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Evaluation of Assessment and Management Frameworks in the British Columbia Depuration Fishery for Intertidal Clams

Examen des cadres d'évaluation et de gestion concernant la pêche de dépuration des coquillages intertidaux en Colombie-Britannique

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Abstract

We reviewed the experimental program in the depuration fishery for intertidal clams in British Columbia. The program consisted of beaches that were regularly surveyed between harvests to evaluate the effectiveness of various harvest rates in ensuring sustainable populations and harvest opportunities. Five beaches were evaluated: three unharvested controls (Mill Bay, Royston and Wall Beach) and two harvested beaches (Booth Bay and Goldstream). Two other beaches, China Cloud Bay and Long Bay, were afforded unrestrained harvest opportunities followed immediately by surveys to establish harvest rates in non-quota clam fisheries. Simple production models currently used to set harvest thresholds were re-evaluated, and population models were used to project biomass, abundance and quotas for several years following surveys.

Population responses to experimental harvest rates changed little from the previous evaluation. Booth Bay remained a highly productive beach even at high harvest rates (25-53%). Population levels and production at Goldstream remained relatively stable at harvest rates of 10-20%. The controls exhibited a range of responses, with a declining trend at Wall Beach and increasing trends at Mill Bay and Royston. None of the new information suggested that target and threshold limits currently used to set harvest rates required changing. Information from China Cloud and Long Bays indicated that harvest rates were approximately 11-13%, considerably less than previous estimates of unrestrained harvest rates.

Relatively low vulnerability of small clams to survey methods was noted from Industry surveys, and vulnerability and sampling error required reconciliation of survey data before the population model was used. The population model could be used to project quotas for approximately three years. Only the use of the median values (0.50 quantiles) of the projected populations yielded practical projections; more precautionary quantiles (0.05 and 0.25) resulted in rapid reductions in quotas. Our opinion is that the model allows for at least one year of projected quota in most cases before declines in quotas would motivate Industry to re-survey.

The paper recommended that current reference points for setting harvest rates be maintained, that the population model can be used to project population characteristics and quotas, and that issues surrounding vulnerability of small clams in Industry surveys be further evaluated.

Résumé

Nous avons passé en revue le programme expérimental de pêche de dépuration des coquillages intertidaux en Colombie-Britannique. Dans le cadre de ce programme, on a procédé régulièrement à des relevés sur certaines plages entre les récoltes pour évaluer dans quelle mesure divers taux d'exploitation pouvaient assurer la durabilité des populations et des récoltes. Cinq plages ont été utilisées : trois plages témoins non exploitées (Mill Bay, Royston et Wall) et deux plages exploitées (Booth Bay et Goldstream). Deux autres plages (China Cloud Bay et Long Bay) ont fait l'objet d'une pêche sans restriction, suivie immédiatement de relevés qui ont permis l'établissement de taux d'exploitation pour les pêches aux coquillages non contingentées. Les modèles de la production simples que l'on utilise actuellement pour établir les seuils de récolte ont été réévalués, et on s'est servi de modèles de la population pour établir des projections de la biomasse, de l'abondance et des quotas sur plusieurs années après les relevés.

La réponse des populations aux taux d'exploitation expérimentaux ont peu varié par rapport à l'évaluation précédente. La plage de Booth Bay est demeurée hautement productive, même à des taux d'exploitation élevés (25 à 53 %). L'effectif et la production de la population à la plage Goldstream sont demeurés relativement stables à des taux d'exploitation de 10 à 20 %. La réponse observée sur les plages témoins a varié, avec une tendance à la baisse pour la plage Wall et une tendance à la hausse pour les plages de Mill Bay et de Royston. Aucune des nouvelles données recueillies ne laisse entrevoir que les objectifs et les seuils utilisés à l'heure actuelle pour établir les taux d'exploitation devraient être revus. L'information concernant les plages de China Cloud Bay et de Long Bay indiquait des taux d'exploitation d'environ 11 à 13 %, ce qui est considérablement moins élevé que les estimations précédentes des taux d'exploitation sans restriction.

On a observé une vulnérabilité relativement faible des petits coquillages aux méthodes employées dans les relevés, comparativement aux relevés de l'industrie; il a donc fallu corriger l'erreur de vulnérabilité et d'échantillonnage dans les données des relevés avant d'utiliser le modèle de la population. On pourrait utiliser le modèle de la population pour établir des projections sur les quotas pour environ trois années. Cependant, seules les valeurs médianes (0,50 quantiles) des populations projetées ont donné des projections valables, les quantiles plus prudents (0,05 et 0,25) donnant des réductions rapides des quotas. Nous pensons que le modèle permet d'établir une projection sur les quotas pour au moins une année dans la plupart des cas, avant que les déclins dans les quotas ne motivent l'industrie à effectuer de nouveaux relevés.

Les auteurs recommandent donc que les points de référence utilisés présentement pour établir les taux d'exploitation soient maintenus, que le modèle de la population puisse être utilisé pour établir des projections sur les caractéristiques des populations et les quotas, et que la question entourant la vulnérabilité des petits coquillages dans les relevés de l'industrie soit réévaluée.

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Introduction

British Columbia clam fisheries

Intertidal clams have a long history of use by First Nations and early settlers to the British Columbia (B.C.) coast (Quayle and Bourne 1972; Bourne 1982, 1986). Commercial fisheries for clams have been carried out for over 100 years. However, the clam industry in B.C. has undergone a shift in focus in the last 20 years. Prior to 1980, the industry was based primarily on butter clams, *Saxidomus gigantea*, and to a lesser extent on littleneck, *Protothaca staminea*, Manila[1], *Venerupis philippinarum*, and razor clams, *Siliqua patula*. There were occasional landings of horse clams, *Tresus capax* and *T. nuttallii*, cockles, *Clinocardium nuttallii*, and eastern softshell clams, *Mya arenaria*. Industry has recently landed primarily Manila and littleneck clams rather than butter clams, primarily due to processing costs and changes in market demand rather than fluctuations in abundance (Bourne 1986). The fishery for steamer clams expanded greatly between 1980 and 1988, with Manila clams being the dominant species taken (Table 1).

Sewage pollution closures of many oyster leases and clam beds in the 1960s precluded the use of what had been productive and accessible molluscan resources. In an attempt to access these resources, the process of depuration was explored. Depuration is the removal, in a controlled environment, of micro-organisms of public health significance from live molluscs (Quayle 1988). In 1971, a pilot project jointly funded by the federal and provincial governments and the B.C. oyster industry explored the feasibility of depurating oysters at a plant built at Ladysmith Harbour (Devlin 1973). In 1973 and 1974, the plant carried out purification experiments on butter, littleneck and Manila clams. These experiments demonstrated that it was possible to depurate commercial quantities of these species to acceptable bacteria levels within 48 hours[2] and that all species exhibited similar depuration rates (Neufeld and Jackson 1975). However, commercial depuration for market was not economically viable and the plant closed.

Wild clam stocks were heavily exploited in the 1980s, resulting in fishery restrictions (*e.g.*, time and area closures) to address conservation concerns. The closure of numerous beaches due to contamination also hampered production from the fishery. Reduced harvests could not meet market demand and product value increased. At this point, depuration became

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[1] Manila clams are also known as Japanese littlenecks, and have historically been placed in the genera *Venus* and *Tapes* and appeared in recent literature as *T. japonica* and *T. phillipinarum* (Coan *et al*. 2000). The first British Columbia specimens were initially described as *Paphia bifurcata* by Quayle (1938).

[2] Depuration plants are required to undertake verification trials to demonstrate efficacy at decontaminating product. Limits are set on levels of contamination in bivalve shellfish at the commencement of the depuration process (time zero). Shellfish may be depurated in 48 hours if contamination levels do not exceed 2,300 Most Probable Number faecal coliforms per 100 g (MPN fc/100 g). An extended period of 72 hours depuration is allowed at levels above 2,300 but not exceeding 5,400 MPN fc/100 g. Shellfish exceeding 5,400 MPN fc/100 g must be returned to the beach from which they were harvested (J. Pynn, K. Schallie, Canadian Food Inspection Agency (CFIA), pers. comm..).

economically viable and processors began turning to depuration to access contaminated resources and provide a steady market supply.

There are presently five depuration facilities licenced for operation in B.C. Annual landings[3] increased from approximately 100 t in 1990, when only a single plant was in operation, to approximately 440 t in 1997 and 1998 (Table 2). Landings decreased to approximately 350 t in 2000 and 2001, increased to over 400 t in 2002 and decreased in 2003. The decreases were due in part to loss of beaches to stock concerns, increased contamination levels leading to prohibition of harvest and conversion of beaches to aquaculture tenures.

Current assessment and management frameworks

Under current depuration fishery policy, specific groups can be allocated beaches for harvest. Licenced depuration facilities have been allocated marginally contaminated[4] beaches not accessible through the wild clam fishery (Gillespie *et al*. 1998a, Gillespie 2000). First Nations have been allocated access to marginally contaminated beaches that front reserve lands (Gillespie and Bond 1997). Processors or harvester groups (First Nations, Clam Management Boards) seeking depuration permits are required to submit proposed harvest plans to Fisheries and Oceans Canada (DFO). Proposed harvest areas must first receive Environment Canada approval after growing water quality assessments. Following this approval, Canadian Food Inspection Agency (CFIA) criteria must be satisfied for Harvest of Contaminated Shellfish Licences to be issued. Applications are also referred to B.C. Ministry of Agriculture, Fisheries and Food (MAFF) for review prior to licence issuance. DFO Fish Management Branch requires that a pre-harvest survey be carried out on any new beaches proposed for harvest, to establish harvest quotas. Survey designs are developed jointly by the processor or harvester group and DFO Marine Ecosystems and Aquaculture Division, surveys are carried out by processors, harvest groups or contractors and the results submitted to DFO Marine Ecosystems and Aquaculture Division for verification.

Commercial fisheries for Manila and littleneck clams in B.C. are managed under a minimum size limit of 38 mm total length (TL). Manila clams can reach legal size in approximately 3-3.5 years under optimal growing conditions, littlenecks require approximately 3.5-4 years under optimal conditions (Quayle and Bourne 1972). Growing conditions change with tidal elevation on a beach, thus the average time to recruit to legal size over an entire population is usually longer (Gillespie *et al*. 1998b; Gillespie and Kronlund 1999).

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[3] Annual landings include production from Crown foreshore, not foreshore tenured for aquaculture.

[4] Approved growing waters have faecal coliform levels not exceeding a median or geometric mean of 14 Most Probable Number faecal coliforms per 100 ml (MPN fc/100 ml) with no more than 10% of the water samples exceeding 43 MPN fc/100 ml and no point sources of pollution identified in the area. Statistics are based on a minimum of 15 samples taken over a number of years under worst case conditions. Shellfish may be harvested for depuration from waters not meeting approved criteria but where the median or geometric mean do not exceed 88 MPN fc/100 ml with no more than 10% of water samples exceeding 260 MPN fc/100 ml (referred to as "marginally contaminated" in this report). Prohibited waters are those within a certain distance of a point source of contamination (*e.g.*, sewage outfall); the extent of the zone is established by EC staff based on volume and bacterial load (J. Pynn, K. Schallie, CFIA, pers. comm.).

Prior to 2001, certain depuration beaches were included in an experimental harvest program, and were fished at constant harvest rates of 25% or 50% of stock estimates from annual surveys (Table 3; Figure 1). Because DFO and industry funds are finite and annual surveys on all beaches were not feasible, other depuration beaches were assigned long-term total allowable catches (TACs) derived from baseline stock assessment surveys. TACs were set at 25 or 50% of the baseline stock size, depending on the harvest history of the stock. Those beaches that had been recently harvested before removal from the wild fishery (usually an extended period of harvest that was either continuous with commencement of the depuration fishery, or had not lain unfished for more than two years), *i.e.*, were already fished down, were assumed to be supported by annual recruitment. Annual recruitment was assumed to be relatively large when compared to the fishery-depleted standing stock, since recruitment was assumed to come from elsewhere. TACs for these beaches were set at 50% of initial legal sized stock, under the rationale that regular recruitment would replace the relatively small removals (based on relatively low legal biomass levels). Beaches that had not been fished for at least two years and had accumulated legal-sized stock were assumed to be unable to sustain the 50% TAC as they were fished down. TACs for these beaches were set at 25% of initial stock size. In either case, these harvest rates were considered to be conservative relative to the 60% harvest rates believed to occur in conventional commercial fisheries managed with size limits and fishery-based closure criteria (Gillespie and Bond 1997, Gillespie 2000).

In 1996, quotas were allocated for a clam season beginning November 1 and ending October 31 of the following year. The rationale was to allow summer daylight tides for survey work, a period to allow processors to complete analyses and reporting of the surveys, and a reasonable period for quality assurance and verification of survey results by DFO Marine Ecosystems and Aquaculture Division before DFO Fish Management finalized quotas.

In 2000, harvest rates were reduced and determined through application of density thresholds (Gillespie 2000; Table 4). These thresholds were determined pragmatically through evaluation of the experimental harvest beaches and stock responses on an annual basis.

A number of beaches that were available for depuration harvests have been lost to the fishery since 1999, due to stock concerns, conflicts with other interests, changes in water quality or conversion to aquaculture tenures (Table 3).

Objectives

Objectives of this paper (Appendix 1) are:

1. To refine and rationalize biological reference points and management strategy for intertidal clam fisheries;
2. To provide information and advice on sustainable harvest rates in depuration fisheries; and
3. To provide information and advice on required survey frequency.

Methods

Surveys

Survey design varied with the beach and the confidence of the surveyors. Survey designs were either stratified random or stratified two-stage designs (Kronlund *et al*. 1998; Gillespie and Kronlund 1999). Strata were established to cover the full extent of the beach that supported clam beds using industry knowledge or information from previous assessment work. Strata were generally placed over small clam-bearing areas on small beaches, or used to divide larger beaches by tidal height and horizontal distance (usually 100 m sections). Sampling intensity was 30 quadrats/ha, with a minimum of 10 quadrats/stratum, except in the case of large beaches using stratified two-stage designs, where a target of at least 200 quadrats/survey, or approximately 18 quadrats/ha, was used. Quadrats were 0.25 m^2, and were raked and hand-sorted to collect clams. Once established, survey designs remained constant in most cases (Table 5). At Goldstream, the additional stratum was not included in analyses from 2002-2004; at Royston only the six strata that were surveyed for the entire period were included in analyses.

Biological samples were selected in two stages. First a stratum was randomly selected, and then a quadrat from within the stratum was randomly selected. The process was repeated, without replacement for the stratum selection, until all strata were represented and then the process was started over. The process continued until the target sample size (200 clams in the early years of the program and 500 clams after 2000) was attained; all remaining clams in the quadrat were processed to prevent selection bias. All of the clams from selected quadrats were processed for total length (TL), individual weight and age. Ages were determined by interpreting and counting external growth checks using the method of Quayle and Bourne (1972).

A subsample of each biological sample was selected for collection of length-at-annulus (LAA) data. Lengths of individual growth rings (annuli) were measured using electronic callipers. For all beaches except for the two on Lasqueti Island (China Cloud and Long Bay), clams for LAA measurements were randomly selected from biological samples. Clams were sorted into year class bins (excluding one year olds) and 5 clams randomly selected from each age class where possible. In total, 50 clams were used from each beach for LAA analyses. At times more than 5 clams were included from the oldest years. With regard to the Lasqueti Island beaches, all clams selected for biological samples were used for LAA measurements except for Long Bay 2004 where 60 clams were selected as described above.

Both Manila and littleneck clams were harvested in some cases, and the relative abundance of the two species can provide inference about beach characteristics, so littleneck survey estimates are presented in this report.

From 1997/98 to 1999/2000 beaches were harvested at rates of either 25% (Goldstream, Craig Bay) or 50% (Booth Bay, Parksville, Mud Bay) or were unharvested controls (Mill Bay, Royston and Wall Beach). In 2000, biological reference points were introduced to determine harvest rates (Gillespie 2000, Table 4). The unharvested controls were surveyed to track changes in stock size and characteristics that might be the result of environmental conditions rather than harvest.

Selection of beaches for the program was constrained by issues of stewardship and the decision rules for assigning harvest rates. In the first case, an attempt was made to distribute costs of the program equitably to all industry participants. Each participant was assigned a beach to be harvested at 50%, 25% and 0 (unharvested control). This was complicated somewhat by a shared stewardship arrangement at Parksville and Craig Bay, where two processors were involved. Consideration was also given to the size of the beach included in the experimental harvest program. Beaches selected were large enough to be considered significant contributors to harvests and in some cases (Goldstream, Mud Bay and Royston) where previous assessment information was available. Final selection of beaches for the program occurred after all of these considerations, not as random assignment of treatments. The lack of random selection of program beaches and assignment of harvest rates limits the ability to draw inferences regarding other beaches in British Columbia.

Several beaches have been lost to the original program either through changes in water quality classification (they have become prohibited or the contaminated classification has been removed) or through conversion to tenures (Table 3). Data from beaches discussed in Gillespie (2000) but no longer available to the program were included in production model analyses but were not considered in predictive modelling, primarily due to short time series of available data.

We were also interested in determining what harvest rates might be in an unrestrained fishery (*i.e.*, no TAC). We allowed industry to harvest two beaches (China Cloud Bay and Long Bay on Lasqueti Island) and survey the remaining stock immediately after harvest. Landings were added to the post-harvest biomass estimates to approximate pre-harvest biomass, and the harvest rate determined by simple division.

Landings

Landings were reported by depuration facilities following harvests. In most cases, landed weights were measured at the beach at time of harvest or upon delivery to a processing plant. In some cases, landed weights were measured after a period of wet storage which resulted in some mortality (termed “shrinkage”). In some cases, where mixed clam products were sold, landed weights for individual species were only roughly estimated, while in others, the species were sorted and weighed separately. Inconsistencies in species identification apparent in historic landings (see sections detailing individual beaches, below) were presumed to have been corrected before harvests in 1996/97 began.

