Apr 2001	159	159	157	159	--	159
Valdes Is. (29-5)	S	Mar 2001	196	196	195	196	--	116
Gabriola Is. (17-10)	S	Mar 2002	68	68	68	68	68	--
Okisollo Channel (13-8, 13-10, 13-12)	S	Mar 2002	39	39	39	39	39	--
Sentry Shoal (14-13)	S	Feb 2002	--	--	--	--	--	--
Valdes Is. (29-5)	S	Mar-Apr 2002	15	15	15	15	15	--
Valdes Is. (29-5)	S	Mar 2008	134	--	--	--	--	--
Mayne Is. (18-1)	S	Mar 2009	61	61	61	61	61	61
Valdes Is. (29-5)	S	Oct 2009	53	53	53	53	53	53
		Total	1278	1144	1132	591	236	389

Spiny Scallops

Location (PFMA)	Type	Date	N	Shell Height	Sex	Weight	Thickness	Usable Ages
Area 15	I	2000	609	609	562	--	--	--
Gabriola Is. (17-10)	I	Apr 2000	711	711	711	--	--	--
Mayne Is. (18-1)	I	Mar 2000	1267	1267	1267	--	--	--
Shelter Pt. (14-13)	I	Mar 2000	1463	1463	1443	--	--	--
Valdes Is. (29-5)	I	Jun 2000	1097	1097	1097	--	--	--
J. de F. (20)*	I	Mar 2001	1307	1307	1307	--	--	--
Mayne Is. (18-1)	S	Apr 2001	657	657	640	657	--	657
Valdes Is. (29-5)	S	Mar 2001	642	642	642	642	--	554
Gabriola Is. (17-10)	S	Mar 2002	132	132	132	132	132	--
Okisollo Channel (13-8, 13-10, 13-12)	S	Mar 2002	521	521	518	521	521	--
Sentry Shoal (14-13)	S	Feb 2002	386	386	377	386	--	--
Valdes Is. (29-5)	S	Mar-Apr 2002	335	335	326	335	334	--
Valdes Is. (29-5)	S	Mar 2008	245	--	--	--	--	--
Mayne Is. (18-1)	S	Mar 2009	348	348	348	348	347	348
Valdes Is. (29-5)	S	Oct 2009	118	118	118	118	118	118
		Total	9838	9593	9488	3139	1452	1677

*Juan de Fuca Strait

Table 5. Summary of video/ROV samples collected from the experimental / exploratory dive fisheries for pink and spiny scallops in British Columbia, 2001 – 2002 and 2008 – 2009.

Location (PFMA)	Date	Type	Quadrat Size	No. Transects	No. Quadrats	No. Days
Mayne Is. (18-1)	Apr 2001	video	0.25 m^2	8	504	4
Valdes Is. (29-5)	Mar 2001	video	0.25 m^2	7	379	4
Gabriola Is. (17-10)	Mar 2002	video	0.25 m^2	10	926	2
Okisollo Channel (13-8, 13-10, 13-12)	Mar 2002	video	0.25 m^2	19	1354	3
Sentry Shoal (14-13)	Feb 2002	video	0.25 m^2	12	1990	3
Valdes Is. (29-5)	Mar-Apr 2002	video	0.25 m^2	11	2106	2
Valdes Is. (29-5)	Mar 2008	ROV	variable	10	460	1
Mayne Is. (18-1)	Mar 2009	ROV	variable	14	647	3
Valdes Is. (29-5)	Oct 2009	ROV	variable	17	922	4

Table 6. Results of log-transformed linear regressions of total scallop biomass and legal scallop biomass against total count of scallops from SCUBA surveys. R-squared (r^2) is the squared Pearson Product-Moment Correlation Coefficient from the regression. Mean biomass estimates are expressed in grams per 0.25 m^2 quadrat. Sigma (σ) is the standard error of the regression. Bias is the back-transformed error term from the regression, equivalent to $e^{\sigma^2/2}$. *Regression coefficients are x_0 (intercept) and x_1 (slope).*

Survey	Total Biomass					
	r^2	Mean	σ	bias	x_0	x_1
Mayne 2001	0.89	75.4	0.270	1.02	3.416	0.874
Valdes 2001	0.77	70.0	0.329	1.06	3.500	0.845
Okisollo 2002	0.85	70.6	0.314	1.05	3.053	0.932
Sentry 2002	0.78	87.7	0.326	1.06	3.587	0.931
Gabriola 2002	0.89	90.0	0.199	1.02	3.796	0.892
Valdes 2002	0.76	55.8	0.380	1.08	3.673	0.970
Valdes 2008	0.83	13.6	0.367	1.07	2.944	0.936
Mayne 2009	0.52	17.7	0.481	1.12	2.897	1.066
Valdes 2009	0.41	10.9	0.634	1.22	2.909	0.788

Survey	Legal Biomass					
	r^2	Mean	σ	bias	x_0	x_1
Mayne 2001	0.30	73.3	1.353	2.50	2.337	1.000
Valdes 2001	0.03	105.8	1.784	4.91	2.952	0.437
Okisollo 2002	0.18	45.5	1.779	4.86	1.038	1.007
Sentry 2002	0.35	109.3	0.932	1.54	3.256	1.059
Gabriola 2002	0.41	83.5	0.583	1.19	3.778	0.775
Valdes 2002	0.51	60.1	0.721	1.30	3.464	1.059
Valdes 2008	0.35	13.5	1.030	1.70	2.628	0.869
Mayne 2009	0.25	16.5	0.900	1.50	2.537	1.121
Valdes 2009	0.06	13.1	1.660	3.96	2.259	0.653

Table 7. Ratio of scallop legal biomass to scallop total biomass and 95% confidence intervals (C.I.) from ratio estimation by linear regression through the origin.

Survey	r^2	Ratio	95% C.I.
Mayne 2001	0.87	0.57	(0.55 – 0.59)
Valdes 2001	0.80	0.57	(0.53 – 0.61)
Okisollo 2002	0.66	0.37	(0.34 – 0.40)
Sentry 2002	0.98	0.93	(0.92 – 0.94)
Gabriola 2002	0.97	0.88	(0.86 – 0.90)
Valdes 2002	0.99	0.94	(0.93 – 0.96)
Valdes 2008	0.95	0.72	(0.69 – 0.75)
Valdes 2009	0.93	0.85	(0.81 – 0.90)
Mayne 2009	0.97	0.88	(0.85 – 0.91)

Table 8. Revised scallop density estimates (g/m^2) and bootstrapped 95% confidence intervals (C.I.s) based on mean total biomass from the regression model. Legal density is estimated from total density by applying the ratio estimator from Table 7. The original legal density estimates are provided for comparison purposes (Lauzier et al. 2005, R.B. Lauzier unpublished data, A.M. Surry and K.H. Fong unpublished data).

Survey	Revised Total Density		Revised Legal Density		Original Legal Density	
	Mean	95% C.I.	Mean	95% C.I.	Mean	95% C.I.
Mayne 2001	301.8	(274.0 – 330.0)	171.8	(156.0 – 187.8)	298.5	(280.1 – 316.4)
Valdes 2001	280.0	(249.3 – 309.9)	160.0	(142.5 – 177.1)	446.1	(407.7 – 496.2)
Okisollo 2002	282.2	(261.5 – 302.4)	104.6	(97.0 – 112.1)	207.7	(191.5 – 225.4)
Sentry 2002	350.8	(330.6 – 373.1)	326.5	(307.7 – 347.3)	347.3	(328.8 – 365.4)
Gabriola 2002	360.2	(328.9 – 394.0)	317.8	(290.2 – 347.6)	359.8	(331.6 – 392.1)
Valdes 2002	223.4	(205.2 – 242.2)	211.1	(193.9 – 228.9)	262.8	(245.6 – 279.7)
Valdes 2008	54.6	(45.6 – 63.3)	39.5	(33.0 – 45.8)	98.4	(86.8 – 110.0)
Mayne 2009	70.7	(55.4 – 89.3)	61.9	(48.5 – 78.2)	69.6	(56.0 – 84.4)
Valdes 2009	43.4	(36.3 – 50.8)	37.0	(30.9 – 43.3)	77.2	(70.4 – 84.0)

Table 9. Total and legal biomass estimates (kg) and 95% confidence intervals (C.I.s) calculated by applying density estimates and bootstrapped confidence intervals from Table 8 to the estimated bed area for pink and spiny scallop dive/video and dive/ROV surveys at Mayne Island in 2001 and 2009 and Valdes Island in 2001, 2002, 2008, 2009. The original legal biomass estimates are provided for comparison purposes (Lauzier et al. 2005, R.B. Lauzier unpublished data, A.M. Surry and K.H. Fong unpublished data).

Survey	Bed Are (ha)	Revised Total Biomass (kg)		Revised Legal Biomass (kg)		Original Legal Biomass (kg)	
		Mean	95% C.I.	Mean	95% C.I.	Mean	95% C.I.
Mayne 2001	111.2	335,559	(304,666 – 366,934)	191,001	(173,417 – 208,860)	331,981	(311,459 – 351,858)
Mayne 2009	158.1	111,780	(87,611 –141,110)	97,879	(76,716 –123,563)	110,038	(88,536 – 133,436)
Valdes 2001	289.3	810,167	(721,303 – 896,648)	462,913	(412,138 – 512,326)	1,291,013	(1,179,884 – 1,435,994)
	133.5	374,139	(333,101 – 414,076)	213,775	(190,327 – 236,595)		
Valdes 2002	289.3	646,162	(593,661 – 700,815)	610,586	(560,976 – 662,230)	760,516	(710,808 – 809,357)
	133.5	298,400	(274,155 – 323,639)	281,971	(259,061 – 305,821)		
Valdes 2008	289.3	157,924	(131,928 – 183,047)	114,211	(95,410 – 132,380)	284,770	(251,199 – 318,340)
	133.5	72,930	(60,925 – 84,532)	52,743	(44,061 – 61,134)		
Valdes 2009	289.3	125,665	(104,924 – 147,067)	107,098	(89,422 – 125,338)	223,417	(203,738 – 243,096)
	133.5	58,033	(48,455 – 67,916)	49,458	(41,295 – 57,881)		

Table 10. Sample size (n), maximum reported shell height (H_{max}) and summary of model parameters, standard errors, and 95% confidence intervals (C.I.) and P-values for the relationship between shell height (mm) and age (years) fitted to the von Bertalanffy growth model for pink and spiny scallops. Values presented are for data from 2001 dive/video surveys and 2009 dive/ROV surveys at Mayne and Valdes Islands (excluding samples where aging error is suspected) as well as from previously reported results by MacDonald et al. (1991). Model parameters are asymptotic shell height (H_∞), Brody Growth Coefficient (K), and the time when shell height equals zero (t_0). The analysis for the 2001 – 2009 data utilized bootstrapped confidence intervals, while MacDonald et al. (1991) utilized confidence intervals based on normal distribution theory.