Production modelling

We developed simple models relating production (change in density of legal size clams) to the post-harvest density of legal size clams and density of sublegal size clams from the previous year[5]. Post–harvest legal density, $D_{i'}$, was calculated using the equation:

$$D_{i'} = D_i(1 - HR_i) \tag{1}$$

where:

- D_i is the density of legal size clams in year i prior to harvest: and
- HR_i is the harvest rate in year i.

Change in legal density, *DD*, was calculated as:

$$\Delta D = D_{i+1} - D_{i'}. \tag{2}$$

Sublegal densities were simply those estimated from surveys. The production relationship was modelled using simple linear regressions.

Population modelling

A model was developed to simulate the evolution of the age-size structure of a clam population[6]. The model considered harvest, growth and natural mortality. The settlement rate was assumed to be zero when the model was used as a predictive tool and some other constant value when the model was used to estimate natural mortality rates. In order to run the model and to estimate some of the parameters, it was necessary to reconcile discrepancies in the three sources of data: length at annulus, biological samples and density.

Growth parameters were estimated from length-at-annulus data. Data were fit to a variant of the familiar von Bertalanffy equation:

$$L(a) = (L_\infty + e_\infty)(f(a)) + e_{meas} \tag{3}$$

where:

$$f(a) = 1 - e^{-k(a - t_0)} \tag{4}$$

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[5] Equations and notation for production modelling are summarized in Appendix 2. Equations and notation used in population modelling are in Appendices 3 and 4, respectively.

[6] Equations and notation used in population dynamics models are summarized in Appendix 3. Equations describing dynamics for Manila clam population models.

$$L_{\infty} + e_{\infty} = e^{mean\left(\log\left(\frac{L(a)}{f(a)}\right)\right)} \tag{5}$$

- $L(a)$ is the length of a clam at age a;
- L_{∞} is the mean asymptotic length of all clams in the sample;
- e_{∞} is clam-specific random variation in the asymptotic length ($e_{\infty} \sim N\left(0, s_{\infty}^{2}\right)$);
- e_{meas} is measurement error and random variation in growth of individual clams ($e_{meas} \sim N\left(0, s_{meas}^{2}\right)$);
- k is the intrinsic rate of increase in the von Bertalanffy model;
- t_0 is the theoretic age at which length is zero in the von Bertalanffy model.

This variant, which is frequently used for tag-recapture data (*e.g.*, Laslett, Eveson and Polacheck 2002), was chosen primarily because it readily transforms into a growth model that is applicable even when size-selective harvest has altered the size-structure of the population:

$$L(a+1) = \left(\frac{f(a+1)}{f(a)}\right)(L(a)) + e_{growth} \tag{6}$$

where e_{growth} is random variation in growth ($e_{growth} \sim N\left(0, s_{growth}^{2}\right)$). Each clam has its own asymptotic length but shares k and t_0 with the rest of the sample.

Values of k and t_0 were estimated by minimizing the corresponding sum of squares of error:

$$SSQ(k, t_0) = \sum_{n=1}^{N} \sum_{a=1}^{a_{\max}} \left(L(a) - f(a)(L_{\infty} + e_{\infty})\right)^2 \tag{7}$$

where:

- N is the total number of clams in the sample; and
- $a_{\max}$ is the total number of age classes.

For a given combination of k and t_0, the corresponding asymptotic length was approximated for each clam and the corresponding value of $SSQ(k, t_0)$ was calculated using Equation 7. The combination of k and t_0 resulting in a minimum value of $SSQ(k, t_0)$ were found using the nlminb function in S-Plus (Insightful Corporation 2004). The corresponding asymptotic lengths were used to estimate L_{∞} and s_{∞}^{2}.

A standard allometric equation was used to model the relationship between length and weight of the clams:

$$\overline{W}(L) = a\left(L^{b}\right)e^{\left(\frac{s_{w}^{2}}{2}\right)} \tag{8}$$

where:

- W is the weight of an individual clam;
- s_{w}^{2} is the variance associated with the weight-length relationship; and
- a and b are non-random variables in the relationship.

The corresponding parameter values were estimated by minimizing:

$$SSQ(a, b) = \sum_{n=1}^{N}\left[\log\left(\frac{W}{aL^{b}}\right)\right]^{2}. \tag{9}$$

Equation 8 was used to estimate the mean weight of clams of a given length. This in turn was combined with Equation 3 to approximate mean weight at age:

$$\overline{W}(a) = a\left[\left(L_{\infty}\right)\left(f(a)\right)\right]^{b} e^{\left(\frac{s_{w}^{2}}{2}\right)}. \tag{10}$$

With the ability to convert length to weight, the biological sample can be reconciled with density data. The density data were taken for a bigger sample of clams and therefore assumed to be more accurate. $A_{L,a}^{1}$ was the length-age structure as observed in the biological sample. The sublegal and legal-sized biomasses of the biosample were estimated using Equation 8. $A_{L<L_{Legal},a}^{1}$ was multiplied by a common factor to get the same sublegal biomass as estimated from the biomass data. $A_{L\geq L_{Legal},a}^{1}$ was adjusted similarly. The result was $A_{L,a}^{2}$.

The second step was to reconcile the size-age structure with the size-at-age model. This was treated as an issue of size-dependent vulnerability. Legal-sized clams were assumed to be fully vulnerable to the survey:

$$V(L) = 1, L \geq L_{Legal} \tag{11}$$

and a logisitic function was applied to the sublegal clams:

$$V(L) = \frac{1+e^{-v0\left(L_{Legal}-v1\right)}}{1+e^{-v0\left(L-v1\right)}}, L < L_{Legal} \tag{12}$$

where *v0* and *v1* are estimated parameters. When Equation 12 was combined with Equation 3, it was possible to calculate the probability of size for any given age:

$$P\left(L \middle| L < L_{Legal}, a\right) = \Psi_a\left(V(L)\right)\left(P\left(L \middle| a\right)\right). \tag{13}$$

Parameter values most compatible with $A^2_{L<L_{Legal},a}$ were determined by minimizing the function:

$$MLE(v0, v1) = -\sum_{clam(L<L_{Legal})} \left(\log\left(P\left(L \middle| L < L_{Legal}, a\right)\right)\right). \tag{14}$$

Estimated values of *v0* and *v1* were independent of the age-structure of the biosample and the harvest history of the beach. The fully reconciled size-age structure, $A^3_{L,a}$, was then calculated as:

$$A^3_{L,a} = \frac{A^2_{L,a}}{V(L)}. \tag{15}$$

The natural mortality rate was estimated in two ways; a snapshot approach and a survey-series approach. The snapshot approach was investigated because it had smaller data requirements. The survey-series approach was considered because it made use of more of the available data.

The snapshot approach required a full survey (length-at-annulus, biological sample and density data) from the current year and the harvest-history of the beach. The settlement rate was assumed to be constant. The virgin age structure was determined using:

$$P(a) = \left(1 - e^{-M}\right)\left(e^{-M(a)}\right). \tag{16}$$

The virgin size structure is given by Equation 3. The projection model (discussed later) is run from this virgin state and without randomization; beginning at the start of the harvest history and ending at the year of the survey. From this simulation, we get an estimate of A_a, the age structure. Maximum likelihood methods, *e.g.*, Bain and Engelhard (1991), are useful for estimating parameters where uncertainty is not normally distributed. M and the settlement rate are chosen to minimize:

$$MLE(M) = -\sum_{a=2}^{A} A_a\left(\log\left(\hat{A}_a(M)\right)\right) \tag{17}$$

The natural mortality rate was also estimated from unharvested beaches with an extensive survey history (Mill Bay and Royston). As well as natural mortality, abundance-at-age was also assumed to be affected by variability in cohort strengths, year-to-year error in estimating abundance and unexplained error. The reconciled survey data was fit to:

$$\log\left(\hat{A}_{a,y}\right) = \log\left(A_0\right) - M(a) + g_c + h_y + e_{A_{a,y}} \tag{18}$$

using linear regression:

$$S_{xx} = \sum_{a=1}^{A}\sum_{c=1}^{C}\left(a - \bar{x}_c\right)^2 , \tag{19}$$

$$S_{xy} = \sum_{a=1}^{A}\sum_{c=1}^{C}\left(a - \bar{x}_c\right)\left(\log\left(A_{a,c}\right) - \bar{y}_c\right), \text{ and} \tag{20}$$

$$\hat{M} = \frac{S_{xy}}{S_{xx}} . \tag{21}$$

where:

$$\log(A_0) + g_c = \bar{y}_c - M\bar{x}_c \tag{22}$$

$$h_y = mean\left(\log(A_{a,y}) - \log(A_0) + g_c + Ma\right) \tag{23}$$

- A_0 is initial abundance, $\hat{A}_{a,y}$ is estimated abundance at age *a* in year *y*, and $A_{a,c}$ is abundance at age *a* in cohort *c*;
- g_c is the relative strength of cohort *c* on a log scale ($g_c \sim N\left(0, s_c^2\right)$);
- h_y is the effect of survey year on abundance ($h_y \sim N\left(0, s_y^2\right)$);
- $e_{A_{a,y}}$ is random error in abundance not due to age, cohort or year ($e_{A_{a,y}} \sim N\left(0, s_A^2\right)$);
- $\bar{x}_c$ is a mean of the unique age-values observed for the cth cohort; and
- $\bar{y}_c$ is the mean of the log of abundance-values observed for the cth cohort.

The variance of *M* was estimated as well as the cohort strengths (g_c) and year-specific effects (h_y). The variability in cohort strength, g_c, did not directly affect the projection model because zero settlement was assumed. However, when g_c was estimated, h_y and $e_{A_{a,y}}$ could be estimated more accurately.

The estimated values of h_y were important to the projection model because they indicated uncertainty in overall abundance associated with a survey. This uncertainty is incorporated into the projection model. By acknowledging year-to-year uncertainty, the estimates of $e_{A_{a,y}}$ were made more accurate. $e_{A_{a,y}}$ values were used to estimate random variability in cohort-abundance within the same survey and this variability was also incorporated into the projection model.

The variance of the age structure was estimated as:

$$\mathrm{var}\left(\log\left(N_a\right)\right) = \left(\frac{1}{a_{\max} - 3}\right)\left(\sum_{a=2}^{A}\sum_{n_a=1}^{N}\log\left(\frac{\hat{N}_a(M)}{N_a}\right)^2\right) \tag{24}$$

The projection model was based upon: reconciled data, the growth model, the natural mortality rate, a harvest strategy based upon Table 4 (for harvested beaches) and an assumption of zero settlement.

The projection model started out with a reconciled size-age distribution. In order to acknowledge survey error in estimating abundance for the year, a random value of h_y was sampled and applied to $A_{s,a}^3$. In order to acknowledge uncertainty in the initial age-structure, a value of $e_{abundance_{age,year}}$ was sampled for each age represented in $A_{s,a}^3$. However, after the values of $e_{abundance_{age,year}}$ were applied, the size-age distribution was adjusted so that there was no corresponding change in the sublegal or legal-sized biomass. Once the randomization was implemented, the projection model becomes a cycle of harvest, growth, and natural mortality. One thousand randomized starting points were generated in this way.

Harvest was assumed to occur immediately after the survey. The harvest rate (for the harvested beaches) was determined from Table 4. The harvest rate was a fraction of legal biomass. Harvest was modelled by multiplying $A_{L>L_{Legal}}^3$ by one minus the harvest rate.

Growth was modelled with Equation 6. Natural mortality was simulated by multiplying the entire size-age distribution by $\exp(-M)$.

Subsequent quotas are calculated using Table 4, the probablistic state of the clam population and q_{quota}. q_{quota} is a quantile. The q_{quota} quantile of population density is put into Table 4 to get the applicable harvest rate. This harvest rate is applied to the q_{quota} quantile of biomass in order to get quota. The same quota is applied to all the probabilistic simulations. If quota exceeds legal-sized biomass, then a harvest rate of 100% is applied.

The harvest-growth-mortality cycle was repeated as many times as desired.

Beach Areas

The surveyed areas of some beaches have changed over time (Table 5). Survey estimates calculated abundance and biomass on a density (per metre-squared) basis, as were projections. Where total biomass and quota are presented, the calculated densities have been multiplied by the area from the most recent survey and converted to tonnes.

Results

Control beaches

Mill Bay

Mill Bay (48º39’N, 123º33’W) is located on the west side of Saanich Inlet, north of Goldstream (Figure 1). The survey area is relatively small, and consists of two strata on the north side of the bay, west of Whiskey Point, and two strata on the south side of the bay near the mouth of the creek. The intervening area had a soft mud substrate which did not support large populations of Manila or littleneck clams. The area was harvested for depuration in 1994 and 1995, with a total of approximately 5 t of littlenecks reported. Survey results from 1997 indicated that historic landings are likely misidentifications, and probably represent a mixture of Manila and littleneck clams.

Mill Bay was first surveyed in August 1997; the survey was a stratified random design consisting of four strata totalling 0.56 ha (Table 5). Legal Manila biomass varied from 4.3 t in 1997 to 10.9 t in 2001 (Table 6). There was a general increasing trend from 1997 to 2001, with legal biomass decreasing in the subsequent two years (Figure 2). Results of the 2000 survey were anomalous as legal biomass declined 39% between 1999 and 2000, then climbed 126% in 2001. We are not confident that the 2000 results accurately represent stock size of legal Manilas in that year, although we cannot determine why the estimates were so low (see Goldstream and Discussion sections below).

Sublegal Manila biomass varied from 1.3 t in 2000 to 2.8 t in 1998 (Table 6). Sublegal biomass peaked in 1998 with a declining trend apparent through 2000 and a moderate increasing trend to 2003 (Figure 2). There is no previous survey information available to judge whether these levels are comparable to historic stock levels.

Age structure at Mill Bay was largely dominated by older clams from 1997 to 1999 (Figure 3). The 1997 year-class was first detected as three-year-olds on the 2000 survey, was detectable as four- and five-year-olds in 2001 and 2002, and may have made up the five- and six-year-old cohorts in 2003 (with some ageing error). The 2000 year-class was detected as three-year-olds in 2003.

Royston

Royston (49º39’N, 124º56’W) is a relatively large site on the southern side of Comox Harbour between the breakwater and Gartley Point (Figure 1). The site includes the estuary of the Trent River and is crossed by Roy Creek. Royston was harvested for depuration between 1992 and 1995, with total landings of approximately 100 t of Manila clams reported. Late in 1995 Environment Canada changed the classification of the beach from Contaminated to Prohibited, preventing further harvests for depuration.

A contract survey of the area was completed in 1993 (Lipovsky, unpublished manuscript) which used a different methodology and a different survey area. A survey was undertaken at Royston in 1995, but this survey used different protocols, included 2.50 ha of area to the west of the wharf and covered only 8.29 ha on the east side of the wharf. Due to differences in areas surveyed the results of both surveys are not directly comparable with surveys undertaken in 1997-2004.

Royston was surveyed between 1997 and 1999 with a survey area of 12 strata totalling 10.00 ha (Table 5) on the eastern side of the wharf, ending near the mouth of the Trent River. Surveys were not carried out in 2000, and industry argued that the survey was too costly. When surveys were resumed in 2001, only the western half of the area was surveyed. Valid comparisons of stock dynamics were made using data from the western half of the survey area only.

Surveys indicated that Manila stocks consisted primarily of sublegal clams; sublegals accounted for 53-67% of the estimated biomass and 71-83% of the estimated abundance between 1997 and 2002 (Table 7). Legal Manila biomass increased from 12.7 t in 1997 to 62.3 t in 2003, then declined to 47.0 t in 2004 (Figure 4). Sublegal biomass also increased from 16.7 t in 1997 to 50.4 t in 2003, then declined to 23.7 t in 2004.

Early surveys at Royston, although not directly comparable, indicated that Manila stocks in the area had been much larger than at the beginning of the program. In 1993, legal density was 1.27 kg m^{-2} and sublegal density was 0.77 kg m^{-2} (Lipovsky, unpublished manuscript). In 1995, legal Manila density was 0.30 kg m^{-2} and sublegal density was 0.80 kg m^{-2} (unpublished data). Manila densities from the June 1997 survey were 0.25 kg m^{-2} for legals and 0.33 kg m^{-2} for sublegals. Densities did not reach historic levels until 2003, a decade later, when densities of 1.25 and 1.01 kg m^{-2}, for legal and sublegal Manilas respectively, were measured.

Age structure at Royston was dominated by younger clams from 1997 through 1999 (Figure 5). Strong 1994 and 1995 cohorts are detected in the 1997 and 1998 surveys, and are still apparent as six- and seven-year-olds in 2001. A strong 1998 cohort appears as four-, five- and six-year-olds from 2002 to 2004.

Wall Beach

Wall Beach (49º18'N, 124º17'W) is a relatively small beach south of Craig Bay (Figure 1). It has a sand/gravel substrate, crossed by freshwater runoff from a storm drain outfall. The beach was closed due to faecal contamination in the early 1990s. It was occasionally utilized by harvesters in the regular clam fishery prior to closure. It was initially chosen as an unharvested control for comparison to the Parksville and Craig Bay sites.

Wall Beach was surveyed from 1997 to 2004, with the exception of 2000. Surveys consisted of 11 strata totalling 2.18 ha (Table 5). Surveys indicated that Manila clam stocks consisted primarily of sublegal clams, which accounted for 88-93% of total Manila biomass and 96-98% of total Manila abundance (Table 8).

Throughout the experimental harvest program, Wall Beach exhibited a decreasing trend in biomass of both legal and sublegal Manila clams, with some increase in legal Manilas between the 1999 and 2001 surveys (Figure 6). Biomass of legal Manilas decreased from 4.4 t in 1997 to 1.1 t in 2003 and sublegal biomass from 31.3 t in 1997 to 11.1 t in 2003 (Table 8). Legal and sublegal biomass and abundance increased slightly in 2004. Because there were no depuration harvests to remove stock from the beach (survey samples totalled less than 50 kg per year) and no evidence of winter kill or other catastrophic mortality, these decreases remain unexplained.

Although Wall Beach does not support a large proportion of legal sized clams, the age structure was dominated by older clams in 1997 (Figure 7). A strong 1996 cohort was detected in 1999, and a moderately strong 1999 year-class was seen as two-year-olds in 2001.

Harvest beaches

Booth Bay

The Booth Bay harvest area (48º52'N, 123º34'W) is primarily within Booth Inlet, on the west side of Saltspring Island (Figure 1). Booth Bay has been harvested for depuration since 1991. Landings totalling approximately 300 t, all reported as littleneck clams, were reported from Booth Bay between 1991 and the survey in July 1996. The 1996 survey indicated that the stock in the harvest area was primarily Manila clams, so these reports are assumed to be misidentified.

Surveys conducted under the experimental harvest program have been of stratified random design, consisting of 16 strata totalling 3.13 ha (Table 5). During the experimental harvest program, biomass levels at Booth Bay have remained relatively high, ranging between 89.8 and 188.3 t of legal Manilas and 50.0 and 70.9 t of sublegal Manilas (Table 9). The beach supported remarkable densities of both legal and sublegal Manilas, ranging from 147-295 legals m^{-2} and 168-278 sublegals m^{-2}. There were no general overall trends in biomass or abundance, except that legal abundance was less than sublegal before 2000 and greater than sublegal after 2000 (Figure 8).

Booth Bay was surveyed in 1999 but not harvested (Table 9). A harvest was taken in 2000, but only removed 25% of the estimated biomass of legals from the 1999 survey. This may have allowed accumulation of legal Manilas over two years of low harvest rates.

Age structure at Booth Bay was dominated by older clams in the 1996 survey, and the population showed signs of regular recruitment between 1994 and 1996 as three-year-olds in the 1997 through 1999 surveys (Figure 9). Strong cohorts in 1997 and 1998 are apparent in the 2001 and 2002 surveys.

Goldstream

Goldstream (48º29’N, 123º33’W) is at the southern end of Finlayson Arm, Saanich Inlet (Figure 1). The harvest area is a large, gently sloping estuary crossed by several active stream channels. The substrate is a thick layer of silt, except in and near the stream channels, where it is primarily gravel and sand. The harvest permit extends from the overhead power lines adjacent to the mouth of Arbutus Creek to the southern tip of Sawluctus Island.

The Goldstream site was first harvested in 1990, and has been continuously harvested since. Landings in 1990 were reported as Manila clams only, and landings in 1991-1993 were reported as littleneck clams only. In total, landings of approximately 40 t of Manilas and 130 t of littlenecks were reported from Goldstream between 1990 and the survey in August 1997. As with Booth Bay, these landings were assumed to be misidentified, and that landings for each year likely represented a mixture of the two species. Previous concerns described by Gillespie (2000) for reported landings from this site were corrected by sampling landings to determine species composition.

Surveys were undertaken at Goldstream in 1994 (Gillespie *et al*. 1998a) and 1996 (Gillespie and Kronlund 1999). The 1994 survey differed drastically in layout from later surveys, and encompassed only 3.84 ha. The 1996 survey had four of the five strata that made up later surveys, and encompassed 4.54 ha. Surveys from 1997 through 2001 had five strata totalling 5.34 ha (Table 5). Because of differences in the areas surveyed in 1994 and 1996, these surveys are not directly comparable to those undertaken in 1997-1999. Data from an additional stratum surveyed from 2002-2004 have not been included in this analysis to keep the survey area under consideration constant.

Legal biomass at Goldstream varied from 48.4 t in 2000 to 101.0 in 1998 (Table 10). Sublegal biomass ranged from 1.8 t in 2003 to 26.3 t in 1997. There was a consistent declining trend in sublegal abundance from 1997 to 2003, with a small increase in 2004 (Figure 10). Legal biomass increased sharply in 1998 and slowly declined to 2003, with a small recovery in 2004. The anomalous results from the 2000 survey, where legal biomass declined by 52% from 1999 and then climbed by more than 80% to 2001, cannot be considered to accurately represent legal stock levels. The anomaly is not present in either the sublegal Manila or legal littleneck estimates.

Surveys completed in 1994 and 1996, although not directly comparable to the 1997-99 surveys, indicate that legal biomass levels have been relatively consistent, but that sublegal density has declined. Manila density in 1994 was 2.54 kg m^{-2} for legals and 0.16 kg m^{-2} for sublegals (Gillespie *et al*. 1998a). Manila biomass in 1996 was 1.11 kg m^{-2} for legals and 0.47 kg m^{-2} for sublegals (Gillespie and Kronlund 1999). Mean legal density peaked at 1.89 kg m^{-2} in 1998 and gradually decreased to 1.36 kg m^{-2} in 2003 with a slight increase in 2004. Sublegal density decreased from 0.49 kg m^{-2} in 1997 to less than 0.10 kg m^{-2} during 2002-2004.

Age structure at Goldstream showed evidence of strong cohorts in 1993 through 1995, starting as two-, three- and four-year-olds in the 1997 survey, and traceable through at least the 2001 survey (Figure 11). A strong 1998 year-class was first detected as two-year-olds in 2000, and can be tracked through the 2004 survey as six-year-olds.

Post-harvest beaches

Two beaches were managed in a different manner to other beaches in the program. Harvesters and processors were allowed to harvest these beaches without limitation of a TAC, and were then required to complete a survey immediately following harvest. The objective of this approach was to determine what the range of harvest rates might be on a beach in the absence of restrictive management tactics.

Each of these beaches was harvested in 2000 in the conventional program following assessment surveys in the summer of 1999. The beaches were not harvested in 2001, and the post-harvest program was begun in 2002.

China Cloud Bay, Lasqueti Island

China Cloud Bay (49º29'N, 124º21'W) is a small bay on the east side of False Bay, Lasqueti Island (Figure 1). Locally known as Mud Bay, it was officially renamed in 2003. The survey area consisted of 7 strata, totalling 2.6 ha (Table 5). A single year of harvest and subsequent survey was completed in 2002 (Table 11).

The beach was harvested for two days and the survey completed the following day. The processor indicated that he would have harvested one more day had time permitted (*i.e.*, they ceased harvesting prematurely because they had to complete the survey on the same set of tides). The final harvest rate was approximately 11% of the initial biomass.

Long Bay, Lasqueti Island

Long Bay (49º30'N, 124º12'W) is located on the north side of Lasqueti Island (Figure 1). The survey area consisted of five strata totalling 1.3 ha (Table 5). Three years of harvest and subsequent surveys were completed between 2002 and 2004 (Table 12).

As with China Cloud Bay, the processor indicated that a third day of harvest would have taken place in each year had the surveys not been required on the same tides. Final harvest rates ranged from 11% to 13%.

Production modelling

Addition of new data to the simple production models described by Gillespie (2000) did not result in significant changes to resulting relationships. Additional data increased variation in the relationship, resulting in the R^2 value dropping from 0.5801 to 0.4245 for the relationship between change in legal density and post-harvest legal density in the previous year (Figure 12). The slope of the relationship remained relatively constant.

The fit of the relationship between change in legal density and sublegal density in the previous year improved slightly, with the R^2 value increasing from 0.1229 to 0.1867. The relationship between sublegal density and change in legal density is relatively weak, likely because some beaches (*e.g.*, Mud Bay East, Mud Bay West and Wall Beach) exhibited slow growth. As a result these beaches supported relatively large proportions of sublegal clams that did not grow through to legal size in a timely manner.

Population modelling

Four beaches were considered in the population modelling: Booth Bay, Goldstream, Mill Bay and Royston. Mill Bay and Royston were control beaches with extensive survey histories, but were not harvested during the duration of this program. Booth Bay and Goldstream were index beaches with annual surveys and regular commercial harvests.

A third unharvested beach, Wall Beach also had an extensive series of surveys. However, growth was very slow on Wall Beach (Figure 13) and as such this site is likely a poor representation of harvested beaches. Wall Beach was not considered in any other analyses.

One year-old clams are not included in the calculations. Very few one-year old clams are observed in the biological samples. Even with vulnerability corrections, the observation of one-year-olds is feared to be too sporadic to include.

Growth parameters

Growth model parameters were variable, with asymptotic length greatest at Goldstream and least at Booth Bay, and intrinsic rate of increase highest at Booth Bay and lowest at Royston (Table 13). Mean size-at-age and related confidence intervals are similar for three of the four beaches analyzed (Figure 13). The lower confidence intervals are approximately the same for all four beaches. Goldstream has a larger mean-size-at age and upper confidence bound on size-at-age, likely leverage from one or two large, fast-growing clams in the sample.

Length-weight parameters

Estimated length-weight parameters and resulting relationships are similar for all four beaches (Table 14, Figure 14).

Vulnerability parameters

Vulnerability parameters varied greatly between beaches and years (Table 15). Royston 1999 was a particularly successful survey in that clams as small as 20 mm were almost fully vulnerable to the survey (Figure 15). Each beach had at least one survey where $L_{0.5}$ was greater than 29 mm TL. The least successful surveys with respect to vulnerability were Mill Bay 2003 and Goldstream in 2003 and 2004, where $L_{0.5}$ was greater than 34 mm TL.

Reconciling data

The reconciliation process was an important step to resolve the effects of sampling error and vulnerability of smaller clams on the progression of cohorts over a series of years of survey. Without reconciliation, year-classes appeared to increase in abundance until they reached an age of about five years (Figure 16). After reconciliation, there was a general decline in abundance as clams got older. This was important as a year-class of clams can logically only decrease in abundance as it gets older.

For the Booth Bay 1996 survey, there was significant discrepancy between the size distribution of the biological sample and the relative proportions of legal and sublegal size clams in the density data. As a result, there was a significant impact when the two data sources were reconciled. For the other surveys, the biological samples and density data were in relatively close agreement.

The vulnerability correction for Royston 1999 had very little impact because even small clams were fully vulnerable. Generally, the impact of vulnerability correction is more significant.

Natural mortality estimates

We estimated natural mortality in two ways: the first was using information from individual surveys, termed “snapshot surveys”, and the second was using time-series data from control beaches.

Estimates from snapshot surveys show considerable variability both between beaches and between years on the same beach (Table 16, Figure 17). The large *95CBfactor* values indicate that sometimes there was simply a poor fit of the data to the model, at times so poor that the estimated rates are negative.

We also fit reconciled age structure to estimates of mortality, cohort-strength and year-strength from unharvested beaches (Table 17, Figure 18). The points in the figure represent reconciled survey data. Each line represents a cohort, and where one line is generally above or below another, the corresponding cohorts have different strengths. Bends in the lines represent year-to-year variation in the estimated abundance and the lines generally bend towards the corresponding survey values, resulting in a reasonable fit to the data.

Projection models

We projected biomass forward using natural mortality rates estimated from snapshot surveys (*i.e.*, the natural mortality rate estimated from each individual survey was used for projections from that year forward) and a q_{quota} value of 0.5 for the harvested beaches (Figure 19). Some of the projections, such as Royston 2003, resulted in dramatic overestimates of legal-biomass when compared to subsequent survey estimates. Examination of deterministic projections of age structure (no year-year or age-age variability) for Royston 2003 showed that at the time of the survey, even with data-reconciliation, there was an abundance of five to seven year-old clams (Figure 20). Natural mortality was therefore underestimated, resulting in an accumulation of old clams and an increasing legal-sized biomass. Similar projections for Royston 2004 showed that these year-classes were not as strong and had less of an impact on the estimated natural mortality rate. The projections appeared reasonable and there was not an unrealistic increase in legal-sized biomass. When mortality is estimated from a snapshot, the projections are often very different than the corresponding survey results.

The snapshot approach can result in inaccurate estimates of natural mortality. When natural mortality is underestimated, legal biomass can be grossly overestimated, and any resulting quotas will be unrealistically optimistic.

We found it more useful to examine mortality estimates time series of surveys from unharvested control beaches (Table 17). Upper 95% confidence bounds of these estimates were approximately 0.3 and 0.2 for Mill Bay and Royston, respectively. We chose to use a precautionary a value of 0.3 as the natural mortality rate for all projections.

We projected legal biomass from snapshot surveys using a fixed natural mortality rate of 0.3 (Figure 21). The only unreasonable increases in legal-biomass occurred for Booth Bay 1996. As discussed previously, for Booth Bay 1996 there was significant discrepancy between biological sample data and density data. Deterministic projections of age structure for Royston in 2003 and 2004 were also more reasonable when M was fixed at 0.3 (Figure 22).

The final remaining choice for the projection models was determining which quantiles of the distributions of projected biomass and density, q_{quota}, were appropriately precautionary. To this point, we had used the median quantile, q_{quota}=0.5, to set harvest rates and examine responses of beaches to harvest. Quotas could be made more precautionary by setting q_{quota} to a smaller value; q_{quota}=0.25 for example.

Projected legal biomass using q_{quota}=0.25 and M=0.3 for the two harvested beaches (Figure 23) are remarkably similar to projections when q_{quota}=0.05 (Figure 23). This is due in large part to decreased quotas that result from the use of the lower quantiles of legal biomass and legal density (Table 18, Figure 24).

Discussion

Data quality

Survey data

Gillespie (2000) described survey design, process, data entry and analytical difficulties encountered early in the joint experimental program. All of these were presumed to have been corrected for surveys after 1999.

Estimated confidence intervals were generally between 10-20% of the mean estimate for legal biomass and between 10-30% for sublegal biomass, except at low levels of biomass (Figure 25). Notably wide confidence intervals (wider than 25% of the estimated mean) were calculated for surveys at Wall Beach and Mill Bay (legal and sublegal biomass) and Long Bay (sublegal biomass only)(Table 19).

Confidence intervals are calculated from estimates of sampling variance, therefore samples that fall in areas of extremely high abundance can have as dramatic an effect as samples that fall in areas with no clams. Because clam harvesters tend to affect stock distribution primarily through depletion of areas where particularly high abundance aggregations occur, the general effect of repeated fisheries is to reduce variability on the beach, resulting in tighter confidence intervals when stock levels are uniformly low over the entire sampling area. Thus, the small confidence intervals around estimates from depleted areas, such as Craig Bay, Parksville and Royston are not surprising.

Confidence intervals at Booth Bay are relatively low for so large a stock. However, the survey design developed by the processor utilizes a relatively large number of strata for the survey area, and partitions high and low density areas very well, resulting in low variation within strata, and a low overall confidence interval.

We have little confidence that results from Goldstream and Mill Bay surveys in 2000 reflect true stock levels on those beaches in that year. Stock levels are considerably higher in 1999; the sudden decline could be explained by a catastrophic winter kill in the winter of 1999/2000 (Bower *et al.* 1986, Bower 1992). However, stock levels rebound to nearly the 1999 level in 2001. Reductions in sublegal biomass and abundance are insufficient to explain this recovery through growth from sublegal to legal size classes. We do note, however, that both surveys were carried out by the same crew.

A more pragmatic explanation is that surveys in 2000 underestimate legal Manila stock levels. There is no simple explanation for this. Legal Manilas are the focus of the survey and the easiest size class to detect. Underestimates of other size classes are not apparent, thus sampling the wrong quadrat size does not seem likely. The TAC at Goldstream is based on estimates of both biomass and density of legal Manila clams; deliberate deception by surveyors would negatively affect the allowable harvest, so there is no motivation to "cheat".

Although we have previously assessed vulnerability of small clams to standard survey methods (Gillespie *et al.* 1998b), there is evidence from comparison of year-class strengths between years from depuration surveys that vulnerability is a more important issue than previous results indicated. Screening experiments at Savary Island in 1995 indicated that over 95% of Manila clams =20 mm TL were collected using hand sorting techniques. Vulnerability in depuration surveys was considerably less, as $L_{0.5}$ routinely exceeded 30 mm TL at Mill Bay and Goldstream, and in fact only fell below 20 mm TL once, at Royston in 1999.

Possible reasons for decreased vulnerability include different distributions of recently settled clams and older clams, difficulty detecting small clams in the dug substrate, or that small clams simply were not collected in survey samples. Assessment of the first two potential scenarios will require broader sampling outside the normal distribution of legal size clams or screening of substrate from completed quadrats to determine digger efficiency. The last potential cause is possible when survey objectives are not clearly understood by diggers, who have been trained to avoid collecting sublegal clams in the course of a fishery. The implications of vulnerability are discussed further in the Population Modelling section below.

Landings data

Although landings remain unverified, procedures to accurately estimate species composition and estimate total removals from the beach at harvest, rather than factoring in "shrinkage", were established. The concerns of Gillespie (2000) were assumed to have been minimized after 1999.

General population trends

The previous evaluation of this program noted a wide range of population responses to harvest levels (Gillespie 2000). Continuation of the program has collected more information that supports observations made in 2000. Booth Bay remains the sole beach in the program to sustain relatively high harvest rates without suffering significant declines in population (Figure 26). Goldstream showed an initial increase in population followed by a gradual decline that may have been stabilized when harvest rates shifted from 20% to 10%. The unharvested control beaches have exhibited a range of dynamics in the absence of harvests: Wall Beach has suffered population declines while Mill Bay and Royston showed some recovery with evidence of declines in the last two and one years, respectively.

Recruitment and growth

Recruitment varies from beach to beach and area to area. Mill Bay exhibited an increasing trend in legal biomass (a result of recruitment of sublegals and growth of remaining legals) between 1997 and 2001, particularly obvious if the anomalous results of the 2000 survey are disregarded (Figure 2). Goldstream exhibited an increase in legal biomass between 1997 and 1998 and maintained relatively high legal biomass (again ignoring the 2000 survey results) despite moderate harvest rates through 2004, indicating that recruitment was continuing to support the population (Figure 10). Booth Bay maintained high legal biomass throughout the experimental period, with an increase in legal abundance and biomass between 1999 and 2001, when harvest rates were substantially reduced (Figure 8). All of these beaches are situated in relatively close proximity in Saanich Inlet and Stuart Channel, areas protected from the open waters of the Strait of Georgia by the Saanich Peninsula and Gulf Islands (Figure 1).