Pink Scallops – 2001 - 2009

Variable	Value	SE	95% C.I.	P
n	389	--	--	--
H_{max}	65.0	--	--	--
H_∞	68.0	3.4662	62.3 – 78.0	$< 2 \times 10^{-16}$
K	0.41	0.0613	0.3 – 0.5	8.69×10^{-11}
t_0	-0.06	0.1498	-0.4 – 0.2	0.684

Pink Scallops – MacDonald et al (1991)

Variable	Value	SE[1]	95% C.I.	P[2]
n	697	--	--	--
H_{max}	~ 67	--	--	--
H_∞	67.0	1.2220	64.6 – 69.4	--
K	0.41	0.0356	0.3 – 0.5	--
t_0	-0.19	0.1578	-0.5 – 0.1	--

Spiny Scallops – 2001 - 2009

Variable	Value	SE	95% C.I.	P
n	1677	--	--	--
H_{max}	78.3	--	--	--
H_∞	72.4	1.0542	70.6 – 74.2	$< 2 \times 10^{-16}$
K	0.44	0.0227	0.4 – 0.5	$< 2 \times 10^{-16}$
t_0	-0.01	0.0620	-0.1 – 0.1	0.844

Spiny Scallops – MacDonald et al (1991)

Variable	Value	SE[1]	95% C.I.	P[2]
n	301	--	--	--
H_{max}	80.5	--	--	--
H_∞	93.7	2.6423	88.5 – 98.9	--
K	0.32	0.0254	0.3 – 0.4	--
t_0	0.46	0.0559	0.4 – 0.6	--

[1] SE was calculated from the data presented in MacDonald et al. (1991).
[2] No P values were provided by MacDonald et al. (1991).

Table 11. Estimates of total instantaneous survival (S), total instantaneous mortality (Z), total annual mortality (A), and instantaneous natural mortality (M) based on Chapman-Robson (1960) catch curve analysis. The 95% confidence intervals (C.I.) are calculated from the standard error (SE). Data is from 2001 dive/video surveys and 2009 dive/ROV surveys and excludes samples where aging error is suspected.

Pink Scallops

Survey	Age Range	Survival (*S*)			Mortality (*Z*)			*A*	*M*
		S	SE	95% C.I.	Z	SE	95% C.I.		
Mayne 2001	2 – 5	29.52	3.16	(23.34 – 35.71)	1.22	0.11	(1.01 – 1.43)	0.70	--
Valdes 2001[1]	3 – 4	30.19	4.48	(21.41 – 38.97)	1.20	0.15	(0.91 – 1.49)	0.70	1.20
Mayne 2009	3 – 5	30.91	6.29	(18.58 – 43.23)	1.17	0.20	(0.78 – 1.57)	0.69	1.17
Valdes 2009	2 – 5	27.94	5.48	(17.20 – 38.69)	1.28	0.20	(0.89 – 1.66)	0.72	1.28

Spiny Scallops

Survey	Age Range	Survival (*S*)			Mortality (*Z*)			*A*	*M*
		S	SE	95% C.I.	Z	SE	95% C.I.		
Mayne 2001	4 – 6	18.27	1.92	(14.50 – 22.04)	1.70	0.11	(1.49 – 1.91)	0.82	--
Valdes 2001[1]	3 – 6	46.54	1.70	(43.21 – 49.86)	0.76	0.04	(0.69 – 0.84)	0.53	0.76
Mayne 2009	4 – 5	14.47	2.30	(9.96 – 18.98)	1.93	0.16	(1.62 – 2.24)	0.86	1.93
Valdes 2009	4 – 5	14.29	4.01	(6.42 – 22.15)	1.95	0.28	(1.40 – 2.50)	0.86	1.95

Table 12. Estimates of instantaneous natural mortality (M) and annual natural mortality (M_a) obtained from life history parameters estimated from 2001 dive/video surveys and 2009 dive/ROV surveys at Mayne and Valdes Islands. Samples where aging error is suspected were excluded. See text for description of each method.

	Method	Species	*M*	M_a
1.	Hoenig (1983)	Both	0.77	0.54
2.	Charnov and Berrigan (1990) Charnov (1993) Jensen (1996)	Pink	0.62 – 0.75	0.46 – 0.53
		Spiny	0.65 – 0.78	0.48 – 0.54
3.	Alveson and Carney (1975)	Pink	1.31	0.73
		Spiny	1.31	0.73
4.	Roff (1984)	Pink	1.13	0.69
		Spiny	1.17	0.68

*Table 13. Yield (kg) and hypothetical harvest rates (HR) using Garcia's (1989) maximum sustainable yield (MSY) estimator for a single year of biomass (B_c) and catch (Y_c) where stocks follow a Fox (1970) model. F_{MSY} is given by X * M where X is a constant and annual mortality M_a = 0.5. B_c and Y_c are combined legal biomass estimates and catch for Mayne and Valdes Islands in 2001. Results from the Gulland (1971) model where X = 0.2 are provided for comparison using the legal biomass for Valdes Island in 2001 for B_0.*

Fox Model

Bed Area	B_c	Y_c	X	MSY	MSY * 0.5	HR (%)
Revised	404,754	15,114	0.2	24884	12442	3.07
Original	653,914			36968	18484	2.83
Revised	404,754	15,114	0.5	54678	27339	6.75
Original	653,914			85701	42850	6.55
Revised	404,754	15,114	1.0	105114	52557	12.98
Original	653,914			167346	83673	12.80

Gulland Model

Bed Area	Bo	--	X	MSY	MSY*0.5	HR (%)
Revised	374,100	--	0.2	44892	22446	6.00
Original	810,167			97220	48610	6.00

FIGURES

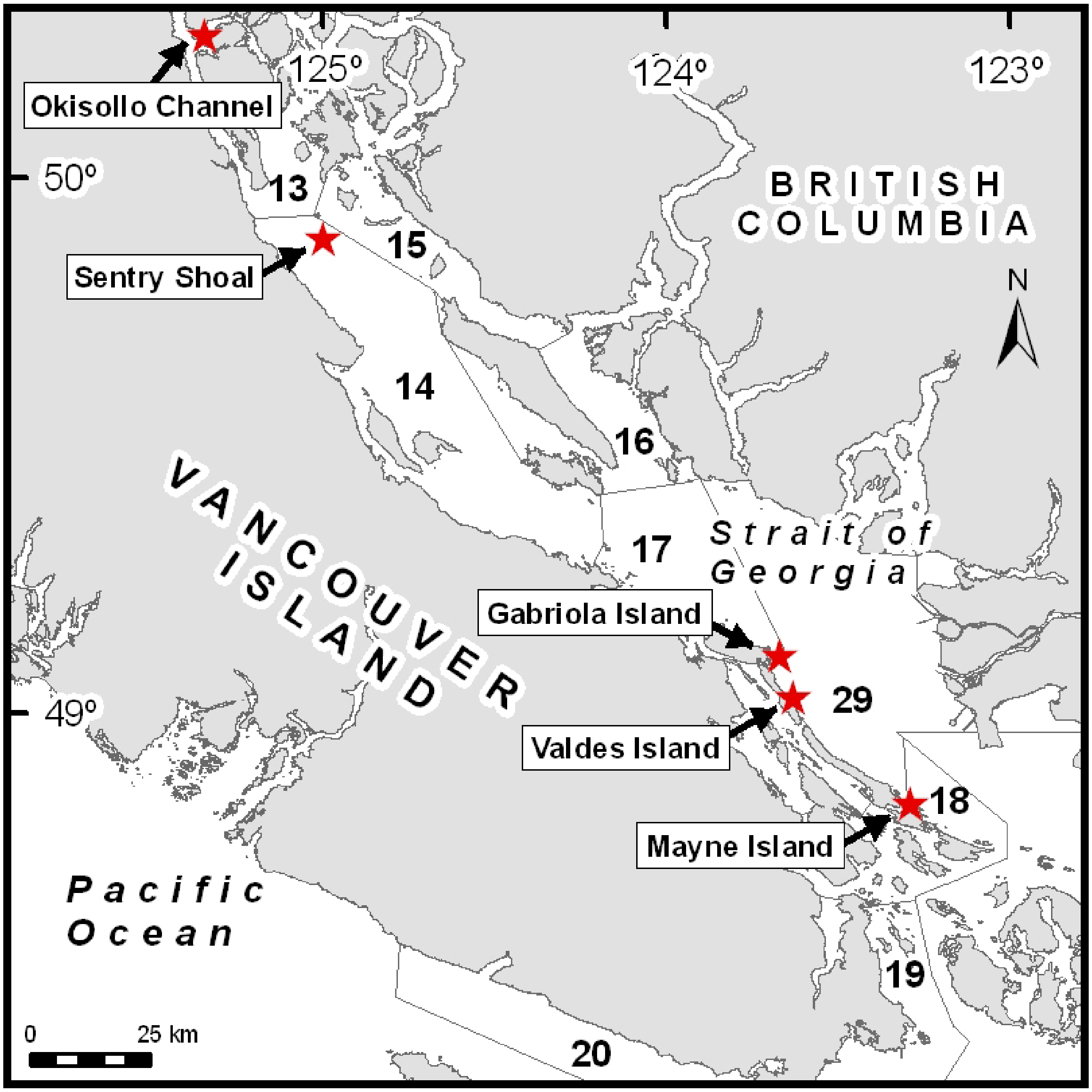

Figure 1. Location of Pacific Fishery Management Areas (PFMAs)and scallop dive/video and dive/ROV survey sites in BC waters.