Regrettably, few data are available in reasonable time series for beaches in other areas. Royston exhibited slow recovery to moderate levels in the absence of harvest between 1997 and 2003 (Figure 4). Wall Beach legal biomass remained low throughout the experimental period; some evidence of decline is present between 1997 and 1999 (Figure 6). The harvest beaches that were matched to these controls, Parksville and Craig Bay for Wall Beach and Mud Bay East and West for Royston, were quickly depleted and either closed for stock concerns in the former two cases, or eventually lost to tenure in the latter two cases (Table 3).

Growth was similar for most beaches examined; the two exceptions were Wall Beach and Goldstream. Wall Beach does not support rapid growth of Manila clams, as evidenced by low asymptotic length from the growth model (Table 13, Figure 13) and by consistently large sublegal biomass and abundance relative to legal biomass and abundance (Figure 6). Faster growth rates at Goldstream may be an artefact of sampling with one or two fast-growing clams exerting leverage on mean length-at-age, as evidenced by the increased upper 95% confidence intervals (Figure 13).

Fishery management

As in the previous review (Gillespie 2000), it is still apparent that no single harvest rate is appropriate for all beaches. Booth Bay is productive enough to maintain high densities of legal Manilas, and thus high target harvest rates (Figure 8, Table 20), despite final harvest rates that average more than 30% over nine years (Table 9). Conversely, some beaches that moved directly from regular commercial harvest (*e.g.*, Craig Bay, Mud Bay East, Mud Bay West and Parksville) should have been harvested at curtailed rates or closed for recovery (Table 20), and quickly closed for stock concerns (Table 3; Gillespie 2000).

The addition of new data to the productivity models described by Gillespie (2000) has not resulted in significant changes to the relationships developed previously. If the line of best fit through the data is interpreted as “average production”, then production at 20 clams m^{-2} is still approximately 0 and production at 30 legal clams m^{-2} is approximately 8 clams m^{-2} (Figure 12). Booth Bay continues to support annual harvest rates between 25 and 53% and the target harvest rate has never fallen below 40%, so this maximum is not unreasonable (Table 9). Goldstream has supported harvests between 10 and 20%, and decreasing the target harvest rate to 10% appears to have prevented complete closure (Table 10). In summary, there is no evidence that the threshold and limit reference points recommended by Gillespie (2000) need to be changed.

Information from post-harvest survey beaches indicates that harvest rates in fisheries unrestricted by a TAC may be considerably lower than previously thought. Qualitative information provided by Fishery Managers estimated unrestricted harvest rates to be approximately 60% of the available legal biomass (Gillespie and Bond 1997, Gillespie 2000). Although harvests at China Cloud and Long Bays were admittedly incomplete, estimation of another day's harvest by increasing the final harvest rates by 50% would still produce harvest rates less than 20%. Had these beaches been assigned a TAC using the standard decision rules, the Long Bay TAC would have been set at 20% in each year (legal density prior to harvest was estimated to be 110 clams m^{-2} in 2002 and 90 clams m^{-2} in 2003 and 2004) and the China Cloud Bay TAC would have been set at 10% (legal density 64 clams m^{-2} in 2002).

However, factors other than stock levels contributed to the decision to halt harvests. Harvests at China Cloud and Long Bays were left until late in the season (late August and early September) and at least one day of good tides had to be reserved for survey activities. Declining demand for clams and abundant supply from other sources made harvests on these beaches less attractive. We believe that further harvests would have been considered under other circumstances. We do not believe that the harvest rates achieved in 2002-2004 are representative of "normal" harvests when unrestrained by quota management.

Alternative management frameworks

Most clam fisheries on the west coast of North America rely largely on passive management through size limits, often augmented by seasonal or area closures. Razor and hardshell clam fisheries in Alaska primarily utilize size limits for conservation and area closures to allocate between commercial, recreational and subsistence sectors (Foster 1997, Bechtol and Gustafson 1998). B.C. recreational fisheries are managed using daily bag limits, while commercial fisheries rely on size limits, time and area closures, licence limitation, area-specific licencing, and/or TACs based on individual beach survey information, historic production, in-season catch information, or index beaches (Gillespie and Bond 1997, Gillespie 2000, Gillespie *et al*. 2001, Jones *et al*. 2001, Webb 2004MS). Washington razor clam fisheries use time and area closures in addition to a size limit and Puget Sound hardshell fisheries utilize size limits and time and area closures (Lindsay and Simons 1997, J. Whitney, WDFW Mill Creek, pers. comm.). Oregon clam fisheries are managed primarily by size limits (Robinson 1997). California has relatively few bays and estuaries that support significant populations of intertidal clams, and has not supported commercial clam fisheries since the 1940's (Schink *et al*. 1983, Shaw 1997). Recreational fisheries are managed primarily by size limits, bag limits and seasonal or area closures (Leet *et al*. 2001; Moore 2001a,b,c; Pattison 2001; Reilly 2001).

As methodology has developed, there has been a general trend towards informed fishery management decisions through the use of stock surveys. Razor clam fisheries in Haida Gwaii, B.C. (Jones and Garza 1998; Jones *et al*. 1998, 2001) and on the Pacific Coast of Washington State (Ayres and Simons 1999) are managed using annual survey information. Quinn and Szarzi (1993) and Szarzi *et al.* (1995) used survey information to explore sustainable yield of razor clams in Cook Inlet, Alaska. Manila clam fisheries in Area 7 use annual survey and landings information to set harvest thresholds (Gillespie *et al*. 2001). Bechtol and Gustafson (1998) developed an age structured model of littleneck clam populations at Chugachik Island, Alaska. Annual survey data are used to manage recreational fisheries for hardshell clams in Puget Sound, Washington (J. Whitney, WDFW Mill Creek, pers. comm.).

Alternatives to active management using survey information do exist: specifically size limits, catch limits based on historic production or in-season evaluation of landings and CPUE. Size limits alone are not conservative, as evidenced by several stock collapses in the experimental program when only a portion of the legal sized stock was harvested (Gillespie 2000).

Use of historic production has been successfully employed over large areas where diggers can effectively rotate fishing effort over several beaches, with depleted beaches left fallow until they are “discovered” a number of years later. We doubt that this approach would work well for individual beaches unless only a small proportion of average long-term production was used. Using average production runs the risk of over-harvesting the stock roughly half of the time, when stock levels fall below the average.

Because diggers concentrate on areas of high abundance, most of the stock available on a beach can be removed before they have to harvest less abundant areas, and CPUE would likely fall rapidly after the high density areas were fished down. As well, plant capacity limits the amount of clams taken from a beach on a given tide, further adding to hyperstability issues related to CPUE as a fishery indicator.

Any of these approaches represent a reversal of the desired trend of informed fishery decisions based on assessment data gathered during surveys.

Predictive population models

Growth parameters estimated from length-at-annulus data were relatively consistent between beaches; differences at Goldstream may be due to a few clams demonstrating optimal growth. The leverage from these few clams will likely be reduced as larger samples accumulate from this beach and average growth rates will likely converge. Length-weight parameters are similar for all beaches, subtle differences in all but the most extreme examples (*e.g.,* Wall Beach) will likely be resolved with larger sample sizes.

The reconciliation of biological sample data and density data was only problematic for the Booth Bay 1996 survey, as biomass projections for this survey were unrealistic. Therefore, this step in the reconciliation does not appear to be crucial, but allows us to tune our data as much as possible.

Vulnerability of small clams to the survey appears to be very significant because reconciliation allows transformation of unrealistic age-distributions observed in biological samples to more realistic distributions where younger age-classes generally outnumber older age-classes. Vulnerability is also significant because it changes from year to year and beach to beach.

Natural mortality estimates from single surveys are volatile and generally unreliable. In contrast, the extensive survey history of control beaches (Mill Bay and Royston) resulted in reasonable estimates of natural mortality and associated variance. Methodology could also be developed to estimate natural mortality rates from the index beaches (Booth Bay and Goldstream). Since it wasn't possible to estimate natural mortality rates, a precautionary approach for the application of the projection model is to assume a high value for the natural mortality rate based on the upper 95% confidence interval.

In general, legal biomass and quotas for harvested beaches decline each year as projections proceed (Table 18). Ultimately, consultation with Industry will be necessary to jointly determine when the economic losses due to reduced quota in simulation will be potentially outweighed by incurring the costs of a new survey to restart the process. We suspect that two years of quota can be projected from a survey, but that a third year of quota will depend largely on Industry knowledge and the trade-off of lower quotas and costs of a survey.

In the projection model, a range of quantiles of legal biomass and legal density chosen to model harvested beaches was examined (Table 18). Extremely conservative options (*e.g.*, 0.05 quantile) would not be feasible economically, as these reduced quotas so rapidly that annual surveys would be the only viable option available to Industry. Moderately conservative options (0.25 and 0.05 quantiles) did not result in significant differences in biomass levels, but the lower quantile maintained biomass at the expense of quota, again likely resulting in economically motivated requirements for annual survey to maintain acceptable quotas. In the short term, it appears that the only economically tenable option (*i.e.*, an option that could result in multiple years of quota from a single survey) is the use of the median (0.50 quantile) when projecting legal biomass and determining harvest rates from projected legal density (although this inherently carries a higher risk of over-estimation of biomass and density and hence overharvest). Because the continuation of the program requires Industry support, and Industry support is economically motivated, it appears the only option until better data and methods are available is to use median estimates for the projection model.

Survey requirements

Application of the projection model requires basic survey data (abundance and biomass by size class, biological sample data and length-at-annulus data). Growth is estimated from length-at-annulus data, and continued pooling of data over years will eventually produce long-term estimates of mean growth and reduce variability around parameter estimates.

Biological samples are used to characterize size and age distributions of the surveyed populations and are reconciled with the proportions of legal and sublegal clams from the overall survey samples. These two data sets should be compared while all sampled clams are still available and biological sample sizes increased as necessary to better match information from the two sources. If biological samples are increased in size until differences between the data sets is reduced, then reconciliation of the two data sets would have minimal impact or could possibly be eliminated entirely.

Vulnerability of small clams is estimated by comparing the length-at-age observed in the biological sample to that predicted from the growth model, and has a considerable effect during the reconciliation process. Efforts need to be made to examine and improve low levels of vulnerability of small clams to survey protocols. This may be as simple as quality assurance and training by experienced staff during survey activities, but should also require either post-screening of survey samples (*fide* Gillespie *et al.* 1998b) for evaluation or routine screening (*fide* Kingzett and Bourne 1998) to alleviate vulnerability issues.

Increased and improved surveys of control beaches could lead to development of better estimates of natural mortality rates and the variance associated with these estimates and reduce the most significant sources of uncertainty, s_h^2 and s_e^2, which are estimated from control beach time series. However, economics in the fishery and collaborative programs appear to be restrictive, and control beaches have been identified as the element of the program that is least beneficial to Industry in the short term (*i.e.*, control beaches incur survey costs that are not offset by harvest quotas). If these surveys are deemed essential to the program, it may be that DFO resources would be required to conduct them, and this would reduce DFO resources available for other elements of the program. An alternative is pursuit of methods to estimate natural mortality from harvested beaches with extensive survey histories and reasonable quality harvest data. Until better estimates are available, a natural mortality rate of 0.3 should be used in projection modelling.

Three years of projection appears to be a logical maximum, as the age of recruitment to legal size is approximately five years (Figure 13) and the age of first detection in the survey is approximately two years. Having stated this, it still appears that declining quotas (due to the recommended conservative decision regarding natural mortality rate) will motivate Industry to survey every second year.

Conclusions and Recommendations

The following recommendations are presented:

1. **The biologically-based threshold and limit reference points used to determine harvest rates currently used to manage the depuration fishery for intertidal clams should be maintained.** The sliding scale of harvest rates has allowed harvests to continue, although at lower harvest rates in some cases, rather than resulting in continued declines in population and eventual closure of beaches for recovery.
2. **Probabilistic projection models can be used to predict stock size, density and resulting harvest rates and quotas for three years from a single survey.** A maximum of three years projection is reasonable given vulnerability of small clams in

surveys. Economic motivation, *i.e.*, the benefits of incurring survey costs to restart the projection outweigh the loss of quota as projections proceed, will likely result in surveys occurring every two to three years. Decisions to require re-survey of an individual beach will be reached in consultation with Industry. This will reduce survey frequency on index beaches and allow survey resources to be re-allocated to beaches that have not been recently surveyed. Managers should continue to have regular open communication with processors and First Nations about other indications of stock strength. In particular, information on unusual mortalities and recognize that these events render the predictive model results invalid; beaches would have to be re-assessed to determine changes in stock size and age structure and the model re-run to establish valid quotas.

3. **Issues surrounding vulnerability estimates from survey time series indicate that additional training, supervision and improved quality assurance is required during Industry surveys.** Additional training would ensure that Industry diggers fully understand survey objectives, and quality assurance, in the form of screening quadrats after they have been dug, will allow evaluation of digger efficiency and provide information to determine whether vulnerability reconciliation is required.

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References

Ayres, D.L. and D.D. Simons. 1999. Razor clam fisheries and status of the razor clam stocks, June 1995 through May 1997. Wash. Dept. Fish Wildl. Fish Prog. Rep. MRD 99-01. 55 p.

Bain, L.J. and M.E. Engelhardt. 1991. Introduction to Probability and Mathematical Statistics. 2nd ed. Duxbury Press.

Bechtol, W.R. and R.L. Gustafson. 1998. Abundance, recruitment and mortality of Pacific littleneck clams *Protothaca staminea* at Chugachik Island, Alaska. J. Shellfish Res. 17(4): 1003-1008.

Bourne, N.F. 1982. Distribution, reproduction and growth of Manila clam, *Tapes philippinarum* (Adams and Reeve), in British Columbia. J. Shellfish Res. 2: 47-54.

Bourne, N.F. 1986. Bivalve fisheries: their exploitation and management with particular reference to the Northeast Pacific region. p. 2-13. *In*: G.S. Jamieson and N. Bourne [eds.]. North Pacific workshop on stock assessment and management of invertebrates. Can. Spec. Publ. Fish. Aquat. Sci. 92.

Bower, S.M. 1992. Winter mortalities and histopathology in Japanese littlenecks (*Tapes philippinarum* [A. Adams and Reeve]) in British Columbia due to freezing temperatures. J. Shellfish Res. 11: 255-263.

Bower, S.M., R. Harbo, B. Adkins and N. Bourne. 1986. Investigation of Manila clam (*Tapes philippinarum*) mortalities during the spring of 1985 in the Strait of Georgia, with a detailed study of the problem on Savary Island. Can. Tech. Rep. Fish. Aquat. Sci. 1444: 25 p.

Coan, E.V., P. Valentich Scott and F.R. Bernard. 2000. Bivalve Seashells of Western North America. Santa Barbara Museum of Natural History Monographs 2. Santa Barbara, CA. 764 p.

Devlin, I.H. 1973. Operation report: oyster depuration plant, Ladysmith, B.C. Environ. Can., Fish. Mar. Serv., Indus. Devel. Br. Proj. Rep. 57: 108 p.

Foster, N.R. 1997. The molluscan fisheries of Alaska. p. 131-144. *In*: C.L. MacKenzie, Jr., V.G. Burrell, Jr., A. Rosenfeld and W.L. Hobart. The history, present condition, and future of the molluscan fisheries of North and Central America and Europe. Vol. 2, Pacific Coast and supplemental topics. NOAA Tech. Rep. NMFS 128.

Gillespie, G.E. 2000. Preliminary review of experimental harvest rates in the depuration fishery for intertidal clams. Can. Stock Assess. Secret. Res. Doc. 2000/122: 57 p.

Gillespie, G.E. and J. Bond. 1997. Evaluation of harvest models for Manila clam fisheries in British Columbia. Can. Stock Assess. Secret. Res. Doc. 97/144: 44 p.

Gillespie, G.E. and A.R. Kronlund. 1999. A manual for intertidal clam surveys. Can. Tech. Rep. Fish. Aquat. Sci. 2270: 144 p.

Gillespie, G.E., A.R. Kronlund and G.D. Heritage. 1998a. Intertidal clam stock estimates for selected depuration harvest beaches – 1994. p. 3-46. *In*: B.J. Waddell, G.E. Gillespie and L.C. Walthers [eds.]. Invertebrate Working Papers reviewed by the Pacific Stock Assessment Review Committee (PSARC) in 1995. Part 1. Bivalves. Can. Tech. Rep. Fish. Aquat. Sci. 2214.

Gillespie, G.E., A.R. Kronlund and G.D. Heritage. 1998b. Assessment of Manila clam stocks at Savary Island, British Columbia – 1995. p. 245-317. *In*: B.J. Waddell, G.E. Gillespie and L.C. Walthers [eds.]. Invertebrate Working Papers reviewed by the Pacific Stock Assessment Review Committee (PSARC) in 1995. Part 1. Bivalves. Can. Tech. Rep. Fish. Aquat. Sci. 2214.

Gillespie, G.E., T.C. Norgard and F.E. Scurrah. 2001. Status of Manila clam (*Venerupis phillipinarum*) stocks in Area 7, British Columbia, with a proposal for active management of a data-limited fishery. Can. Sci. Advis. Secret. Res. Doc. 2001/089. 59 p.

Insightful Corporation, 2004. Splus Version 6.2, Professional Edition. Insightful Corporation, Seattle, USA.

Jones, R.R. and D.A. Garza. 1998. Co-management of the razor clam (*Siliqua patula*) fishery at Haida Gwaii, British Columbia, Canada. p. 385-391. *In*: G.S. Jamieson and A. Campbell [eds.]. Proceedings of the North Pacific Symposium on Invertebrate Stock Assessment and Management. Can. Spec. Publ. Fish. Aquat. Sci. 125.