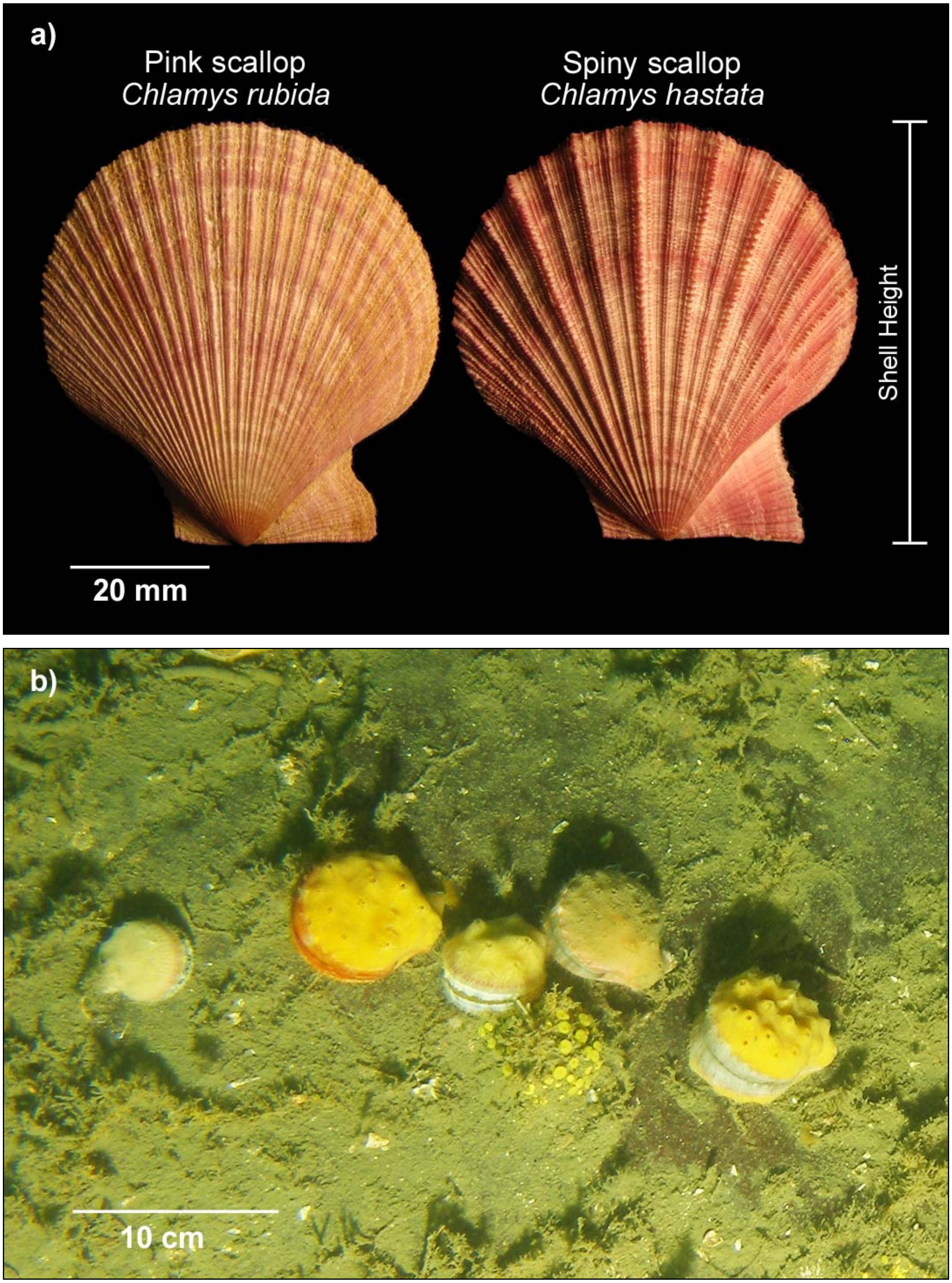

*Figure 2. a) Pink and spiny scallop (*Chlamys rubida *and* C. hastata*) shells; b) live* Chlamys sp*. scallops with encrusting sponge.*

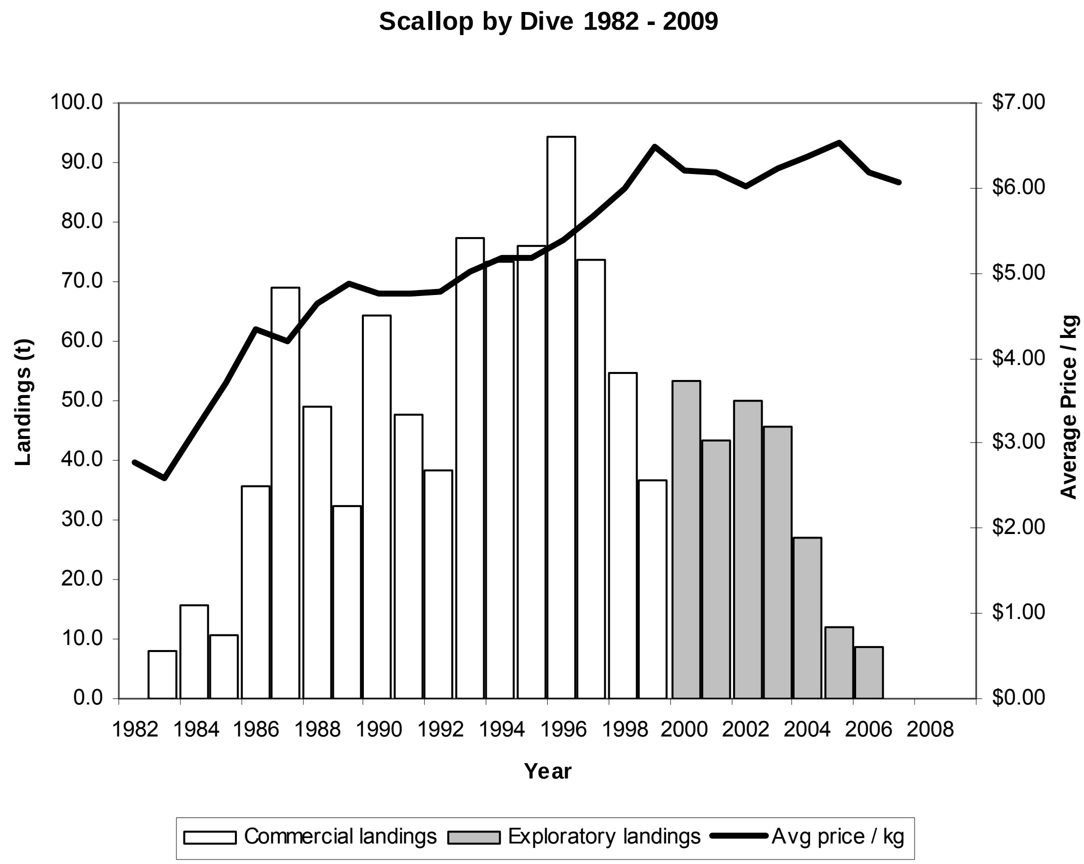

Figure 3. Landings (t) and average price per kilogram ($/kg) for commercial and experimental / exploratory dive fisheries for pink and spiny scallops in British Columbia, 1982 – 2009. Note that landings in 1982 and after 2006 are not reportable due to the low number of participants in the fishery.

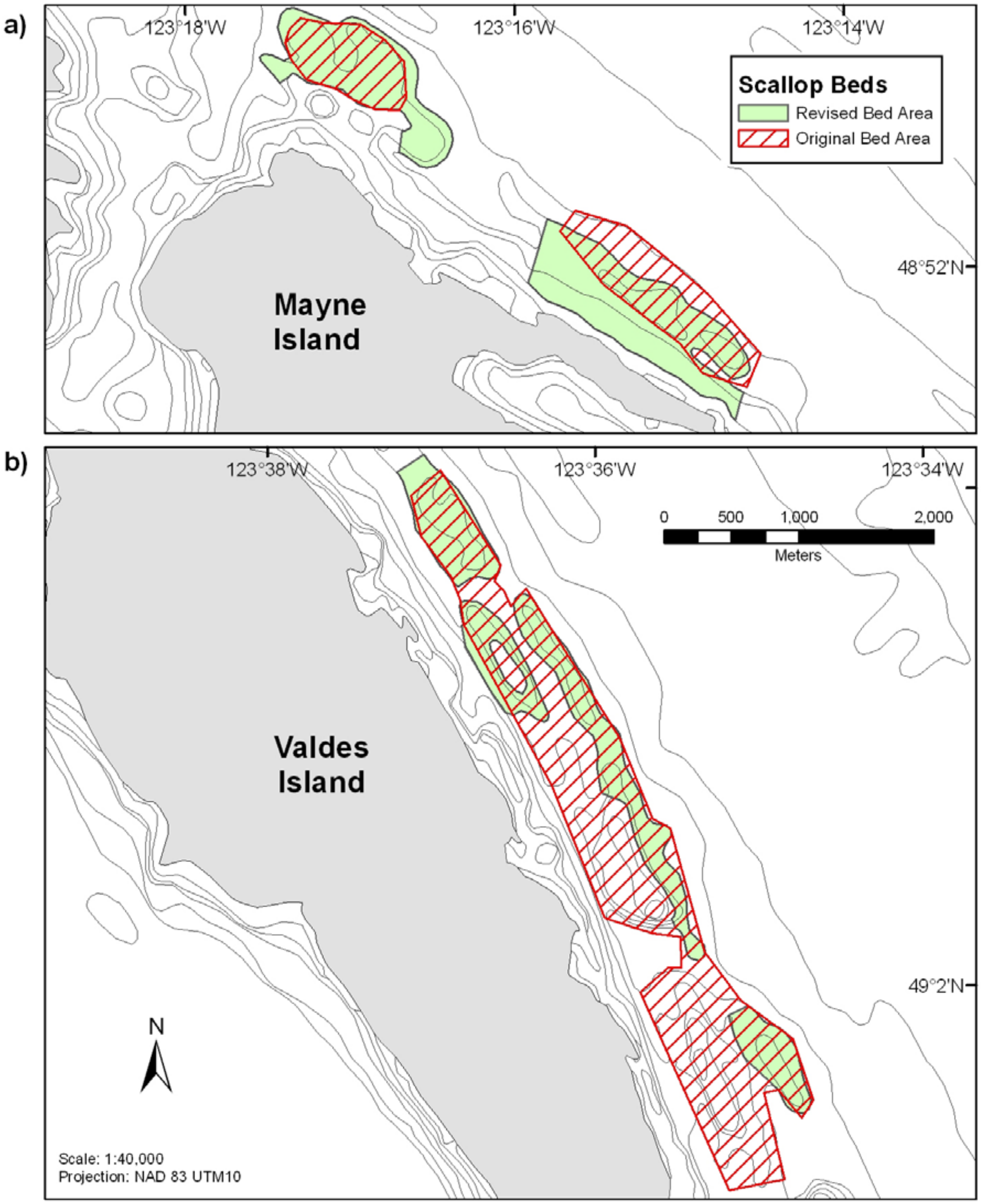

Figure 4. Scallop beds surveyed in 2001 – 2002 and 2008 – 2009 at a) Mayne Island in PFMA 18-1 and b) Valdes Island in PFMA 29-5.