Jones, R.R., L. Lee and C.J. Schwarz. 1998. Intertidal population estimate of razor clams (*Siliqua patula*) at beaches near Massett, Haida Gwaii/Queen Charlotte Islands, and applications to fishery management. p. 199-211. *In*: G.S. Jamieson and A. Campbell [eds.]. Proceedings of the North Pacific Symposium on Invertebrate Stock Assessment and Management. Can. Spec. Publ. Fish. Aquat. Sci. 125.

Jones, R., C. Schwarz, B. DeFreitas and L. Lee. 2001. Results of surveys of intertidal razor clams (*Siliqua patula*) on beaches near Massett, Haida Gwaii, and recommendations for management. Can. Sci. Advis. Secret. Res. Doc. 2001/152. 40 p.

Kingzett, B.C. and N.F. Bourne. 1998. Assessment of intertidal clam population surveys at Seal Island, British Columbia, 1940-1992. p. 47-125. *In*: B.J. Waddell, G.E. Gillespie and L.C. Walthers [eds.]. Invertebrate Working Papers reviewed by the Pacific Stock Assessment Review Committee (PSARC) in 1995. Part 1. Bivalves. Can. Tech. Rep. Fish. Aquat. Sci. 2214.

Kronlund, A.R., G.E. Gillespie and G.D. Heritage. 1998. Survey methodology for intertidal clams. p. 127-243. *In*: B.J. Waddell, G.E. Gillespie and L.C. Walthers [eds.]. Invertebrate Working Papers reviewed by the Pacific Stock Assessment Review Committee (PSARC) in 1995. Part 1. Bivalves. Can. Tech. Rep. Fish. Aquat. Sci. 2214.

Laslett, G.M., J.P. Eveson and T. Polacheck. 2002. A flexible maximum likelihood approach for fitting growth curves to tag-recapture data. Can. J. Fish. Aquat. Sci. 59(9): 976-986.

Leet, W.S., C.M. Dewees, R. Klinbeil and E.J. Larsen [eds.]. 2001. California's Living Marine Resources: A Status Report. California Dept. Fish Game. 593 p.

Lindsay, C.E. and D. Simons. 1997. The fisheries for Olympia oysters, *Ostreola conchaphila*; Pacific oysters, *Crassostrea gigas*; and Pacific razor clams, *Siliqua patula*, in the State of Washington. p. 89-113. *In*: C.L. MacKenzie, Jr., V.G. Burrell, Jr., A. Rosenfeld and W.L. Hobart. The history, present condition, and future of the molluscan fisheries of North and Central America and Europe. Vol. 2, Pacific Coast and supplemental topics. NOAA Tech. Rep. NMFS 128.

Lipovsky, V. Unpublished manuscript. Survey of standing Manila clam population in the Royston intertidal area. Report prepared for Unique Seafoods, Nanaimo, B.C.; submitted to DFO Fish Management, Nanaimo, B.C. 8 p.

Moore, T.O. 2001a. Pacific razor clam. p. 443-444. *In*: W.S. Leet, C.M. Dewees, R. Klinbeil and E.J. Larsen [eds.]. 2001. California's Living Marine Resources: A Status Report. California Dept. Fish Game.

Moore, T.O. 2001b. Gaper clams. p. 445-446. *In*: W.S. Leet, C.M. Dewees, R. Klinbeil and E.J. Larsen [eds.]. 2001. California's Living Marine Resources: A Status Report. California Dept. Fish Game.

Moore, T.O. 2001c. Washington clams. p. 447-448. *In*: W.S. Leet, C.M. Dewees, R. Klinbeil and E.J. Larsen [eds.]. 2001. California's Living Marine Resources: A Status Report. California Dept. Fish Game.

Pattison, C.A. 2001. Pismo clam. p. 135-137. *In*: W.S. Leet, C.M. Dewees, R. Klinbeil and E.J. Larsen [eds.]. 2001. California's Living Marine Resources: A Status Report. California Dept. Fish Game.

Neufeld, N. and K. Jackson. 1975. Clam depuration project, Ladysmith, B.C. Environ. Can., Fish. Mar. Serv., Indus. Devel. Br. Proj. Rep. 83: 35 p.

Quayle, D.B. 1938. *Paphia bifurcata*, a new molluscan species from Ladysmith Harbour, B.C. J. Fish. Res. Board Can. 4: 53-54.

Quayle, D.B. 1988. Pacific oyster culture in British Columbia. Can. Bull. Fish. Aquat. Sci. 218: 241 p.

Quayle, D.B. and N.F. Bourne. 1972. The clam fisheries of British Columbia. Fish. Res. Board Can. Bull. 179: 70 p.

Quinn, T.J. II, and N.J. Szarzi. 1993. Determination of sustained yield in Alaska's recreational fisheries. p. 61-84. *In*: Proceedings of the International Symposium on Management Strategies for Exploited Fish Populations. Alaska Sea Grant Rep. 93-02.

Reilly, P.N. 2001. Littleneck clams. p. 451-452. *In*: W.S. Leet, C.M. Dewees, R. Klinbeil and E.J. Larsen [eds.]. 2001. California's Living Marine Resources: A Status Report. California Dept. Fish Game.

Robinson, A.M. 1997. Molluscan fisheries in Oregon: past, present and future. p. 75-87. *In*: C.L. MacKenzie, Jr., V.G. Burrell, Jr., A. Rosenfeld and W.L. Hobart. The history, present condition, and future of the molluscan fisheries of North and Central America and Europe. Vol. 2, Pacific Coast and supplemental topics. NOAA Tech. Rep. NMFS 128.

Schink, T.D., K.A. McGraw and K.K. Chew. 1983. Pacific coast clam fisheries. Wash. Sea Grant Tech. Rep. WSG 83-1. 72 p.

Shaw, W.N. 1997. The shellfish industry of California – past, present and future. p. 57-74. *In*: C.L. MacKenzie, Jr., V.G. Burrell, Jr., A. Rosenfeld and W.L. Hobart. The history, present condition, and future of the molluscan fisheries of North and Central America and Europe. Vol. 2, Pacific Coast and supplemental topics. NOAA Tech. Rep. NMFS 128.

Szarzi, N.J., T.J. Quinn II and D.N. McBride. 1995. Assessment of shallow-water clam resources: case study of razor clams, eastern Cook Inlet, Alaska. ICES Mar. Sci. Symp. 199: 274-286.

Webb, R. 2004MS. Intertidal clams. Invertebrate post-season review 2003. Unpublished manuscript, Fish Management Branch, South Coast Division, Nanaimo, B.C. 34 p.

Table 1. Annual British Columbia commercial intertidal clam fishery landings, landed values and numbers of licences issued, 1951-2003.

	Landings (t)						Value ($M Cdn)	Licences Issued
Year	Butter	Littleneck	Manila	Mixed	Razor	Total		
51	1,597	237	81	65	61	2,041	$0.1	NA
52	2,490	224	184	65	57	3,020	$0.2	NA
53	1,674	140	176	20	70	2,080	$0.1	NA
54	1,314	66	204	5	123	1,712	$0.1	NA
55	2,170	36	207	3	99	2,515	$0.2	NA
56	1,454	14	99	0	108	1,675	$0.1	NA
57	1,606	10	29	11	84	1,740	$0.1	NA
58	987	18	15	6	75	1,101	$0.1	NA
59	1,094	22	25	13	90	1,244	$0.1	NA
60	1,800	41	6	23	101	1,971	$0.1	NA
61	857	46	48	34	104	1,089	$0.1	NA
62	1,533	92	69	43	77	1,814	$0.1	NA
63	1,144	59	59	0	67	1,329	$0.1	NA
64	570	69	26	1	48	714	$0.1	NA
65	704	82	97	0	68	951	$0.1	NA
66	831	105	149	1	35	1,121	$0.1	NA
67	975	139	92	0	46	1,252	$0.2	NA
68	399	91	164	15	12	681	$0.1	NA
69	378	107	81	7	8	581	$0.1	NA
70	792	144	79	15	18	1,048	$0.2	NA
71	568	361	153	11	62	1,155	$0.2	NA
72	645	631	265	1	17	1,559	$0.4	NA
73	298	207	134	0	76	715	$0.2	NA
74	531	328	182	0	69	1,110	$0.4	NA
75	746	236	158	6	27	1,173	$0.3	NA
76	655	173	199	70	82	1,179	$0.3	NA
77	649	209	394	59	78	1,389	$0.5	NA
78	383	159	753	245	47	1,587	$0.8	NA
79	613	273	251	374	101	1,612	$0.9	NA
80	760	358	288	151	75	1,632	$1.0	NA
81	119	179	318	161	30	807	$0.7	NA
82	102	242	598	155	68	1,165	$1.1	NA
83	77	324	1,048	279	31	1,759	$1.7	NA
84	130	294	1,677	410	100	2,611	$2.8	NA
85	251	191	1,913	477	90	2,922	$3.3	NA
86	158	284	1,893	371	142	2,848	$3.8	NA
87	68	373	3,607	87	142	4,277	$6.8	NA
88	134	290	3,909	27	155	4,515	$7.8	NA
89	92	433	2,764	159	117	3,565	$7.0	1,870

Table 1. continued.

Year	Landings (t)						Value	Licences
	Butter	Littleneck	Manila	Mixed	Razor	Total	($M Cdn)	Issued
90	109	465	1,456	339	114	2,483	$5.3	2,068
91	42	201	982	137	117	1,479	$3.3	1,908
92	132	116	923	112	55	1,338	$2.7	1,814
93	102	132	1,059	133	44	1,470	$3.4	1,639
94	48	136	1,327		105	1,616	$4.1	1,844
95	48	114	1,328		131	1,621	$3.8	2,448
96	41	63	1,306		75	1,485	$3.6	1,906
97	108	91	1,354		109	1,662	$3.5	1,572
98	51	71	1,516		40	1,678	$5.3	907
99	140	83	1,337		78	1,638	$5.3	915
00	98	134	1,128		236	1,596	$4.9	977
01	27	147	1,420		166	1,760	$6.1	964
02	103			1,649	159	1,911	$6.4	993
03	66			1,366	164	1,596	$5.4	1,011

Notes:

1951 to 1969 landings from Quayle and Bourne (1970), 1970 to 1993 landings from sales slip records (Webb and Hobbs 1997), 1994 to 2002 landings from plant hails (Webb 2004MS), 2003 landings are preliminary.

Landings for 1992 to 2003 include aboriginal licenced harvest in Area 7 and non-tenured depuration harvests.

Manila clam landings for 1994 to 2001 include landings reported as mixed clams, these likely account for less than 10% of total Manila landings.

Mixed clam landings for 2002 and 2003 include both littleneck and Manila landings as there was insufficient information from hails to split the species.

Table 2. Annual landings from depuration facilities in British Columbia 1990-2003.

	Landings (t)		
Year	Manila	Littleneck	Total
1990	n/a[1]	n/a[1]	n/a[1]
1991	-	n/a[1]	n/a[1]
1992	n/a[1]	n/a[1]	n/a[1]
1993	n/a[1]	n/a[1]	n/a[1]
1994	n/a[1]	n/a[1]	n/a[1]
1995	n/a[1]	n/a[1]	n/a[1]
1996	209.3	15.1	224.4
1997	408.4	31.2	439.7
1998	399.9	39.5	439.4
1999	370.1	27.9	398.1
2000	295.5	47.2	342.7
2001	312.9	33.2	346.1
2002	379.5	28.8	408.2
2003	256.2	28.6	284.8
Total	1,904.3	722.2	2,626.6

Notes:
Landings are from commercial fisheries only and do not include production depurated from clam leases.
[1] – landings cannot be released due to restrictions of the Privacy Act.

Table 3. Assessment programs for beaches harvested for depuration of intertidal clams in British Columbia.

Beach	Assessment Program	Last Assessed	Active
Bamberton	Baseline	2001	Yes
Base Flats	Baseline	1994	Closure lifted 1994[2]
Berray Road	Baseline	1998	Tenure 1999
Booth Bay	Annual	2004	Yes
Brenton-Page, Ladysmith	Annual	2003	Yes
Cachalot Inlet	Baseline	2001	Yes
China Cloud Bay	Annual[1]	2002	Closure lifted 2003
Craig Bay	Annual	1999	Closed (stock concerns) 1999
Degnen Bay	Baseline	2001	Part tenure 2003, part active
Ganges Harbour	Baseline	1994	Closed (other concerns) 1999[3]
Gartley Point	Baseline	2002	Tenure 2003
Gillies Bay	Annual	2004	Yes
Goldstream	Annual	2004	Yes
Ivy Green	Baseline	1999	Tenure 2003
Kuper Island (6 beaches)	Baseline	1999-2004	One tenure 2003, one closure lifted 2003, four active
Ladysmith Harbour (6 beaches)	Baseline	1994-2002	Yes
Lantzville	Annual	2004	Yes
Long Bay, Lasqueti	Annual[1]	2003	Yes
Long Harbour, Saltspring	Baseline	1996	Last harvest 1999[4]
Malksope Inlet	Baseline	1998	Yes
Mill Bay	Annual	2003	Control[5]
Mud Bay East, Baynes Sound	Annual	1999	Tenure 1999
Mud Bay West, Baynes Sound	Annual	1999	Tenure 1999
Nanaimo River Estuary	Baseline	2003	Yes
Okeover Inlet	Baseline	1997	Last harvest 1999
Parksville	Annual	1999	Closed (stock concerns) 1999
Royston	Annual	2004	Control
Sooke Harbour	Baseline	1995	Yes
Sooke Basin (10 beaches)	Baseline	1994-2003	Yes
Wall Beach	Annual	2004	Control
Willy Island	Baseline	1997-2002	Part tenure 2003

Notes: [1] - indicates beaches with post-harvest surveys; [2] – “closure lifted” indicates beaches returned to regular fisheries as water quality improved; [3] – “other concerns” indicates rationales other than stock concerns or changes in water quality that result in closure; [4] – “last harvested” indicates that harvest permits have not been requested despite no stock or other concerns; [5] – “control” indicates unharvested beaches surveyed under the experimental program.

Table 4. Limit and threshold reference points and associated target harvest rates for beaches in the experimental harvest program (Gillespie 2000).

Reference point	Type	Harvest rate
< 30 legal clams m^{-2}	Limit	0 (Close for recovery)
< 70 legal clams m^{-2}	Threshold	10%
<130 legal clams m^{-2}	Threshold	20%
= 130 legal clams m^{-2}	Threshold	40%

Table 5. Survey design, survey area, number of strata and sample sizes for beaches surveyed under experimental harvest programs for depuration harvests of intertidal clams in British Columbia.

Beach	Stratified Survey Design	Year(s)	Survey Area (ha)	Number of Strata	Number of Quadrats
Booth Bay	Random	96-99, 01-03	3.13	16	169
China Cloud Bay	Random	02	2.60	7	99
Craig Bay	Two-stage	97-99	16.51	20	309
Goldstream	Two-stage	97-01	5.34	5	160
		02-04	5.70	6	175
Long Bay	Random	02-03	1.30	5	62
Mill Bay	Random	97-03	0.56	4	40
Mud Bay East	Two-stage	97, 99	12.00	13	170
Mud Bay West	Two-stage	97-99	14.50	19	237
Parksville	Two-stage	97-99	6.95	6	232
Royston	Two-stage	97-99	10.00	12	168
		01-04	5.00	6	150
Wall Beach	Random	97-99, 01-04	2.18	11	112

Table 6. Survey results, harvest rates (HR), quotas and changes in biomass at Mill Bay, 1997-2003.

	Manila			
Survey Date	Aug-97	Sep-98	Sep-99	Sep-00
Legal Biomass	4,254	7,484	7,832	4,793
95% CI (+/-)	1,273	1,645	2,177	1,799
Sublegal Biomass	1,844	2,842	2,304	1,255
95% CI (+/-)	499	779	857	388
Legal Abundance	212,600	363,680	367,720	202,230
95% CI (+/-)	61,754	79,071	102,715	76,540
Sublegal Abundance	182,920	247,560	183,480	110,000
95% CI (+/-)	49,562	70,995	60,801	33,737
Target HR	-	-	-	-
Quota (kg)	-	-	-	-
Actual HR	0	0	0	0
Change in legal biomass	-	76%	5%	-39%

	Littleneck			
Survey Date	Aug-97	Sep-98	Sep-99	Sep-00
Legal Biomass	214	292	348	224
95% CI (+/-)	144	328	213	153
Sublegal Biomass	527	612	385	408
95% CI (+/-)	261	357	181	166
Legal Abundance	9,800	12,880	13,600	8,520
95% CI (+/-)	6,617	15,608	7,297	5,865
Sublegal Abundance	52,280	57,800	38,520	33,200
95% CI (+/-)	26,967	36,341	21,680	13,987

Table 6. (continued).

	Manila			
Survey Date	May-01	May-02	Jun-03	Jun-04
Legal Biomass	10,855	8,629	7,726	
95% CI (+/-)	2,458	2,577	1,692	
Sublegal Biomass	1,423	1,843	1,936	
95% CI (+/-)	282	345	353	
Legal Abundance	443,040	357,480	309,400	
95% CI (+/-)	94,410	103,001	64,475	
Sublegal Abundance	144,000	163,120	183,800	
95% CI (+/-)	26,916	38,183	36,534	
Target HR	-	-	-	
Quota (kg)	-	-	-	
Actual HR	0	0	0	
Change in legal biomass	126%	-21%	-10%	

	Littleneck			
Survey Date	May-01	May-02	Jun-03	Jun-04
Legal Biomass	1,224	630	429	
95% CI (+/-)	445	450	206	
Sublegal Biomass	635	445	233	
95% CI (+/-)	698	225	179	
Legal Abundance	49,680	26,520	17,760	
95% CI (+/-)	19,698	19,129	9,066	
Sublegal Abundance	60,000	38,320	18,040	
95% CI (+/-)	53,467	19,663	11,946	

Table 7. Survey results, harvest rates (HR), quotas and change in biomass at Royston, 1997-2004.

	Manila			
Survey Date	Jun-97	May-98	May-99	May-00
Legal Biomass	12,727	14,554	19,295	
95% CI (+/-)	1,936	1,879	2,712	
Sublegal Biomass	16,748	30,032	30,945	
95% CI (+/-)	3,053	3,546	4,822	
Legal Abundance	662,667	720,000	978,667	
95% CI (+/-)	97,457	98,861	144,686	
Sublegal Abundance	2,188,000	3,437,333	3,218,667	
95% CI (+/-)	396,554	402,502	544,043	
Target HR	-	-	-	-
Quota (kg)	-	-	-	-
Actual HR	0	0	0	0
Change in legal biomass	-	14%	33%	-

	Littleneck			
Survey Date	Jun-97	May-98	May-99	May-00
Legal Biomass	843	551	3,457	
95% CI (+/-)	393	444	3,661	
Sublegal Biomass	2,639	2,937	3,391	
95% CI (+/-)	599	563	932	
Legal Abundance	45,333	21,333	74,667	
95% CI (+/-)	25,463	15,582	40,810	
Sublegal Abundance	240,000	364,000	370,667	
95% CI (+/-)	52,840	67,299	91,143	

Table 7. (continued).

	Manila			
Survey Date	May-01	May-02	Jun-03	Jun-04
Legal Biomass	38,528	34,329	62,351	47,048
95% CI (+/-)	4,844	3,586	7,662	6,304
Sublegal Biomass	43,717	43,716	50,364	23,660
95% CI (+/-)	6,133	6,238	6,133	4,435
Legal Abundance	1,916,000	1,697,333	3,044,000	2,162,667
95% CI (+/-)	261,387	184,479	325,423	289,256
Sublegal Abundance	4,737,333	4,614,667	5,030,667	2,021,333
95% CI (+/-)	663,620	719,756	657,297	389,931
Target HR	-	-	-	-
Quota (kg)	-	-	-	-
Actual HR	0	0	0	0
Change in legal biomass	-	-11%	82%	-25%

	Littleneck			
Survey Date	May-01	May-02	Jun-03	Jun-04
Legal Biomass	1,265	1,043	1,068	2,063
95% CI (+/-)	514	367	705	935
Sublegal Biomass	4,687	1,665	2,203	1,785
95% CI (+/-)	1,227	516	1,046	546
Legal Abundance	58,667	48,000	50,667	92,000
95% CI (+/-)	23,448	17,273	33,533	38,872
Sublegal Abundance	452,000	160,000	194,667	150,667
95% CI (+/-)	120,386	47,309	89,378	40,589

Table 8. Survey results, harvest rates (HR), quotas and change in biomass at Wall Beach, 1997-2004.

	Manila			
Survey Date	Aug-97	Jul-98	Jul-99	Jun-00
Legal Biomass	4,406	3,094	1,510	
95% CI (+/-)	2,201	1,832	706	
Sublegal Biomass	31,308	26,111	16,172	
95% CI (+/-)	7,782	7,324	3,551	
Legal Abundance	242,270	176,040	127,170	
95% CI (+/-)	123,310	98,050	92,901	
Sublegal Abundance	5,200,430	5,473,370	3,697,950	
95% CI (+/-)	1,104,014	1,168,852	814,116	
Target HR	-	-	-	-
Quota (kg)	-	-	-	-
Actual HR	0	0	0	0
Change in legal biomass	-	-30%	-51%	-

	Littleneck			
Survey Date	Aug-97	Jul-98	Jul-99	Jun-00
Legal Biomass	238	262	927	
95% CI (+/-)	115	140	622	
Sublegal Biomass	386	169	927	
95% CI (+/-)	311	83	459	
Legal Abundance	7,140	8,560	9,750	
95% CI (+/-)	3,540	4,720	5,742	
Sublegal Abundance	52,960	46,200	174,850	
95% CI (+/-)	29,408	22,945	69,898	

Table 8. (continued).

	Manila			
Survey Date	Jun-01	Jun-02	Jun-03	Jun-04
Legal Biomass	1,795	1,895	1,120	1,408
95% CI (+/-)	1,526	1,008	643	764
Sublegal Biomass	25,647	19,135	11,143	13,339
95% CI (+/-)	5,770	4,054	2,764	3,391
Legal Abundance	100,130	101,910	62,470	77,700
95% CI (+/-)	80,703	55,266	35,273	41,237
Sublegal Abundance	5,472,790	3,596,040	1,655,860	2,006,360
95% CI (+/-)	1,230,307	726,405	404,867	548,661
Target HR	-	-	-	-
Quota (kg)	-	-	-	-
Actual HR	0	0	0	0
Change in legal biomass	-	6%	-41%	26%

	Littleneck			
Survey Date	Jun-01	Jun-02	Jun-03	Jun-04
Legal Biomass	109	77	100	63
95% CI (+/-)	53	52	75	61
Sublegal Biomass	249	215	170	270
95% CI (+/-)	162	143	121	279
Legal Abundance	3,360	2,940	3,570	2,780
95% CI (+/-)	1,773	2,404	3,076	2,833
Sublegal Abundance	57,030	31,020	23,110	24,310
95% CI (+/-)	40,255	17,222	15,224	22,937

Table 9. Survey results, harvest rates (HR), quotas and change in biomass at Booth Bay, 1996-2004.

	Manila			
Survey Date	Jul-96	Aug-97	Aug-98	Aug-99
Legal Biomass	113,247	119,551	89,845	104,165
95% CI (+/-)	15,826	12,753	10,495	13,379
Sublegal Biomass	54,197	68,230	50,043	56,697
95% CI (+/-)	9,216	8,807	6,228	7,745
Legal Abundance	5,454,983	6,305,904	4,597,755	5,467,653
95% CI (+/-)	766,124	666,442	503,648	731,210
Sublegal Abundance	7,186,670	8,673,987	6,137,455	6,985,735
95% CI (+/-)	1,511,273	1,164,579	819,450	1,064,476
Target HR	50%	50%	50%	50%
Quota (kg)	56,624	59,776	44,923	52,083
Actual HR	44%	38%	39%	0
Change in legal biomass	-	6%	-25%	16%

	Littleneck			
Survey Date	Jul-96	Aug-97	Aug-98	Aug-99
Legal Biomass	1,922	3,580	2,511	3,150
95% CI (+/-)	794	1,104	776	1,839
Sublegal Biomass	1,663	1,847	1,855	2,725
95% CI (+/-)	483	766	489	1,085
Legal Abundance	70,892	136,313	89,981	117,498
95% CI (+/-)	24,708	39,612	28,088	62,258
Sublegal Abundance	248,944	270,283	226,880	284,831
95% CI (+/-)	83,237	116,131	70,168	120,481

Table 9. (continued).

			Manila		
Survey Date	Aug-00	Aug-01	Aug-02	Aug-03	Aug-04
Legal Biomass		157,120	139,286	176,907	188,301
95% CI (+/-)		14,988	13,232	11,032	14,334
Sublegal Biomass		70,872	69,197	59,044	65,567
95% CI (+/-)		10,008	9,292	6,769	8,421
Legal Abundance		7,898,492	7,097,511	8,692,133	9,217,780
95% CI (+/-)		769,476	706,826	563,944	668,949
Sublegal Abundance		7,325,357	6,814,517	5,258,100	5,858,599
95% CI (+/-)		1,042,757	901,713	625,983	754,525
Target HR		40%	40%	40%	40%
Quota (kg)		62,848	55,714	70,763	75,320
Actual HR	25%	40%	53%	28%	-
Change in legal biomass	-	-	-11%	27%	6%

			Littleneck		
Survey Date	Aug-00	Aug-01	Aug-02	Aug-03	Aug-04
Legal Biomass		4,397	4,655	2,850	4,063
95% CI (+/-)		1,339	1,740	957	1,354
Sublegal Biomass		2,884	2,453	1,955	2,101
95% CI (+/-)		1,136	734	577	771
Legal Abundance		160,584	182,618	110,041	156,106
95% CI (+/-)		50,110	68,646	38,436	54,561
Sublegal Abundance		241,622	220,555	156,049	165,515
95% CI (+/-)		91,760	68,329	50,146	61,626

Table 10. Survey results, harvest rates (HR), quotas and change in biomass at Goldstream, 1997-2004.

	Manila			
Survey Date	Aug-97	Aug-98	Aug-99	Aug-00
Legal Biomass	62,910	101,018	98,341	48,372
95% CI (+/-)	8,325	12,164	11,228	5,996
Sublegal Biomass	26,343	21,894	13,901	10,802
95% CI (+/-)	3,571	3,741	2,069	1,627
Legal Abundance	2,937,250	4,698,250	4,568,990	2,056,210
95% CI (+/-)	419,617	634,538	550,760	247,438
Sublegal Abundance	2,994,860	1,972,170	1,771,140	1,119,910
95% CI (+/-)	408,617	326,714	298,870	197,713
Target HR	25%	25%	25%	10%
Quota (kg)	15,728	25,255	24,585	4,837
Actual HR	4%	30%	25%	10%
Change in legal biomass	-	61%	-3%	-51%

	Littleneck			
Survey Date	Aug-97	Aug-98	Aug-99	Aug-00
Legal Biomass	25,518	32,504	30,518	30,376
95% CI (+/-)	3,867	3,908	6,113	3,591
Sublegal Biomass	18,829	19,909	22,588	12,803
95% CI (+/-)	2,784	3,075	4,710	2,009
Legal Abundance	987,340	1,129,510	1,235,980	1,173,990
95% CI (+/-)	148,315	126,278	247,112	139,917
Sublegal Abundance	2,036,970	1,935,080	2,154,270	1,086,169
95% CI (+/-)	356,785	356,294	600,654	158,809

Table 10. (continued).

	Manila			
Survey Date	Jul-01	Jul-02	Jul-03	Jul-04
Legal Biomass	88,172	77,535	72,772	79,202
95% CI (+/-)	10,317	10,667	8,701	11,422
Sublegal Biomass	6,818	2,791	1,831	2,990
95% CI (+/-)	1,161	776	377	555
Legal Abundance	3,792,470	3,041,300	2,629,850	2,661,610
95% CI (+/-)	475,135	439,116	316,798	381,084
Sublegal Abundance	691,410	286,780	170,960	362,670
95% CI (+/-)	120,063	72,532	35,614	62,711
Target HR	20%	10%	10%	10%
Quota (kg)	17,634	7,754	7,277	7,920
Actual HR	20%	11%	11%	-
Change in legal biomass	82%	-12%	-6%	9%

	Littleneck			
Survey Date	Jul-01	Jul-02	Jul-03	Jul-04
Legal Biomass	43,428	34,665	35,081	57,041
95% CI (+/-)	5,408	3,687	6,169	8,874
Sublegal Biomass	20,808	22,618	12,313	8,641
95% CI (+/-)	2,693	3,253	2,495	1,489
Legal Abundance	1,710,560	1,355,110	1,317,350	2,170,000
95% CI (+/-)	216,710	145,513	235,561	347,606
Sublegal Abundance	2,712,590	2,016,630	973,240	617,000
95% CI (+/-)	499,001	324,281	204,827	111,350

Table 11. Survey results and actual harvest rates achieved at China Cloud Bay, Lasqueti Island, 2002.

	Manila
Survey Date	Sep-02
Legal Biomass	27,956
95% CI (+/-)	6,386
Sublegal Biomass	54,826
95% CI (+/-)	7,080
Legal Abundance	1,484,140
95% CI (+/-)	335,609
Sublegal Abundance	5,560,829
95% CI (+/-)	702,147
Harvest (kg)	3,526
Actual HR	11%

Table 12. Survey results and actual harvest rates achieved at Long Bay, Lasqueti Island, 2002-2004.

		Manila	
Survey Date	Sep-02	Sep-03	Sep-04
Legal Biomass	26,458	22,494	26,476
95% CI (+/-)	3,698	3,744	5,232
Sublegal Biomass	13,538	10,978	8,971
95% CI (+/-)	3,045	3,120	2,511
Legal Abundance	1,251,023	1,016,867	1,148,820
95% CI (+/-)	163,121	162,348	206,227
Sublegal Abundance	1,298,601	940,867	751,860
95% CI (+/-)	290,546	273,393	205,701
Harvest (kg)	3,778	3,359	3,001
Actual HR	12%	13%	11%

Table 13. Growth parameters of Manila clams estimated from length-at-annulus data.

Beach	Year	L_∞	s_∞^2	k	t_0	s_{meas}^2
Booth Bay	2003	46.114	26.013	0.333	0.010	9.559
Goldstream	2004	57.960	87.100	0.300	0.081	14.806
Mill Bay	2003	52.113	59.057	0.282	0.043	9.080
Royston	2003	50.445	60.973	0.272	0.001	9.588
Wall Beach	2004	38.947	17.694	0.299	-0.162	12.247

Table 14. Length-weight relationship parameters for Manila clams estimated from biological sample data.

Beach	a	b	s_W^2
Booth Bay	1.47×10^{-4}	3.154	0.0271
Goldstream	1.31×10^{-4}	3.180	0.0159
Mill Bay	1.48×10^{-4}	3.175	0.0195
Royston	2.24×10^{-4}	3.047	0.0347

Table 15. Vulnerability parameters for Manila clams by beach and year.

Beach	Year	v_0	v_1	$L_{0.5}$
Booth Bay	1996	0.186	98.916	34.277
	1998	0.191	32.047	29.442
	1999	0.195	38.353	32.476
	2001	0.190	26.956	25.796
	2002	0.574	24.396	24.395
	2003	0.416	26.939	26.891
Goldstream	1999	0.111	48.395	30.408
	2000	0.273	31.468	30.408
	2001	0.430	27.045	27.003
	2002	0.164	147.247	33.769
	2003	0.177	136.883	34.085
	2004	0.201	507.356	34.549
Mill Bay	1997	0.284	28.779	28.303
	1999	0.193	33.808	30.515
	2001	0.282	34.052	32.261
	2002	0.457	27.388	27.353
	2003	0.205	110.347	34.622
Royston	1997	0.081	172.155	29.408
	1999	1.000	15.616	15.616
	2001	0.058	294.371	26.103
	2002	0.080	36.780	23.923
	2003	0.126	30.594	25.970
	2004	0.251	27.616	27.067

Table 16. Mortality rates of Manila clams estimated from snapshot surveys.

Beach	Year	*M*	95*CBfactor*
Booth Bay	1996	1.095	8.125
	1998	0.457	1.671
	1999	0.520	1.954
	2001	0.231	4.179
	2002	0.191	3.435
	2003	0.003	1.483
Goldstream	1999	0.225	1.736
	2000	0.319	3.031
	2001	0.121	4.570
	2002	0.302	3.403
	2003	0.095	337,753.936
	2004	-0.073	183,012.836
Mill Bay	1997	0.328	8.125
	1999	0.337	1.671
	2001	0.541	1.954
	2002	0.273	1.954
	2003	0.426	1.954
Royston	1997	0.448	1.320
	1999	0.058	2.166
	2001	0.161	5.826
	2002	0.189	3.960
	2003	0.261	1.817
	2004	0.151	1.954

Note: 95CBfactor is the 95% confidence factor in predicted abundance at age, for example, within a factor of 8.125.

Table 17. Abundance parameters for Manila clams estimated from control beach surveys.

Beach	M	s_{M}	s_{cohort}	s_{year}	$s_{abundance_{age}}$
Mill Bay	0.199	0.047	0.511	0.430	0.584
Royston	0.103	0.048	0.661	0.516	0.612

Table 18. Legal biomass (t), legal density (clams m^{-2}), target harvest rate and quota (t) for Booth Bay and Goldstream using the most recent survey as a snapshot, two levels of q_{quota} and fixing M at 0.3.

a) Booth Bay q_{quota} = 0.05, M = 0.3, beach area = 3.13 ha.

Survey		Year of Quota										
Year		1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
1996	Biomass	113.25	93.57	101.93	60.03							
	Density	130.98	135.47	135.31	73.27							
	HR	0.40	0.40	0.40	0.20							
	Quota	45.30	37.43	40.77	12.01							
1998	Biomass			89.85	61.46	43.61	32.40					
	Density			114.30	74.21	49.42	34.56					
	HR			0.20	0.20	0.10	0.10					
	Quota			17.97	12.29	4.36	3.24					
1999	Biomass				104.17	62.21	63.93	44.66				
	Density				149.86	93.27	86.26	55.03				
	HR				0.40	0.20	0.20	0.10				
	Quota				41.67	12.44	12.79	4.47				
2001	Biomass						157.12	65.68	51.69	34.38		
	Density						205.58	82.07	60.61	36.42		
	HR						0.40	0.20	0.10	0.10		
	Quota						62.85	13.14	5.17	3.44		
2002	Biomass							139.29	55.02	42.69	27.29	
	Density							204.39	78.41	55.24	31.50	
	HR							0.40	0.20	0.10	0.10	
	Quota							55.71	11.00	4.27	2.73	
2003	Biomass								176.91	59.11	38.45	23.67
	Density								284.21	85.72	52.11	31.07
	HR								0.40	0.20	0.10	0.10
	Quota								70.76	11.82	3.84	2.37

Table 18. (continued).

b) Booth Bay q_{quota} = 0.25, M = 0.3, beach area = 3.13 ha.