Mayne Island

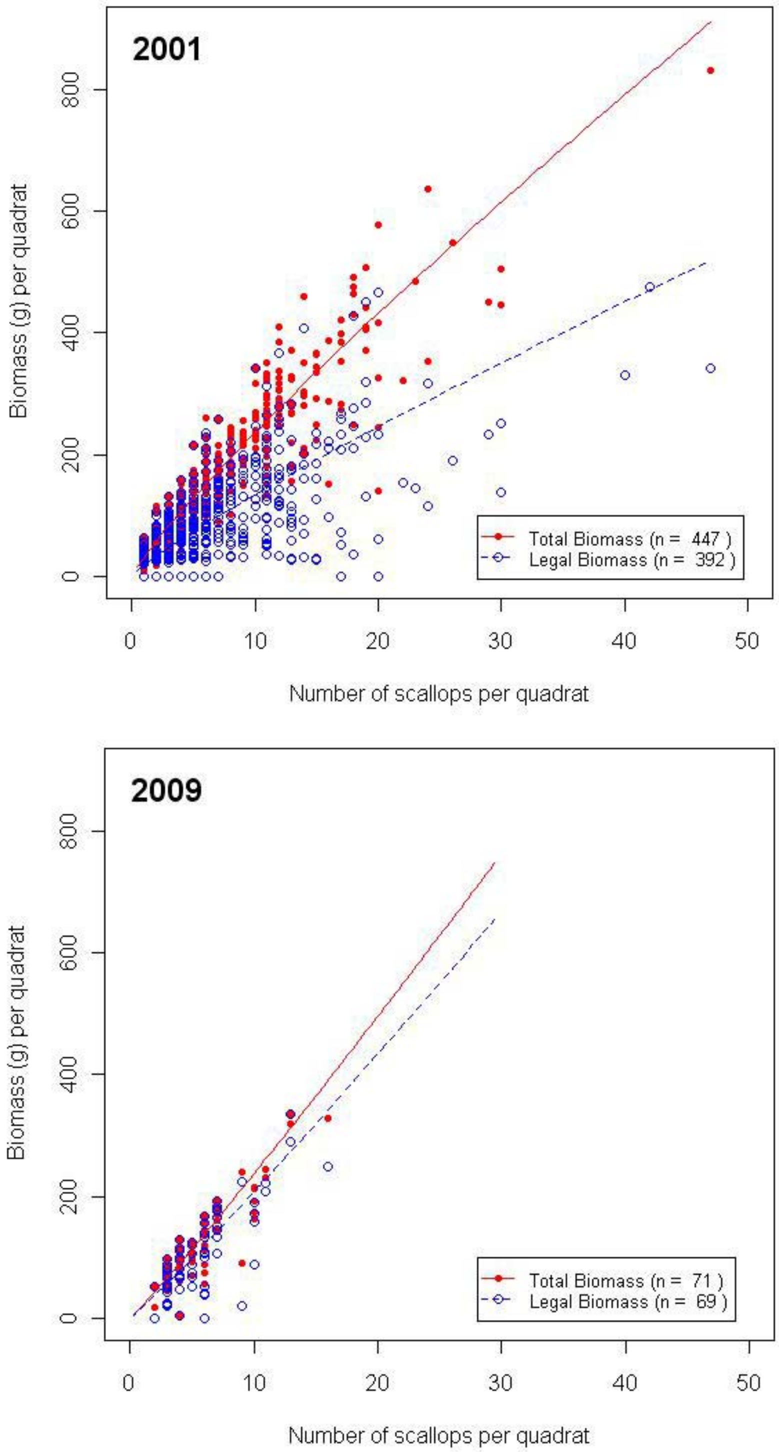

Figure 5. Relationship between biomass (total and legal-sized) and number of scallops per quadrat for SCUBA biological samples from Mayne Island dive/Video and dive/ROV surveys in 2001 and 2009. The log-transformed regression line for total biomass and the ratio estimator for legal biomass are shown as solid and dashed lines, respectively. Lines are drawn to the maximum range of the video and ROV counts per quadrat.

Valdes Island

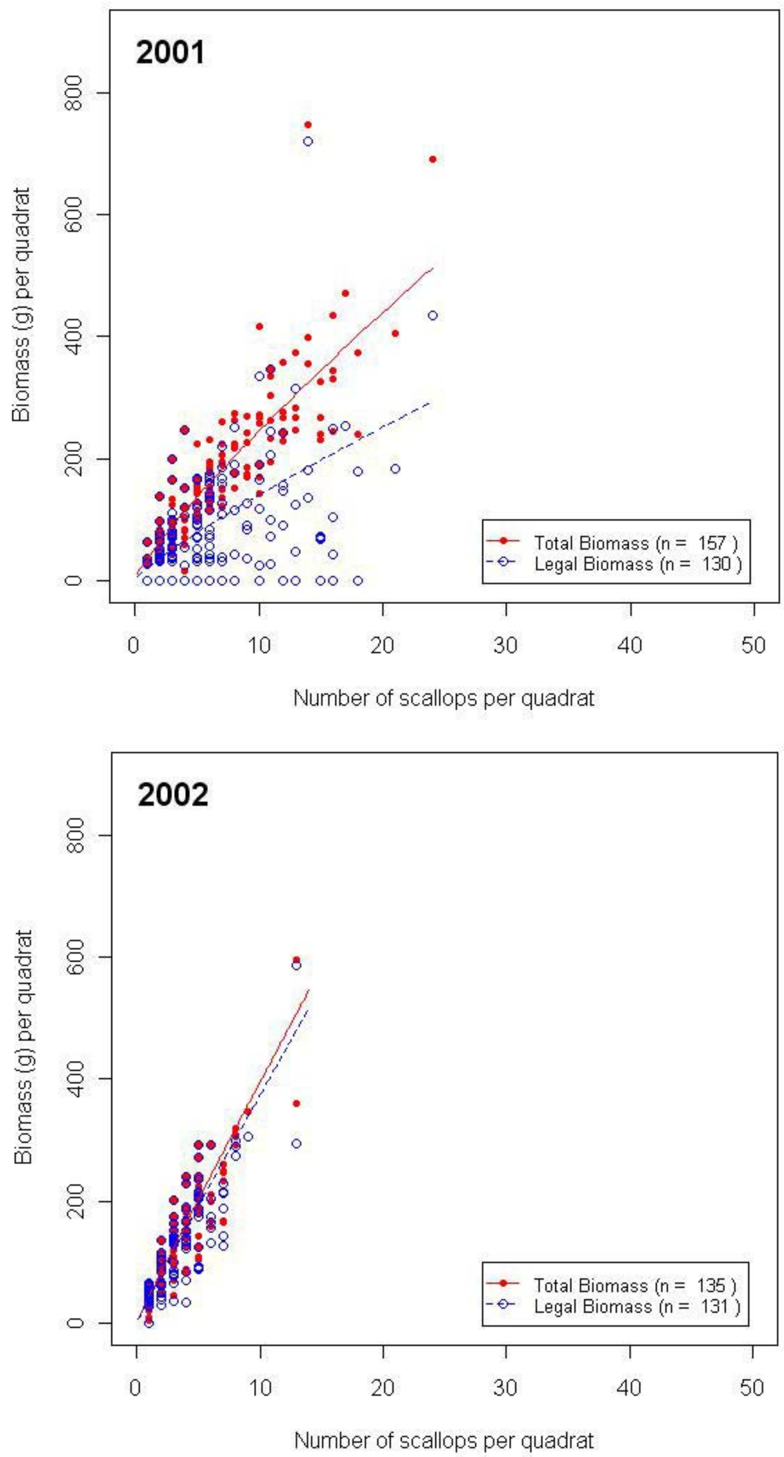

Figure 6. Relationship between biomass (total and legal-sized) and number of scallops per quadrat for SCUBA biological samples from Valdes Island dive/Video surveys in 2001 – 2002. The log-transformed regression line for total biomass and the ratio estimator for legal biomass are shown as solid and dashed lines, respectively. Lines are drawn to the maximum range of the video counts per quadrat.

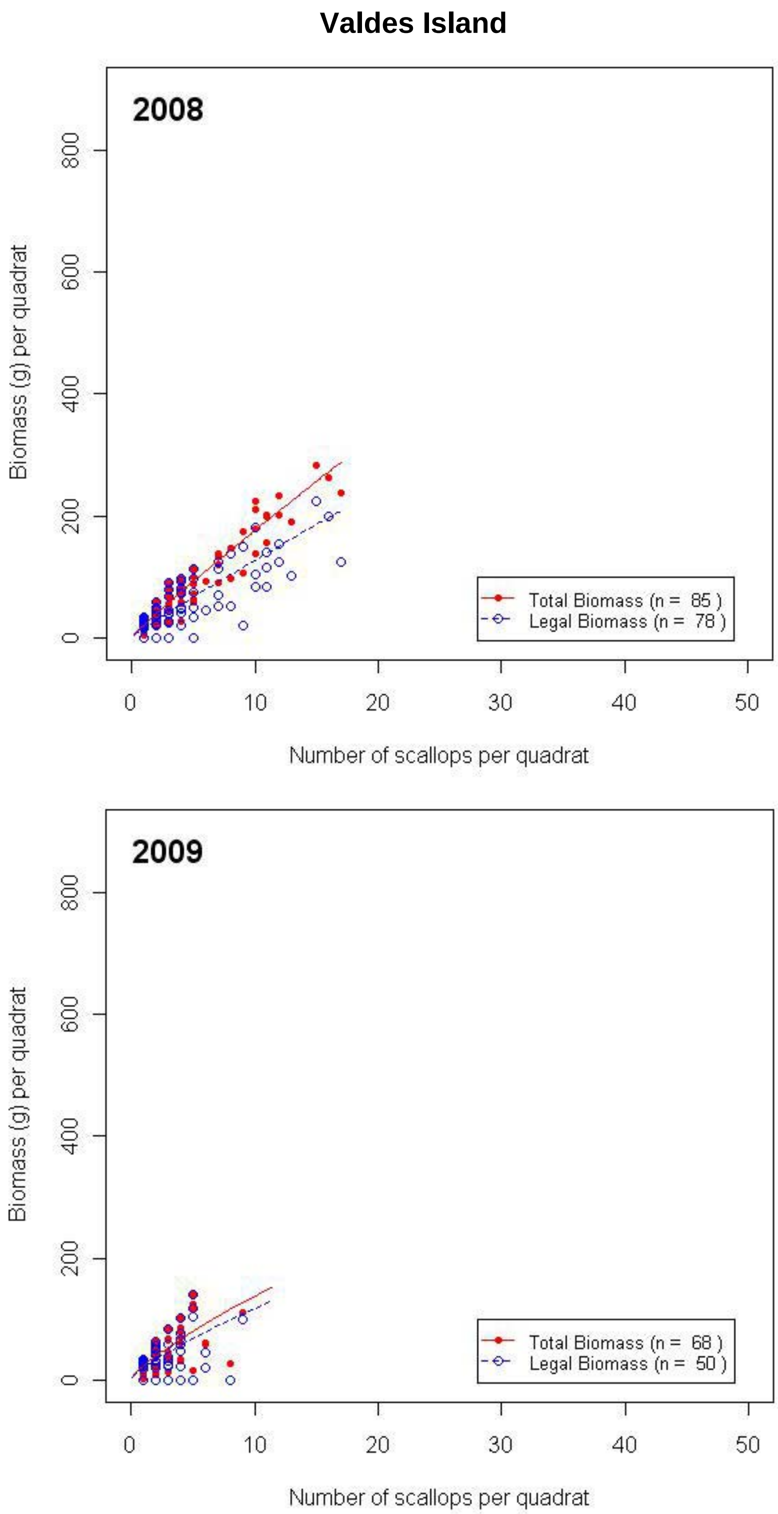

Figure 7. Relationship between biomass (total and legal-sized) and number of scallops per quadrat for SCUBA biological samples from Valdes Island dive/ROV surveys in 2008 – 2009. The log-transformed regression line for total biomass and the ratio estimator for legal biomass are shown as solid and dashed lines, respectively. Lines are drawn to the maximum range of the ROV counts per quadrat.

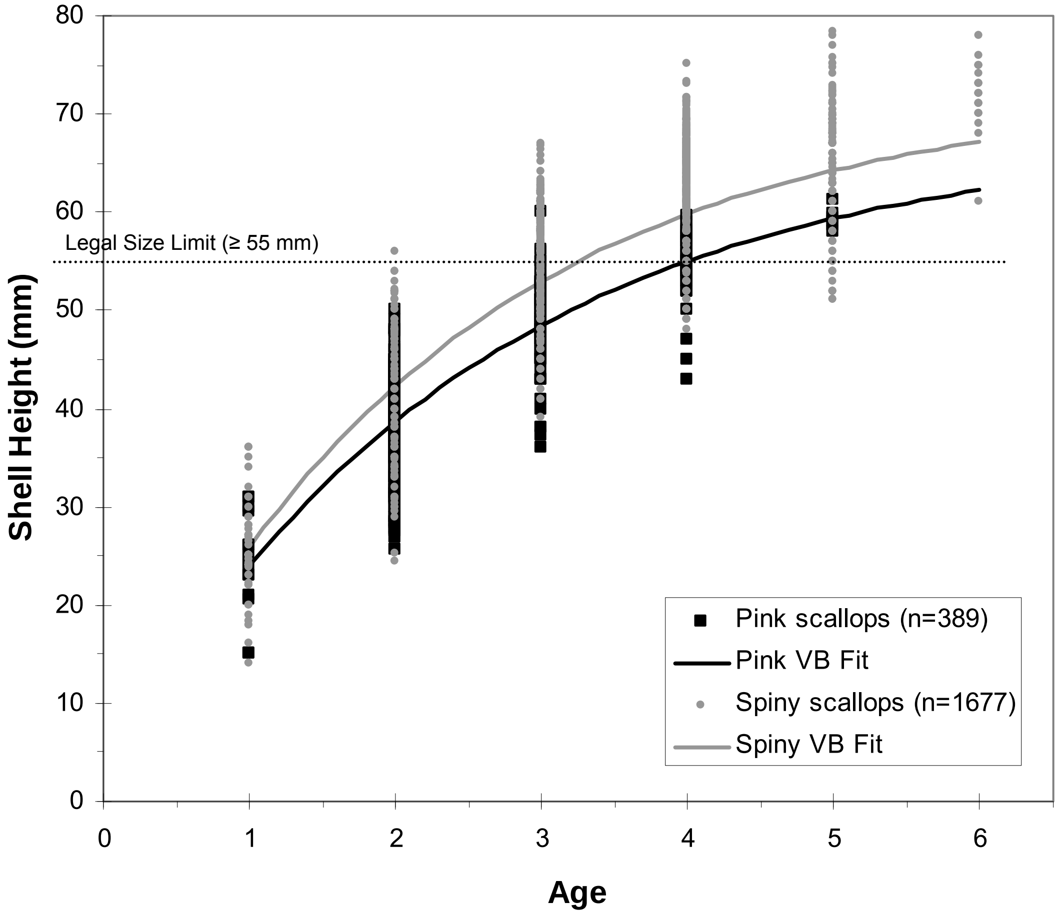

Figure 8. Shell height at age and fitted von Bertalanffy (VB) growth curves for pink and spiny scallops (Chlamys rubida and C. hastata). The minimum legal shell height (55 mm) is drawn for reference. Data is from 2001 dive/video surveys and 2009 dive/ROV surveys at Mayne and Valdes Islands and excludes samples where aging error is suspected.

APPENDIX A. REQUEST FOR SCIENCE INFORMATION AND/OR ADVICE

PART 1: DESCRIPTION OF THE REQUEST – TO BE FILLED BY THE CLIENT REQUESTING THE INFORMATION/ADVICE

Date *(when initial client's submission is sent to Science) (dd/mm/yyyy)***:** 12/11/2009

Directorate, Branch or group initiating the request and category of request	
Directorate/Branch/Group	Category of Request
☒ Fisheries and Aquaculture Management	☒ Stock Assessment
☐ Oceans & Habitat Management and SARA	☐ Species at Risk
☐ Policy	☒ Human impacts on Fish Habitat/ Ecosystem components
☐ Science	☐ Aquaculture
☐ Other (please specify):	☐ Ocean issues
	☐ Invasive Species
	☐ Other (please specify):

Initiating Branch Contact:	
Name: Erin Wylie	Telephone Number: 250 756-7271
Email: erin.wylie@dfo-mpo.gc.ca	Fax Number: 250 756-7162

Issue Requiring Science Advice (i.e., "the question"):
Issue posed as a question for Science response.

What are the recent revisions made to the scallop dive assessment methodology? Have these revisions been peer reviewed to ensure they are scientifically defensible? Will these revisons require, or result in, changes to the current reference points and harvest control rules?

Specific issues / questions to be discussed:
1. Document, evaluate and review current protocols for the collection and analysis of scallop data.
2. Do reference points and harvest control rules need to be revised as a result of the updated assessment methodology and new biological data that has been collected since 2005?
3. What continuing and/or further research activities are required to support assessment and monitoring of scallop populations in BC?

Rationale for Advice Request:
What is the issue, what will it address, importance, scope and breadth of interest, etc.?

In 2000 the unlimited scallop by dive fishery was coverted to a limited experimental fishery to gather information on the stocks and develop appropriate assessment and management strategies. In 2000, a Framework for Pink and Spiny Scallop Fisheries off the West Coast of Canada was presented to PSARC, and in 2005 a subsequent paper was presented to PSARC which analysed two years of data from the experimental scallop fisheries and provided recommendations for the continued assessment and management of the fisheries.

Since the Framework was developed in 2000, FAM has indicated that possible expansion (through both increase in licences and areas fished) of the scallop fishieres may occur. Advances in technology and the aquistion of new equipment have provided opportunities to update and increase efficiency of the survey methodology used to assess scallop stocks. In addition, additional years of biological data may provide the opportunity to update reference points and provide advice on harvest control rules for the dive fishery.

An updated assessment framework is required to review, evaluate and document the revised assessment methodology.

Possibility of integrating this request with other requests in your sector or other sector's needs?

n/a

Intended Uses of the Advice, Potential Impacts of Advice within DFO, and on the Public:
Who will be the end user of the advice (e.g. DFO, another government agency or Industry?). What impact could the advice have on other sectors? Who from the Public will be impacted by the advice and to what extent?

DFO, Industry, First Nations

Date Advice Required:

Latest possible date to receive Science advice (dd/mm/yyyy): Fall 2010

Rationale justifying this date: To incorporate new technologies in the assessment framework, and evaluate the research done with Larocque funding.

Funding:
Specific funds may already have been identified to cover a given issue (e.g. SARCEP, Ocean Action Plan, etc.)

Source of funding: A-base / Larocque Funding

Expected amount: n/a

Initiating Branch's Approval:

Approved by Initiating Director: ☒ Date (dd/mm/yyyy): 15/01/2010

Name of initiating Director: Sue Falinger, Regional Director, F isheries and Aquaculture Management

Send form via email attachment following instructions below:

Regional request: Depending on the region, the coordinator of the Regional Centre for Science Advice or the Regional Director of Science will be the first contact person. Please contact the coordinator in your region to confirm the approach.

National request: At HQ, the Director of the Canadian Science Advisory Secretariat (Denis.Rivard@dfo-mpo.gc.ca) AND the Director General of the Ecosystem Science Directorate (Sylvain.Paradis@dfo-mpo.gc.ca) will be the first contact persons.

PART 2: **RESPONSE FROM SCIENCE**

In the regions: to be filled by the Regional Centre for Science Advice.
At HQ: to be filled by the Canadian Science Advisory Secretariat in collaboration with the Directors of the Science program(s) of concern.

Criteria characterising the request:	**Constraints regarding the planning of a standard peer review/Workshop:**	**Other criteria that could affect the choice of the process, the timelines, or the scale of the meeting:**
☒ Science advice is requested (rather than just information) ☐ A sound basis of peer-reviewed information and advisory precedent already exists. ☐ Inclusiveness is an issue ☐ Advice on this specific issue has been provided in the past. ☐ Urgent request. ☐ DFO is not the final advisory body. ☐ CEAA process ☐ COSEWIC process ☐ Other:	☐ External expertise required ☐ This is a scientifically controversial issue, i.e., consensus does *not* currently exist within DFO science. ☐ Extensive preparatory work is required. ☐ Determination of information availability is required (prior to provision of advice). ☐ Resources supporting this process are not available. ☐ Expected time needed for the preparatory work: ☐ Other (please specify):	☐ The response provided could be considered as a precedent that will affect other regions. ☐ The response corresponds to a new framework or will affect the framework currently in place. ☐ Expertise from other DFO regions is necessary. ☐ Other (please specify):
Recommendation regarding the advisory process and the timelines:		
☐ Science Special Response Process (SSRP)	☐ Workshop	☒ Peer Review Meeting

Rationale justifying the choice of process: Can be accomodated at annual invertebrate peer review meeting

Types of publications expected and if already known, number of report for each series:

☐ Science Advisory Report (1) ☐ Research Document (1)
☐ Proceeding (1) ☐ Science Response Report ( )
☐ Other:

Date Advice to be Provided:

☒ Date specified can be met.
☐ Date specified can NOT be met.