Survey Year		Year of Quota										
		1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
1996	Biomass	113.25	138.09	149.13	105.44							
	Density	130.98	200.25	196.18	127.37							
	HR	0.40	0.40	0.40	0.20							
	Quota	45.30	55.24	59.65	21.09							
1998	Biomass			89.85	85.11	72.39	49.68					
	Density			114.30	102.08	81.27	53.49					
	HR			0.20	0.20	0.20	0.10					
	Quota			17.97	17.02	14.48	4.97					
1999	Biomass				104.17	92.47	83.56	73.49				
	Density				149.86	135.70	115.70	92.11				
	HR				0.40	0.40	0.20	0.20				
	Quota				41.67	36.99	16.71	14.70				
2001	Biomass						157.12	101.46	80.01	58.77		
	Density						205.58	124.45	90.50	61.78		
	HR						0.40	0.20	0.20	0.10		
	Quota						62.85	20.29	16.00	5.88		
2002	Biomass							139.29	85.45	66.60	45.96	
	Density							204.39	118.05	84.53	54.49	
	HR							0.40	0.20	0.20	0.10	
	Quota							55.71	17.09	13.32	4.60	
2003	Biomass								176.91	91.71	50.65	34.39
	Density								284.21	130.98	69.72	45.36
	HR								0.40	0.40	0.10	0.10
	Quota								70.76	36.68	5.07	3.44

Table 18. (continued).

c) Booth Bay q_{quota} = 0.50, M = 0.3, beach area = 3.13 ha.

Survey		Year of Quota										
Year		1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
1996	Biomass	113.25	172.71	208.86	152.74							
	Density	130.98	249.95	278.74	187.90							
	HR	0.40	0.40	0.40	0.40							
	Quota	45.30	69.09	83.54	61.10							
1998	Biomass			89.85	107.22	98.05	78.35					
	Density			114.30	128.26	110.10	83.97					
	HR			0.20	0.20	0.20	0.20					
	Quota			17.97	21.44	19.61	15.67					
1999	Biomass				104.17	118.16	122.70	83.56				
	Density				149.86	171.67	167.00	107.62				
	HR				0.40	0.40	0.40	0.20				
	Quota				41.67	47.26	49.08	16.71				
2001	Biomass						157.12	131.49	97.90	70.43		
	Density						205.58	159.60	112.92	76.05		
	HR						0.40	0.40	0.20	0.20		
	Quota						62.85	52.60	19.58	14.09		
2002	Biomass							139.29	110.47	81.67	55.46	
	Density							204.39	151.56	105.34	66.28	
	HR							0.40	0.40	0.20	0.10	
	Quota							55.71	44.19	16.33	5.55	
2003	Biomass								176.91	120.11	73.24	47.97
	Density								284.21	170.25	100.06	63.19
	HR								0.40	0.40	0.20	0.10
	Quota								70.76	48.04	14.65	4.80

Table 18. (continued).

d) Goldstream q_{quota} = 0.05, M = 0.3, beach area = 5.70 ha.

Survey Year		Year of Quota									
		1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
1998	Biomass	101.61	54.68	33.37	22.51						
	Density	75.55	39.13	20.76	12.63						
	HR	0.20	0.10	0.00	0.00						
	Quota	20.32	5.47	0.00	0.00						
1999	Biomass		98.27	43.88	31.32	19.41					
	Density		71.80	30.18	19.45	11.22					
	HR		0.20	0.10	0.00	0.00					
	Quota		19.65	4.39	0.00	0.00					
2000	Biomass			48.37	34.36	26.26	16.09				
	Density			35.69	21.69	14.19	7.86				
	HR			0.10	0.00	0.00	0.00				
	Quota			4.84	0.00	0.00	0.00				
2001	Biomass				88.17	44.58	33.06	18.99			
	Density				60.97	25.86	16.26	8.46			
	HR				0.10	0.00	0.00	0.00			
	Quota				8.82	0.00	0.00	0.00			
2002	Biomass					77.54	42.16	31.75	23.09		
	Density					51.63	22.80	14.88	9.58		
	HR					0.10	0.00	0.00	0.00		
	Quota					7.75	0.00	0.00	0.00		
2003	Biomass						72.77	37.52	27.44	18.57	
	Density						46.85	19.93	12.56	7.69	
	HR						0.10	0.00	0.00	0.00	
	Quota						7.28	0.00	0.00	0.00	
2004	Biomass							79.20	45.38	34.89	25.39
	Density							48.90	24.68	16.24	10.23
	HR							0.10	0.00	0.00	0.00
	Quota							7.92	0.00	0.00	0.00

Table 18. (continued).

e) Goldstream q_{quota} = 0.25, M = 0.3, beach area = 5.70 ha.

Survey		Year of Quota									
Year		1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
1998	Biomass	101.61	76.07	55.43	34.69						
	Density	75.55	54.44	34.27	19.78						
	HR	0.20	0.10	0.10	0.00						
	Quota	20.32	7.61	5.54	0.00						
1999	Biomass		98.27	62.85	47.28	35.48					
	Density		71.80	42.89	29.25	20.61					
	HR		0.20	0.10	0.00	0.00					
	Quota		19.65	6.29	0.00	0.00					
2000	Biomass			48.37	48.99	28.27	26.48				
	Density			35.69	31.00	20.89	12.96				
	HR			0.10	0.10	0.00	0.00				
	Quota			4.84	4.90	0.00	0.00				
2001	Biomass				88.17	62.22	45.03	32.27			
	Density				60.97	35.85	22.51	14.40			
	HR				0.10	0.10	0.00	0.00			
	Quota				8.82	6.22	0.00	0.00			
2002	Biomass					77.54	57.89	45.60	35.73		
	Density					51.63	31.85	21.45	14.85		
	HR					0.10	0.10	0.00	0.00		
	Quota					7.75	5.79	0.00	0.00		
2003	Biomass						72.77	51.82	43.17	31.51	
	Density						46.85	27.70	19.75	13.14	
	HR						0.10	0.00	0.00	0.00	
	Quota						7.28	0.00	0.00	0.00	
2004	Biomass							79.20	62.30	50.30	37.80
	Density							48.90	34.67	23.26	15.44
	HR							0.10	0.10	0.00	0.00
	Quota							7.92	6.23	0.00	0.00

Table 18. (continued).

f) Goldstream q_{quota} = 0.50, M = 0.3, beach area = 5.70 ha.

Survey Year		Year of Quota 1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
1998	Biomass	101.61	95.70	76.33	52.63						
	Density	75.55	67.41	47.21	29.81						
	HR	0.20	0.10	.010	0.00						
	Quota	20.32	9.57	7.63	0.00						
1999	Biomass		98.27	79.65	68.76	47.13					
	Density		71.80	54.37	42.72	27.44					
	HR		0.20	0.10	0.10	0.00					
	Quota		19.65	7.97	6.88	0.00					
2000	Biomass			48.37	61.20	52.98	38.71				
	Density			35.69	38.70	28.83	18.93				
	HR			0.10	0.10	0.00	0.00				
	Quota			4.84	6.12	0.00	0.00				
2001	Biomass				88.17	78.23	65.20	42.46			
	Density				60.97	44.97	32.34	19.07			
	HR				0.10	0.10	0.10	0.00			
	Quota				8.82	7.82	6.52	0.00			
2002	Biomass					77.54	72.72	63.16	50.49		
	Density					51.63	39.57	29.67	21.04		
	HR					0.10	0.10	0.00	0.00		
	Quota					7.75	7.27	0.00	0.00		
2003	Biomass						72.77	64.67	53.76	40.92	
	Density						46.85	34.42	24.60	16.99	
	HR						0.10	0.10	0.00	0.00	
	Quota						7.28	6.47	0.00	0.00	
2004	Biomass							79.20	77.71	69.08	48.52
	Density							48.90	42.85	32.16	19.97
	HR							0.10	0.10	0.10	0.00
	Quota							7.92	7.77	6.91	0.00

Table 19. Width of 95% confidence interval (expressed as percent of the estimated mean) from beach surveys under the experimental harvest program for depuration clam fisheries.

	Year									
Beach	1996	1997	1998	1999	2000	2001	2002	2003	2004	Average
					Legal Manilas					
Booth Bay	14%	11%	12%	13%		10%	9%	6%	8%	10%
China Cloud Bay							23%			23%
Craig Bay		11%	11%	14%						12%
Goldstream		13%	12%	11%	12%	12%	14%	12%	14%	13%
Long Bay							14%	17%		16%
Mill Bay		30%	22%	38%	28%	23%	30%	22%		28%
Mud Bay East		22%		19%						21%
Mud Bay West		14%	16%	15%						15%
Parksville		12%	13%	14%						13%
Royston		15%	13%	14%		13%	10%	12%	13%	13%
Wall Beach		50%	59%	47%		86%	53%	57%	54%	58%
					Sublegal Manilas					
Booth Bay	17%	13%	12%	14%		14%	13%	11%	13%	13%
China Cloud Bay							13%			13%
Craig Bay		14%	13%	13%						13%
Goldstream		14%	17%	15%	15%	17%	21%	28%	19%	18%
Long Bay							22%	28%		25%
Mill Bay		27%	27%	37%	31%	20%	19%	18%		26%
Mud Bay East		15%		13%						14%
Mud Bay West		11%	14%	12%						12%
Parksville		15%	15%	14%						15%
Royston		18%	12%	16%		14%	14%	12%	19%	15%
Wall Beach		25%	28%	22%		22%	21%	25%	25%	24%

Table 20. Mean density of legal Manilas (clams m^{-2}) and target harvest rates (based on decision rules in Table 4) for beaches in the experimental harvest program for depuration clam fisheries.

					Year				
Beach	1996	1997	1998	1999	2000	2001	2002	2003	2004
					Legal Density (clams m^{-2})				
Booth Bay	174.5	201.8	147.1	174.9		252.7	227.1	278.1	294.9
China Cloud Bay							64.3		
Craig Bay		29.8	11.4	10.0					
Goldstream		55.0	88.0	85.6	38.5	71.1	57.0	49.3	49.9
Long Bay							110.0	72.4	
Mill Bay		38.0	64.9	65.7	36.1	79.1	63.8	55.3	
Mud Bay East		14.9	9.4						
Mud Bay West		23.2	11.0	5.1					
Parksville		20.9	28.9	14.1					
Royston		13.3	14.4	19.6		38.3	33.9	60.9	43.3
Wall Beach		11.1	8.1	5.8		4.6	4.7	2.9	3.6
					Target Harvest Rate				
Booth Bay	40%	40%	40%	40%		40%	40%	40%	40%
China Cloud Bay							10%		
Craig Bay		0	0	0					
Goldstream		10%	20%	20%	10%	20%	10%	10%	10%
Long Bay							20%	20%	
Mill Bay		10%	10%	10%	10%	20%	10%	10%	
Mud Bay East		0	0						
Mud Bay West		0	0	0					
Parksville		10%	0	0					
Royston		0	0	0		10%	10%	10%	10%
Wall Beach		0	0	0		0	0	0	0

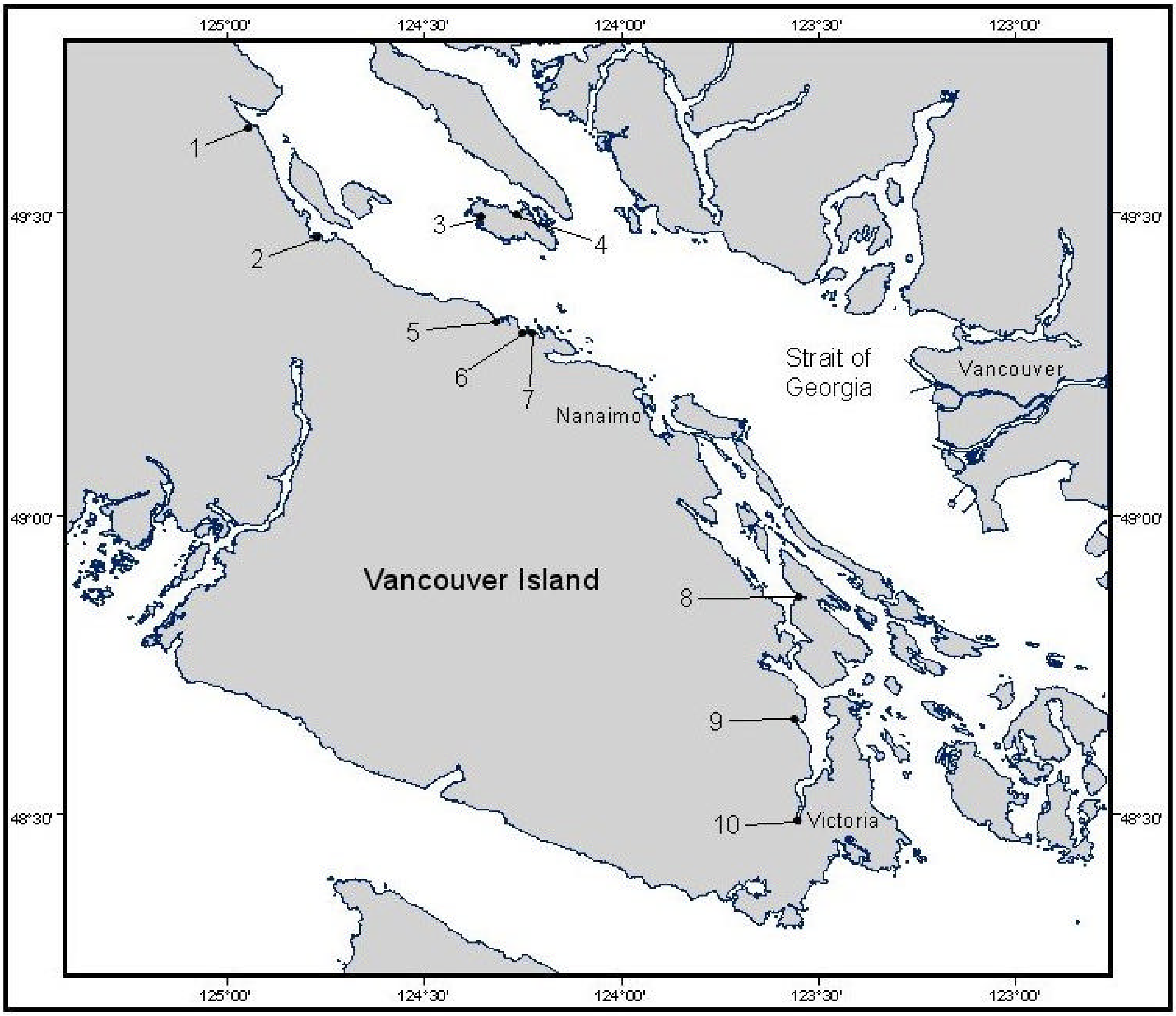
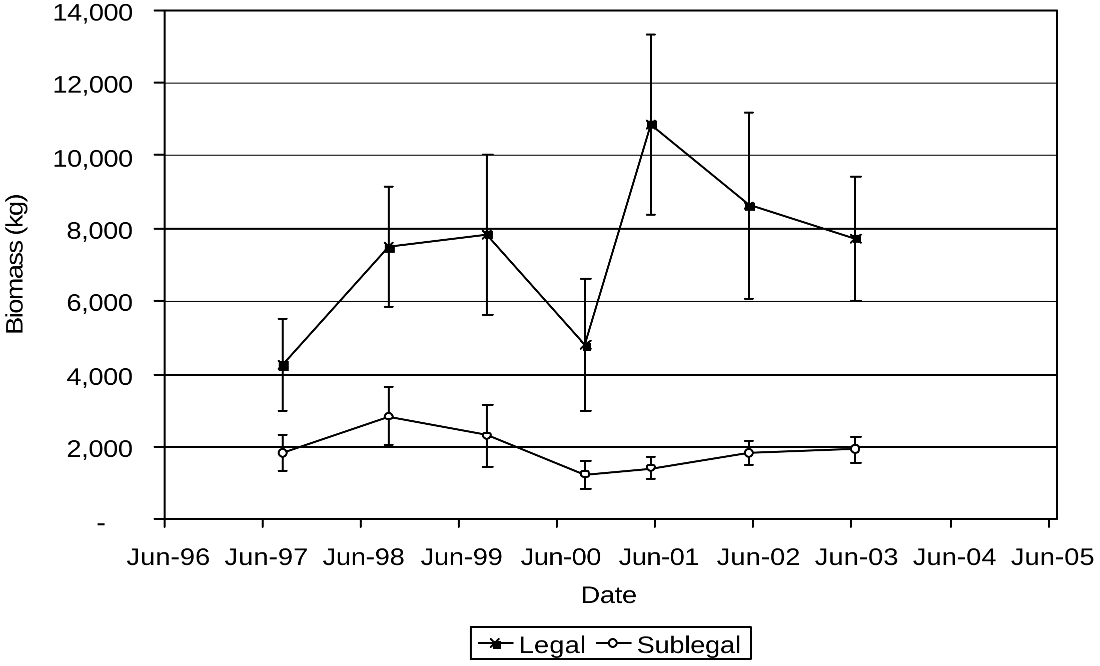


Figure 1. Location of beaches in the experimental harvest program.

Legend: 1 – Royston; 2 – Mud Bay; 3 – China Cloud Bay; 4 – Long Bay; 5 – Parksville; 6 – Craig Bay; 7 – Wall Beach; 8 – Booth Bay; 9 – Mill Bay; 10 – Goldstream.