Alternate date, as agreed to by client Branch lead and Science lead (dd/mm/yyyy):

OR

☐ No Formal Response to be Provided by Science

Rationale:

- ☐ DFO Science Region does not have the expertise required.
- ☐ DFO Science Region does not have resources available at this time.
- ☐ The deadline can not be met.
- ☐ Not a natural science issue (e.g. socio-economic)
- ☐ Response to a similar question has been provided elsewhere:
  Reference:

Additional explanation:

Science Branch Lead:

Name: Maria Surry Telephone Number: 756-7210
Email:

* Please contact Science Branch lead for additional details on this request.

Science Branch Approval:

Approved by Regional Director, Science (or their delegate authority):
☒ Date (dd/mm/yyyy):

Name of the person who approved the request: Larua Richards, Regional Director Science

Once part 2 completed, the form is sent via email attachment to the initiating Branch contact person.

PART 3: PLANNING OF THE ADVISORY PROCESS

Science Branch Approval:

Coordinator of the event: Janice Mattu

Potential chair(s): Ray Lauzier

Suggested date (dd/mm/yyyy) / period for the meeting: Nov 2010

Need a preparatory meeting: no

Leader of the Steering Committee:

APPENDIX B. MANAGEMENT ACTIONS AND KEY EVENTS IN THE PINK AND SPINY SCALLOP COMMERCIAL AND EXPERIMENTAL / EXPLORATORY DIVE FISHERIES IN BRITISH COLUMBIA 1982 – 2010.

Year	Event
1982	• First directed fishery for pink and spiny scallops in British Columbia; • First biological sampling of commercial trawl catch in PFMA 19 to determine appropriate legal size limit; • Size limit set at ≥ 60 mm shell height.
1985 - 1986	• Biological sampling of commercial dive catch in PFMAs 14, 17, 18, and 29 to investigate size at maturity, spawning, growth rates, and aging methods.
1989	• Size limit reduced to ≥ 55 mm shell height.
1993	• Trawl closures to protect dive habitat in PFMAs 17, 18, 19, 29.
1998 (end of year)	• PFMA 29-5 closed due to concerns regarding localized depletion.
1999	• Phase 0 Review presented to PSARC.
1999 (end of year)	• Commercial fishery closed.
2000	• Phase I Assessment Framework presented to PSARC; • Start of experimental fishery under scientific license; • Number of dive licenses unlimited; • Dive fishery restricted to PFMAs 13 – 20 and 29; • First industry biological samples collected from Shelter Point (14-13), PFMA 15-3, Gabriola Island (17-10), Mayne Island (18-1), and Valdes Island (29-5).
2001	• Dive licenses limited to stakeholders with a minimum of 10,000 lbs of landings in 1995 – 1999, or 6,000 lbs in any one of those years; • Stakeholders who didn't meet the eligibility criteria but participated in the first year of the experimental fishery restricted to PFMAs 13 and 20; • Industry biological samples collected in Juan de Fuca Strait (PFMA 20); • First dive/video biomass surveys at Mayne and Valdes Islands (PFMAs 18-1 and 29-5)..
2002	• Dive/video biomass surveys at Okisollo Channel (PFMA 13-8,13-10, 13-12), Sentry Shoal (PFMA 14-13), Gabriola Island (PFMA 17-10), and Valdes Island (PFMA 29-5)
2003	• Phase II Update to Assessment Framework presented to PSARC • License year changed to August 1 – July 31
2004	• Trawl fishery restricted to > 20 m to protect dive habitat and maintain separation between sectors
2006/07	• TAC set for PFMAs 18-1 and 29-5 based on 2005/06 catch
2007/08	• Minimal TAC set for PFMA 29-5 in anticipation of a biomass survey
2008 (March)	• Dive/ROV biomass survey at Valdes Island (PFMA 29-5)
2008/09	• TAC set for 29-5 based on survey results from March 2008
2009 (March)	• Dive/ROV biomass survey at Mayne Island (PFMA 18-1)
2009/10	• TAC set for 18-1 based on survey results from March 2009 • TAC set for 29-5 based on unused quota carried over from 2008/09
2009 (October)	• Dive/ROV biomass survey at Valdes Island (PFMA 29-5)

APPENDIX C. STANDARD SUBSTRATE CLASSIFICATIONS AS UTILIZED BY THE SHELLFISH SECTION AT PBS

Code	Description
0	Wood, Bark, or Wood Debris
1	Bedrock, smooth without crevices
2	Bedrock with crevices
3	Boulders, bigger than a basketball
4	Cobble, between 3 inches and basketball size
5	Gravel, between 3/4 inch and 3 inch
6	Pea Gravel, between 1/8 inch and 3/4 inch
7	Sand
8	Shell
9	Mud
10	Crushed Shell
11	Whole Shell

APPENDIX D. PERL CODE FOR IMAGE PROCESSING PROGRAMS

```
# October 2009
#
# Function to process ROV photos - extracts the exif data from the filename,
# and writes the exif tags to the photos.
#
# Processes jpg files recursively (drills down into subdirectories) based on the
# starting directory.
#
# Note: to create a windows standalone executable, use pp with the following
# syntax: pp -S -o processROV.exe processROV.pl

#!perl

# Add the ExifTool directories to the @INC path
use lib "C:/Perl/site/lib/";
use lib "C:/Perl/site/lib/Image/ExifTool/";

# Call the modules
use Image::ExifTool;
use File::Find;
use Cwd;

# Establish the starting directory
my $dir = getcwd;

my $file = "test.jpg";

open OUTFILE, ">$dir/ROVexif.txt";
print OUTFILE
"filename,date,time,ImageNumber,GPSAltitude,GPSLatitude,GPSLongitude,UserComment\n";

@ARGV = qw(.) unless @ARGV;

# Using the current directory as the start (usually .../photos) and assuming
# that each "dive" or "transect" is in a separate directory, look for jpg files
# in each subdirectory of the current directory.

find(\&exportExif, @ARGV);

sub exportExif {
  /\.jpg/ || /\.JPG/ or return;
  my $file = $_;

  my $exifTool = new Image::ExifTool;
  $exifTool->Options(Duplicates => 0, PrintConv => 0);
  my $info = $exifTool->ImageInfo($file);
  my $num = $$info{ImageNumber};
  my $alt = $$info{GPSAltitude};
  my $lat = $$info{GPSLatitude};
  my $long = $$info{GPSLongitude};
  my $comment = $$info{UserComment};
  my $date;
  my $time;
  ($date, $time) =  split/\s+/,$$info{DateTimeOriginal};  # split up DateTimeOriginal
into date and time
  substr($date,0) =~ s/:/\//g;   # reformat the date to use slashes instead of colons

print OUTFILE "$file,$date,$time,$num,$alt,$lat,$long,$comment\n";
```

```
}
close OUTFILE ;

#my @tags = qw (FileName DateTimeOriginal GPSAltitude GPSLatitude GPSLongitude
UserComment);
#my $info = $exifTool->ImageInfo($file,@tags);
#foreach (keys %$info) {
#    print "$_ => $$info{$_}\n";
#}
```

APPENDIX E. R CODE FOR ESTIMATING BIOMASS

```
# Code to estimate total and legal biomass for scallops from SCUBA dive quadrats
# and video or ROV counts.  Modified from original S-Plus code used by
# Lauzier et al. in 2001 - 2002 (Lauzier et al. 2005).
#
# Maria Surry February 24, 2011
#
################################################################################
#
#  INSTRUCTIONS:
#
# Change the value of the variable 'surv' to the correct location and year.
# This should correspond to the fields "Location" and "Year" from the biodata
# file.
#
# Ensure that the working directory contains biodata.txt and videodata.txt.
# These text files should have the following fields (see example file):
#   biodata.txt: StatArea, Location, Year, QuadSize, CountTotal, WtTotal, LegalWtTotal
#   videodata.txt: StatArea, Location, Year, QuadSize, CountTotal
#
# Create these files by exporting from the scallop dive bio database.
#
################################################################################

# remove all objects in the working directory
rm(list=ls())

# Specify the correct survey name & year
surv <- "Mayne 2009"

#Data normalized to quadrats of this size(m^2)
StandQuadSize <- 0.25
n.boot<-1000

#initial estimates for parameter values
set.seed(756)
x0<-3
x1<-.5

#Equations for estimating parameter values from data.

################################################################################
# Model assuming no zeros in the Biomass
#
# The model is:
# Biomass=exp(x0+x1*lnP+epsilon)
# B is biomass.  P is population.  x0 and x1 are model parameters
# This is just a fancy wrapper on a linear regression of ln(B)~ln(P).
# The regression coefficients are x0 and x1.

#Estimate total biomass from population
estB<-function(x0,x1,P)
{
       B<-exp(x0+x1*log(P) )
       return(B)
}

#Error in logs between predicted and observed biomass.
epsilon<-function(x0,x1,B,P)
       {
```

```
	eps<- log(B)-log(estB(x0,x1,P))
	return(eps)
	}

#Sum of square of error (logs) when biomass is predicted from population
sum.sqr.dif<-function(x,B,P)
	{
	x0<-x[1]
	x1<-x[2]
	eps<-epsilon(x0,x1,B,P)
	sum.sqr<- sum(eps*eps)
	return(sum.sqr)
	}

#Mean square error when biomass is predicted from population
mean.sqr.dif<-function(x,B,P)
	{
	use.data<- (!is.na(B)) &  (!is.na(P))
	n.coef<-2
	sum.sqr<-sum.sqr.dif(x,B[use.data],P[use.data])
	n<-sum(use.data)

	mean.sqr<- sum.sqr/(n-n.coef)
	return(mean.sqr)
	}

#Find the parameter values that best fit the data.
fit.exp<-function(x0,x1,B,P)
	{
	x<-c(x0,x1)
	n.coef<-2
	fit.res<-nlminb(as.vector(x),mean.sqr.dif,B=B,P=P)
	sigma<-sqrt(mean.sqr.dif(fit.res$par,B, P))
	return(list(x0=fit.res$par[1],x1=fit.res$par[2], sigma=sigma))
}

#Resample biosample-quadrats before estimating model parameters
resamp.fit.exp<-function(x0,x1,B,P)
	{
	n<-length(B)
	index<-1:n
	resamp.index<-sample(index,n,replace=T)
	fit.val<-fit.exp(x0,x1,B[resamp.index],P[resamp.index])
	return( fit.val )
}

#Mean  Biomass Density for given parameters and Population (per quadrat)
#Zero population means zero biomass
MeanQuadBmass<-function(params,P.surv)
{
	P<-P.surv[!is.na(P.surv)]
	x0<-params$x0
	x1<-params$x1
	sigma<-params$sigma

	NonZero<- (P>0)
	n<- length(P)

	#Default value is zero
	AvgB<-array(0,n)

	#Use equation where population is not zero
```

```
	#exp(sigma*sigma/2) is necessary to deal with the bias introduced by back-
transforming the data
	AvgB[NonZero] <-estB(x0,x1,P[NonZero])*exp(sigma*sigma/2)
	return (AvgB)
}

#Mean biomass over all quadrats for given parameters and Population
#Zero population means zero biomass
MeanSurvBmass<-function(params,P.surv)
{
	QuadratAverage<-MeanQuadBmass(params,P.surv[!is.na(P.surv)])
	return(mean(QuadratAverage) )
}

#Resample the population values before estimating mean biomass
resamp.MeanSurvBmass<-function(params,P)
{
	n<-length(P)
	index<-1:n
	resamp.index<-sample(index,n,replace=T)
	return(MeanSurvBmass(params,P[resamp.index]))
}

#Resample bio-data and population data before estimating mean biomass
resampAll.MeanSurvBmass<-function(x0.init,x1.init,B.bio,P.bio, P.surv)
{
	resamp.param<-resamp.fit.exp(x0.init,x1.init,B.bio,P.bio)
	resamp.Bmass<-resamp.MeanSurvBmass(resamp.param,P.surv)
	return(resamp.Bmass)
}
#Special version that will take advantage of tapply.  Useful for bootstrapping.
#First variable is ignored
tapply.resampAll.MeanSurvBmass<-function(dummy,x0.init,x1.init,B.bio,P.bio, P.surv)
{return(resampAll.MeanSurvBmass(x0.init,x1.init,B.bio,P.bio, P.surv))}

#Generate bootstrap iterations of mean biomass densities
GenBoot.MeanSurvBmass<-function(x0.init,x1.init,B.bio,P.bio, P.surv,n.boot=1000)
{
	dummy<-1:n.boot

	#tapply is used because it is an efficient way to populate an array
	result<-tapply(1:n.boot, 1:n.boot,FUN=tapply.resampAll.MeanSurvBmass,
			x0.init=x0.init,x1.init=x1.init,B.bio=B.bio,
			P.bio=P.bio, P.surv=P.surv)
	return(result)
}

#Generate statistics

## generate 95%, 90% and 75% CI
EstDens<-function(x0.init,x1.init,B.bio,P.bio, P.surv,n.boot=1000)
{
	#Estimate parameters for model
	params<-fit.exp(x0,x1,B.bio,P.bio)

	#Estimate average
	DensAvg<-MeanSurvBmass(params,P.surv)

	#Generate bootstrap means
	boot.mean<-GenBoot.MeanSurvBmass(params$x0,params$x1,B.bio,P.bio,
P.surv,n.boot=n.boot)
	bias<-mean(boot.mean)-DensAvg
```

```
	bnd<-quantile(boot.mean,probs=c(.025,.05,.125, .875, .95,.975))-bias

	return(list(
	EstAvg=DensAvg,low95=bnd[1],low90=bnd[2],low75=bnd[3],upp75=bnd[4],upp90=bnd[5]
,upp95=bnd[6],

	x0=params$x0,x1=params$x1,ModelSigma=params$sigma,bias=bias) )
	}

#Standardize the data to a specified quadrat size (0.25m2 is the default)
StandQuadSizeBiodata<-function(BioData, StandQuadSize)
{
	BioData[,c("QuadSize","CountTotal","WtTotal","LegalWtTotal")]<-
BioData[,c("QuadSize","CountTotal","WtTotal","LegalWtTotal")]*StandQuadSize/BioData$Qu
adSize
	return(BioData)
}

StandQuadSizeVideoData<-function(VideoData, StandQuadSize)
{
	VideoData[,c("QuadSize","CountTotal")]<-
VideoData[,c("QuadSize","CountTotal")]*StandQuadSize/VideoData$QuadSize
	return(VideoData)
}

#############################################################
# MODEL USING TOTAL WEIGHT

biomass.calc <- function (BioData, VideoData) {

  #Calculate the values

  BmassDens<-EstDens(x0,x1,BioData$WtTotal,BioData$CountTotal,
VideoData$CountTotal,n.boot=n.boot)

  #Save results to a text file in the current working directory

write.table(data.frame(Survey=surv,BmassDens,row.names=NULL),file=paste(surv,"BmassDen
s.csv"),row.names=F,sep=",",quote=F)

  return(BmassDens)
}

###################################################################

# Find the linear relationship between legal biomass and total biomass
lm.wtDiff <- function(dataframe) {
  lm.surv <- lm(LegalWtTotal~WtTotal - 1, data = dataframe)
  EstAvg <- summary(lm.surv)$coefficients[1]
  SE <- summary(lm.surv)$coefficients[2]
  lm.slope <- round(EstAvg,2)
  low95 <- confint(lm.surv,level=0.90)[1]
  upp95 <- confint(lm.surv,level=0.90)[2]
  low90 <- confint(lm.surv,level=0.80)[1]
  upp90 <- confint(lm.surv,level=0.80)[2]
  low75 <- confint(lm.surv,level=0.50)[1]
  upp75 <- confint(lm.surv,level=0.50)[2]
  legalRatio <- data.frame(Survey=surv,EstAvg,low95,low90,low75,upp75,upp90,upp95,SE)

  #Save results to a text file in the current working directory

write.table(legalRatio,file=paste(surv,"_legalRatio.csv"),row.names=F,sep=",",quote=F)
```

```
  return (EstAvg)

  }

################################################################################
##Actually call the functions and spit out the parameter estimates

# import data from text file
# text files should have the following fields:
# biodata.txt: StatArea, Location, Year, QuadSize, CountTotal, WtTotal, LegalWtTotal
# videodata.txt: StatArea, Location, Year, QuadSize, CountTotal
BioData <- read.table("biodata.txt",header=T)
VideoData <- read.table("videodata.txt",header=T)

#Standardize data to quadrat size, remove the extra zeros, create a "Survey" field
#BioData<-StandQuadSizeBiodata(BioData, StandQuadSize=StandQuadSize) #all BioData is
collected with 0.25m^2 quadrats - any other values are mistakes
VideoData <-StandQuadSizeVideoData(VideoData, StandQuadSize=StandQuadSize) #VideoData
quadrats can vary because photo sizes vary
BioData <-BioData[BioData$WtTotal>0, ]
BioData <- data.frame(Survey=paste(BioData$Location,BioData$Year),BioData)
VideoData <- data.frame(Survey=paste(VideoData$Location,VideoData$Year),VideoData)

#Calculate the total biomass and legal ratio
BmassDens <- biomass.calc(BioData,VideoData)
wtDiff <- lm.wtDiff(BioData)

###############################
# plots to show estimates of legal biomass

ytitle<-"Biomass (g) per quadrat"
xtitle<-"Number of scallops per quadrat"

x.st<-.01*c(1:100)*max(VideoData$CountTotal,BioData$CountTotal,na.rm=T)

#set up the legend text
n.total <- length(BioData$WtTotal)
n.legal <- length(BioData$LegalWtTotal[BioData$LegalWtTotal>0])
label.total <- paste("Total Biomass (n = ",n.total,")")
label.legal <- paste("Legal Biomass (n = ",n.legal,")")

#draw the plot
plot(x.st,estB(BmassDens$x0,BmassDens$x1,x.st),type="n",
  main=surv,
  xlab=xtitle,
       ylab=ytitle,
  xlim=c(0,50),
  ylim=c(0,900))
  points(BioData$CountTotal,BioData$WtTotal,col="red",pch=20,)
  points(BioData$CountTotal,BioData$LegalWtTotal,col="blue",pch=21)


lines(x.st,estB(BmassDens$x0,BmassDens$x1,x.st)*exp((BmassDens$ModelSigma^2)/2),col="r
ed")

lines(x.st,estB(BmassDens$x0,BmassDens$x1,x.st)*exp((BmassDens$ModelSigma^2)/2)*wtDiff
,col="blue",lty=2)

  legend(28,100,c(label.total,label.legal),cex=0.8, pt.cex=1.0,lty = c(1,2),pch =
c(20,21), col=c("red","blue"))

savePlot(file=paste(surv,"_biomass"),type="jpg")
```

APPENDIX F. SUMMARY STATISTICS FOR PINK AND SPINY SCALLOP BIOLOGICAL SAMPLES COLLECTED BY THE SCALLOP INDUSTRY (I) OR AS PART OF SCALLOP DIVE/VIDEO OR DIVE/ROV SURVEYS (S) IN 2000 – 2009. STATISTICS ARE GIVEN FOR MALES (M), FEMALES (F), UNKNOWN/UNDETERMINED SEX (U), AND TOTAL SAMPLES.

Pink Scallops: Shell Height (mm)

Location	Type	Date	Sample Size				Minimum				Maximum				Mean				Standard Deviation			
			M	F	U	Total	M	F	U	Total	M	F	U	Total	M	F	U	Total	M	F	U	Total
Area 15	I	2000	13	1	--	14	49.9	53.4	--	49.9	60.0	53.4	--	60.0	55.6	53.4	--	55.4	3.4	--	--	3.3
Gabriola	I	April 2000	37	29	--	66	47.0	43.0	--	43.0	58.0	58.0	--	58.0	51.5	50.7	--	51.1	2.6	3.0	--	2.8
Mayne	I	March 2000	82	54	--	136	31.3	48.6	--	31.3	62.3	59.9	--	62.3	54.0	54.9	--	54.4	4.8	2.6	--	4.1
Shelter	I	March 2000	--	--	9	9	--	--	43.0	43.0	--	--	60.0	60.0	--	--	52.6	52.6	--	--	5.5	5.5
Valdes	I	June 2000	170	111	--	281	39.0	33.0	--	33.0	62.0	62.0	--	62.0	54.6	53.2	--	54.1	3.6	4.9	--	4.2
J de F*	I	March 2001	26	21	--	47	33.7	32.2	--	32.2	60.6	59.6	--	60.6	48.2	49.2	--	48.6	7.5	6.5	--	7.0
Mayne	S	April 2001	93	64	2	159	21.0	26.0	15.0	15.0	58.0	53.0	15.0	58.0	42.6	42.1	15.0	42.1	7.2	6.6	0.0	7.6
Valdes	S	March 2001	86	109	1	196	31.0	31.0	53.0	31.0	61.0	59.0	53.0	61.0	44.3	46.4	53.0	45.5	7.9	7.4	--	7.7
Gabriola	S	March 2002	53	15	--	68	40.0	41.0	--	40.0	56.0	59.0	--	59.0	47.6	47.9	--	47.7	3.0	4.2	--	3.3
Okisollo	S	March 2002	31	8	--	39	30.0	34.0	--	30.0	51.0	49.0	--	51.0	42.0	41.4	--	41.8	5.3	4.7	--	5.2
Sentry	S	Feb 2002	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Valdes	S	Mar-Apr 2002	9	6	--	15	36.0	35.0	--	35.0	55.0	65.0	--	65.0	46.4	48.5	--	47.3	7.3	10.6	--	8.5
Mayne	S	March 2009	36	25	--	61	29.5	34.0	--	29.5	59.7	61.3	--	61.3	48.4	48.5	--	48.4	7.7	8.0	--	7.7
Valdes	S	Oct 2009	32	21	--	53	20.6	23.0	--	20.6	59.9	57.7	--	59.9	37.6	36.7	--	37.2	10.5	9.1	--	9.9

Spiny Scallops: Shell Height (mm)

Location	Type	Date	Sample Size				Minimum				Maximum				Mean				Standard Deviation			
			M	F	U	Total	M	F	U	Total	M	F	U	Total	M	F	U	Total	M	F	U	Total
Area 15	I	2000	301	261	47	609	29.9	26.2	48.4	26.2	75.1	76.3	73.1	76.3	63.2	63.7	63.5	63.4	5.2	6.1	4.7	5.5
Gabriola	I	April 2000	359	352	--	711	29.0	33.0	--	29.0	73.0	74.0	--	74.0	59.3	60.3	--	59.8	5.2	5.0	--	5.1
Mayne	I	March 2000	649	618	--	1267	31.4	29.1	--	29.1	70.6	74.4	--	74.4	58.1	58.8	--	58.4	4.5	4.0	--	4.3
Shelter	I	March 2000	664	779	20	1463	35.0	41.0	19.0	19.0	74.0	75.0	35.0	75.0	59.7	60.8	27.2	59.9	4.7	4.6	5.8	6.1
Valdes	I	June 2000	605	492	--	1097	36.0	39.0	--	36.0	74.0	76.0	--	76.0	62.1	63.4	--	62.6	4.4	5.1	--	4.7
J de F*	I	March 2001	635	672	--	1307	32.7	34.9	--	32.7	74.7	74.0	--	74.7	58.9	58.5	--	58.7	6.2	6.3	--	6.3
Mayne	S	April 2001	338	302	17	657	24.0	25.0	14.0	14.0	67.0	78.0	55.0	78.0	51.2	52.4	27.5	51.1	8.6	7.5	12.5	9.1
Valdes	S	March 2001	333	309	--	642	24.0	30.0	--	24.0	78.0	76.0	--	78.0	54.2	56.1	--	55.1	8.4	8.2	--	8.4
Gabriola	S	March 2002	76	56	--	132	46.0	48.0	--	46.0	70.0	70.0	--	70.0	59.2	59.2	--	59.2	4.8	4.7	--	4.8
Okisollo	S	March 2002	348	170	3	521	23.0	31.0	27.0	23.0	67.0	68.0	30.0	68.0	48.3	52.2	29.0	49.4	7.1	6.3	1.7	7.3
Sentry	S	Feb 2002	184	193	9	386	24.0	40.0	53.0	24.0	72.0	77.0	68.0	77.0	58.8	60.9	61.8	59.9	6.1	5.6	5.2	5.9
Valdes	S	Mar-Apr 2002	176	150	9	335	31.0	38.0	25.0	25.0	73.0	74.0	35.0	74.0	57.2	61.6	29.0	58.4	10.1	6.4	3.0	10.0
Mayne	S	March 2009	190	158	--	348	24.4	20.4	--	20.4	75.8	76.9	--	76.9	60.0	61.2	--	60.5	9.4	7.9	--	8.8
Valdes	S	Oct 2009	49	69	--	118	18.3	22.2	--	18.3	71.6	78.3	--	78.3	55.0	60.4	--	58.1	15.0	11.6	--	13.3

* J de F = Juan de Fuca Strait

Appendix F. (Continued)

Pink Scallops: Weight (g)

Location	Type	Date	Sample Size				Minimum				Maximum				Mean				Standard Deviation			
			M	F	U	Total	M	F	U	Total	M	F	U	Total	M	F	U	Total	M	F	U	Total
Mayne	S	April 2001	93	64	2	159	5.0	6.0	4.0	4.0	26.0	22.0	4.0	26.0	12.3	12.3	4.0	12.2	4.0	3.7	--	3.9
Valdes	S	March 2001	86	109	1	196	3.0	4.0	18.0	3.0	27.0	27.0	18.0	27.0	12.7	14.1	18.0	13.5	6.7	6.2	--	6.4
Gabriola	S	March 2002	53	15	--	68	6.0	7.0	--	6.0	19.0	19.0	--	19.0	11.9	11.7	--	11.8	2.3	3.0	--	2.5
Okisollo	S	March 2002	31	8	--	39	3.0	4.0	--	3.0	14.0	11.0	--	14.0	7.5	7.0	--	7.4	2.8	2.4	--	2.7
Sentry	S	Feb 2002	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Valdes	S	Mar-Apr 2002	9	6	--	15	4.0	4.0	--	4.0	17.0	25.0	--	25.0	12.1	12.5	--	12.3	5.4	7.4	--	6.0
Mayne	S	March 2009	36	25	--	61	1.9	2.6	--	1.9	20.0	21.3	--	21.3	11.1	11.5	--	11.3	5.1	5.8	--	5.4
Valdes	S	Oct 2009	32	21	--	53	1.1	1.3	--	1.1	24.7	23.3	--	24.7	7.9	6.9	--	7.5	6.9	5.6	--	6.4

Spiny Scallops: Weight (g)

Location	Type	Date	Sample Size				Minimum				Maximum				Mean				Standard Deviation			
			M	F	U	Total	M	F	U	Total	M	F	U	Total	M	F	U	Total	M	F	U	Total
Mayne	S	April 2001	338	302	17	657	5.0	6.0	4.0	4.0	38.0	38.0	21.0	38.0	19.8	20.6	6.9	19.9	6.5	5.7	5.4	6.5
Valdes	S	March 2001	333	309	--	642	1.0	3.0	--	1.0	43.0	49.0	--	49.0	20.2	22.4	--	21.3	7.5	8.2	--	7.9
Gabriola	S	March 2002	76	56	--	132	11.0	10.0	--	10.0	29.0	31.0	--	31.0	19.7	20.5	--	20.1	4.3	5.1	--	4.7
Okisollo	S	March 2002	348	170	3	521	2.0	3.0	2.0	2.0	25.0	27.0	3.0	27.0	11.0	13.7	2.7	11.8	4.3	4.5	0.6	4.6
Sentry	S	Feb 2002	184	193	9	386	2.0	7.0	24.0	2.0	56.0	98.0	44.0	98.0	33.0	37.3	35.7	35.2	10.3	12.5	7.3	11.6
Valdes	S	Mar-Apr 2002	176	150	9	335	4.0	6.0	2.0	2.0	35.0	35.0	4.0	35.0	20.3	23.8	2.9	21.4	8.3	6.2	0.8	8.1
Mayne	S	March 2009	190	158	--	348	1.4	2.6	--	1.4	35.2	67.8	--	67.8	18.8	19.8	--	19.3	6.5	8.0	--	7.2
Valdes	S	Oct 2009	49	69	--	118	0.6	1.4	--	0.6	33.3	41.2	--	41.2	18.7	22.3	--	20.8	9.8	8.5	--	9.2

Pink Scallops: Thickness (mm)

Location	Type	Date	Sample Size				Minimum				Maximum				Mean				Standard Deviation			
			M	F	U	Total	M	F	U	Total	M	F	U	Total	M	F	U	Total	M	F	U	Total
Gabriola	S	March 2002	53	15	--	68	11.0	12.0	--	11.0	18.0	16.0	--	18.0	14.2	14.1	--	14.2	1.3	1.4	--	1.3
Okisollo	S	March 2002	31	8	--	39	8.0	9.0	--	8.0	15.0	14.0	--	15.0	12.1	11.8	--	12.1	2.1	1.6	--	2.0
Valdes	S	Mar-Apr 2002	9	6	--	15	9.0	9.0	--	9.0	18.0	18.0	--	18.0	14.1	13.3	--	13.8	3.1	3.3	--	3.1
Mayne	S	March 2009	36	25	--	61	8.0	9.0	--	8.0	21.0	19.0	--	21.0	15.0	14.7	--	14.9	3.1	2.9	--	3.0
Valdes	S	Oct 2009	32	21	--	53	5.0	5.0	--	5.0	19.0	17.0	--	19.0	10.7	10.1	--	10.5	3.9	3.2	--	3.6

Spiny Scallops: Thickness (mm)

Location	Type	Date	Sample Size				Minimum				Maximum				Mean				Standard Deviation			
			M	F	U	Total	M	F	U	Total	M	F	U	Total	M	F	U	Total	M	F	U	Total
Gabriola	S	March 2002	76	56	--	132	13.0	13.0	--	13.0	21.0	21.0	--	21.0	16.8	16.9		16.8	1.6	1.6	--	1.6
Okisollo	S	March 2002	348	170	3	521	8.0	9.0	7.0	7.0	21.0	21.0	8.0	21.0	14.3	15.7	7.7	14.7	2.4	2.2	0.6	2.5
Valdes	S	Mar-Apr 2002	175	150	9	334	8.0	11.0	7.0	7.0	23.0	22.0	9.0	23.0	16.9	18.1	8.2	17.2	3.4	2.2	0.8	3.3
Mayne	S	March 2009	190	157	--	347	8.0	10.0	--	8.0	23.0	25.0	--	25.0	18.0	18.4	--	18.2	2.8	2.5	--	2.6
Valdes	S	Oct 2009	49	69	--	118	5.0	7.0	--	5.0	22.0	22.0	--	22.0	15.8	17.2	--	16.6	4.3	3.2	--	3.7