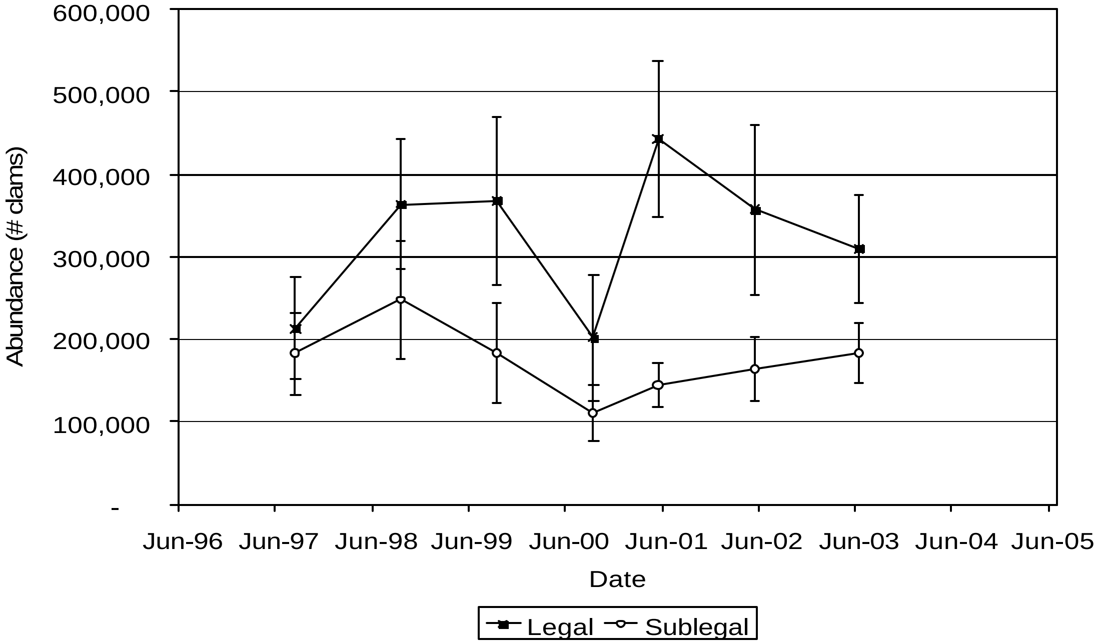


Figure 2. Manila clam stock trajectory at Mill Bay, 1997-2003.

Error bars are 95% confidence intervals.

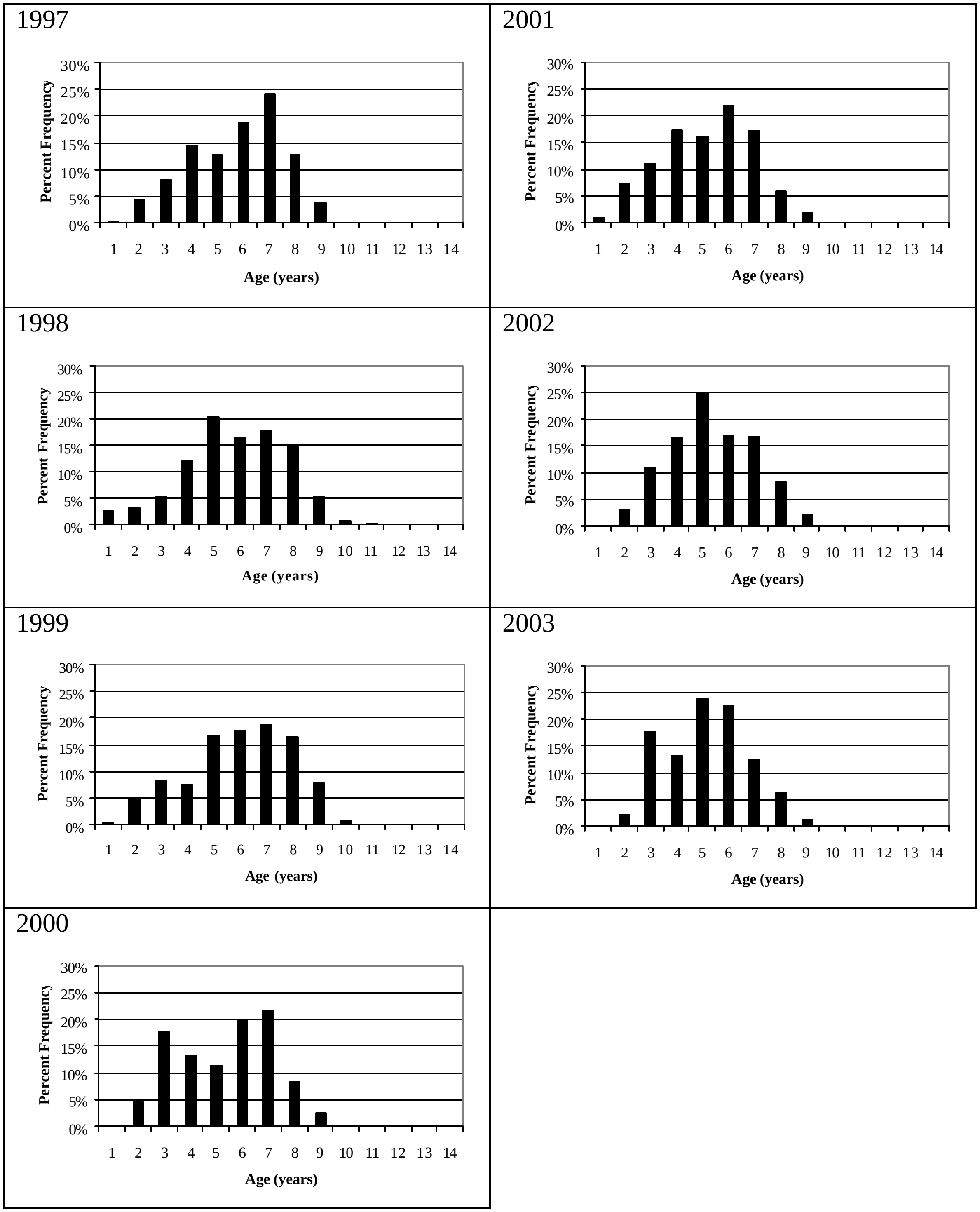


Figure 3. Age structure of Manila clams from Mill Bay, 1997-2003.

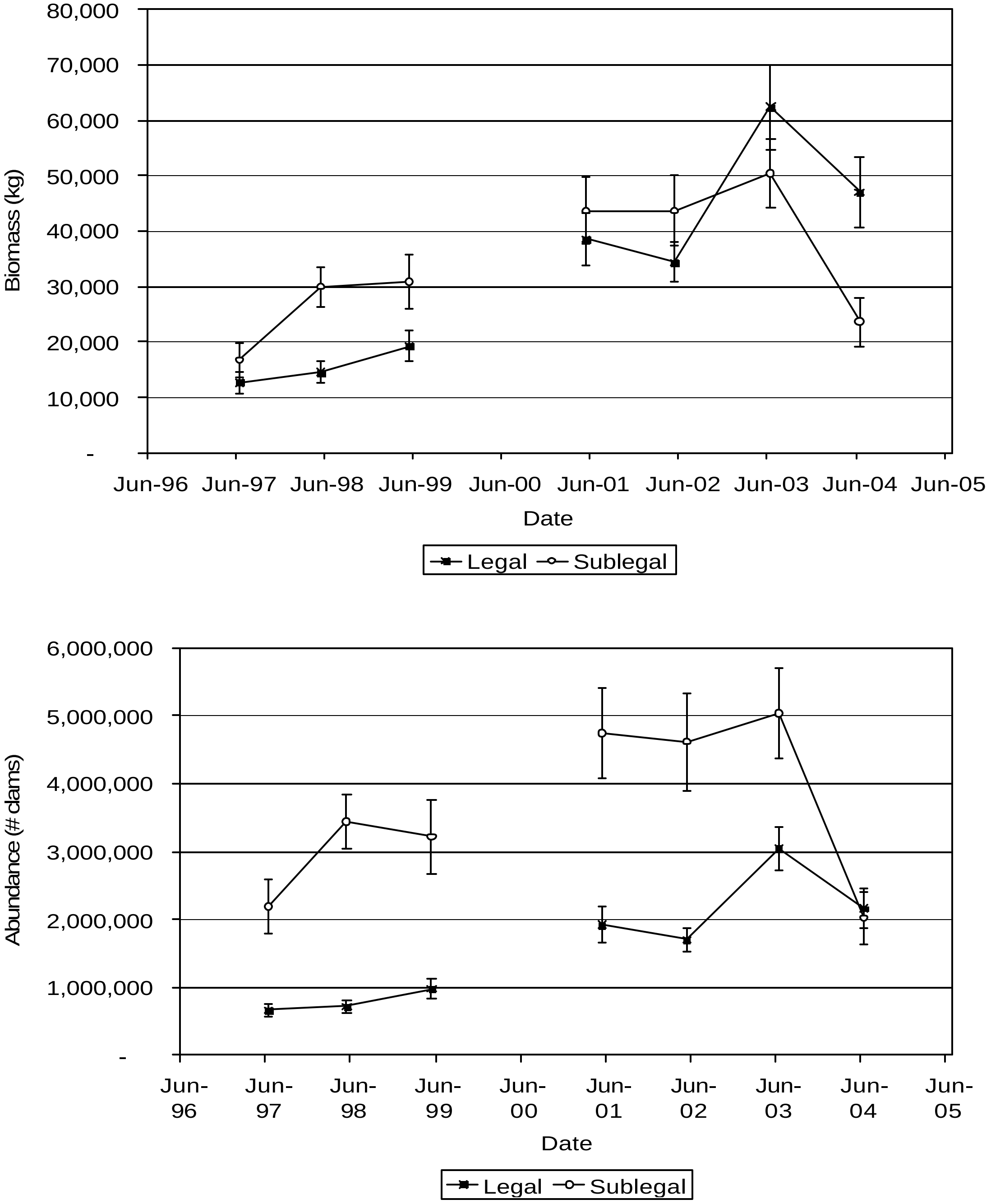


Figure 4. Manila clam stock trajectory at Royston, 1997-2004.

Error bars are 95% confidence intervals.

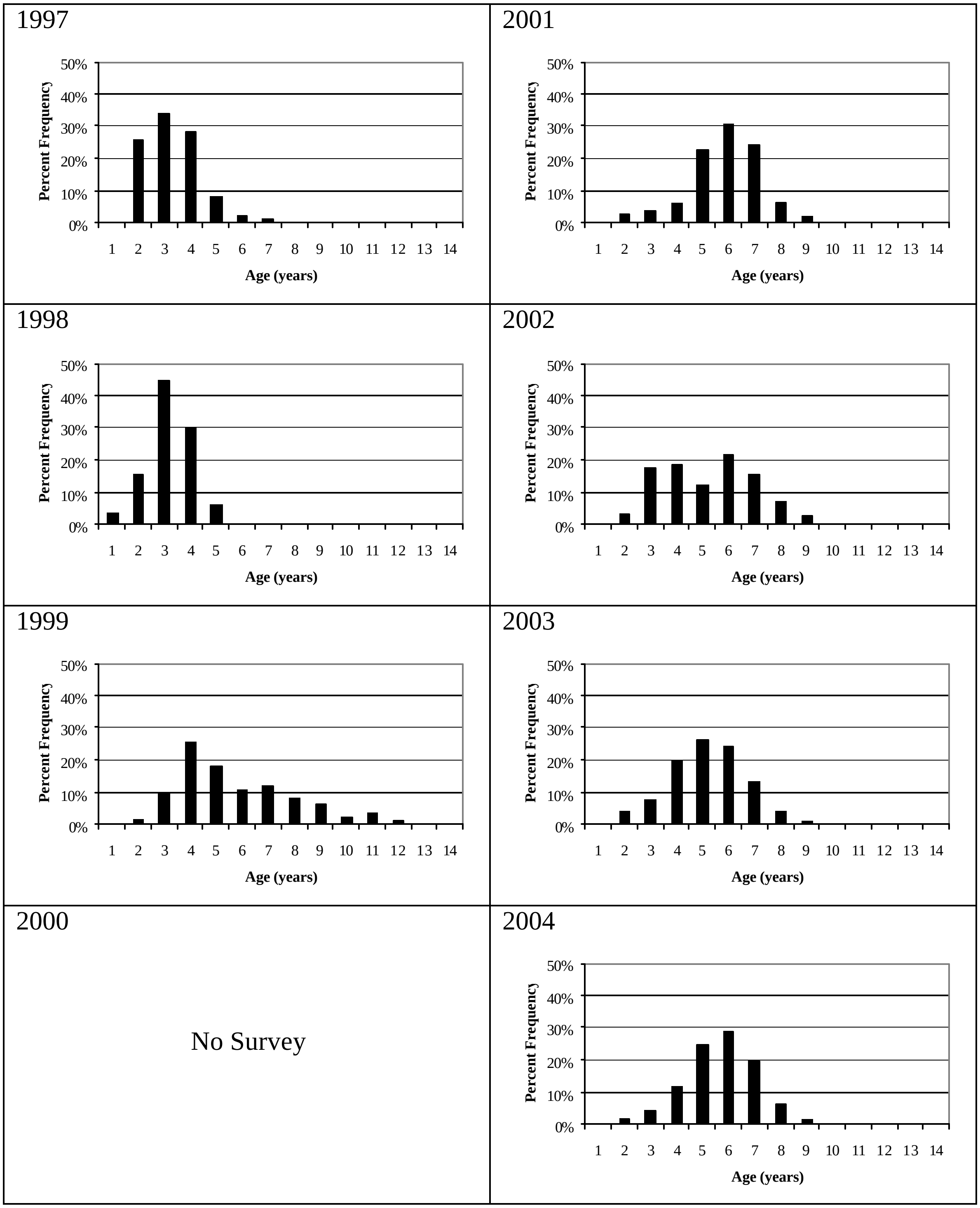
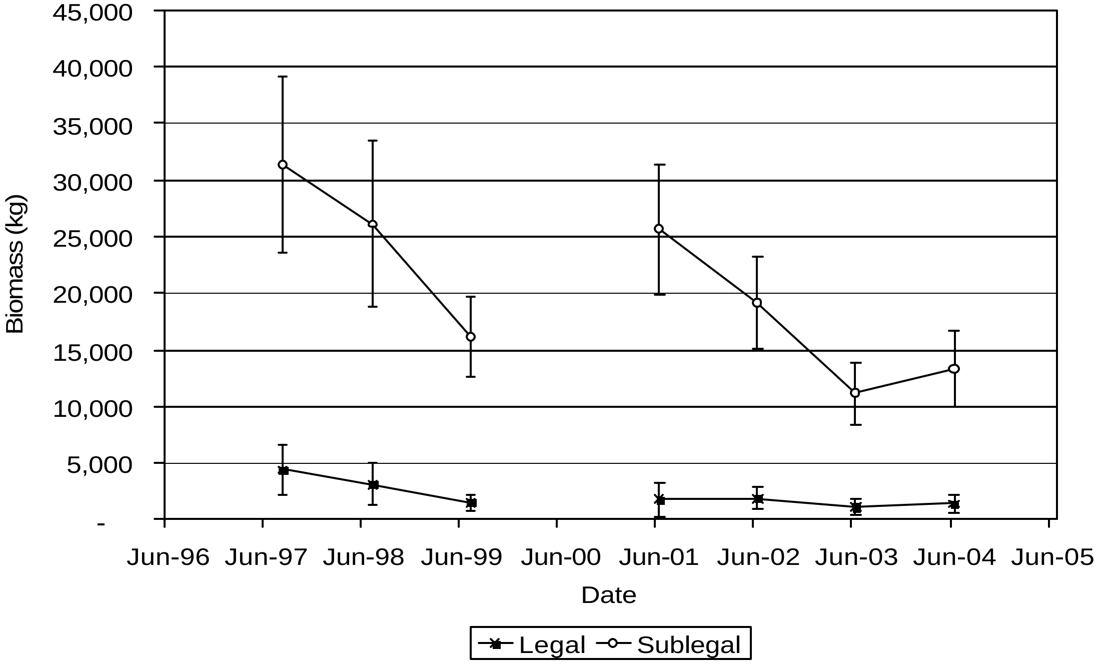


Figure 5. Age structure of Manila clams from Royston, 1997-2004.



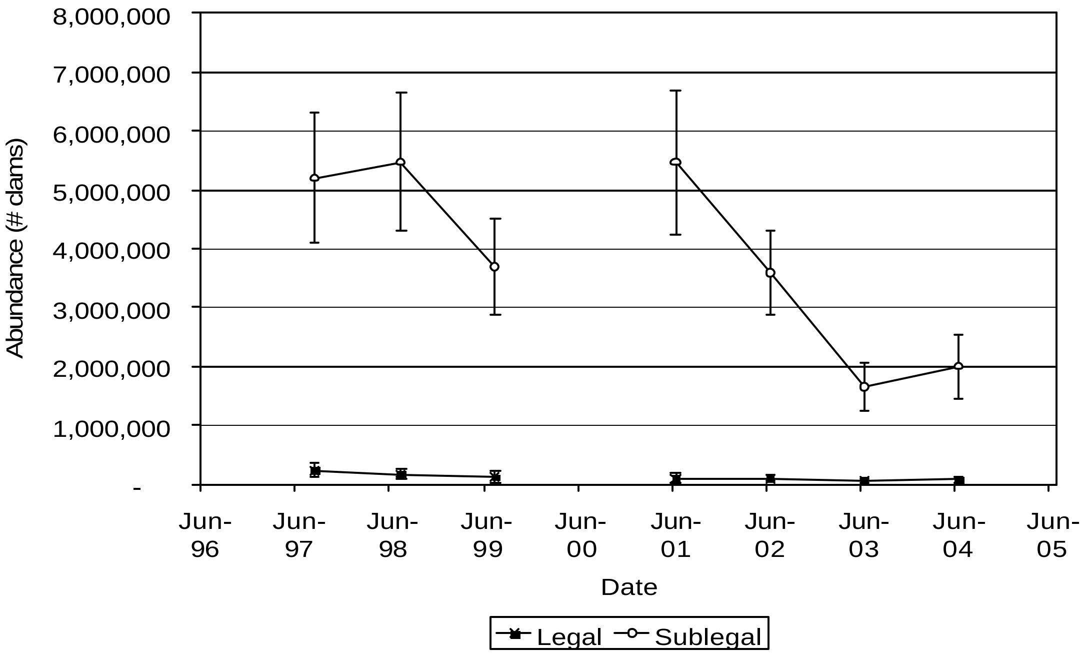


Figure 6. Manila clam stock trajectory at Wall Beach, 1997-2004.

Error bars are 95% confidence intervals.

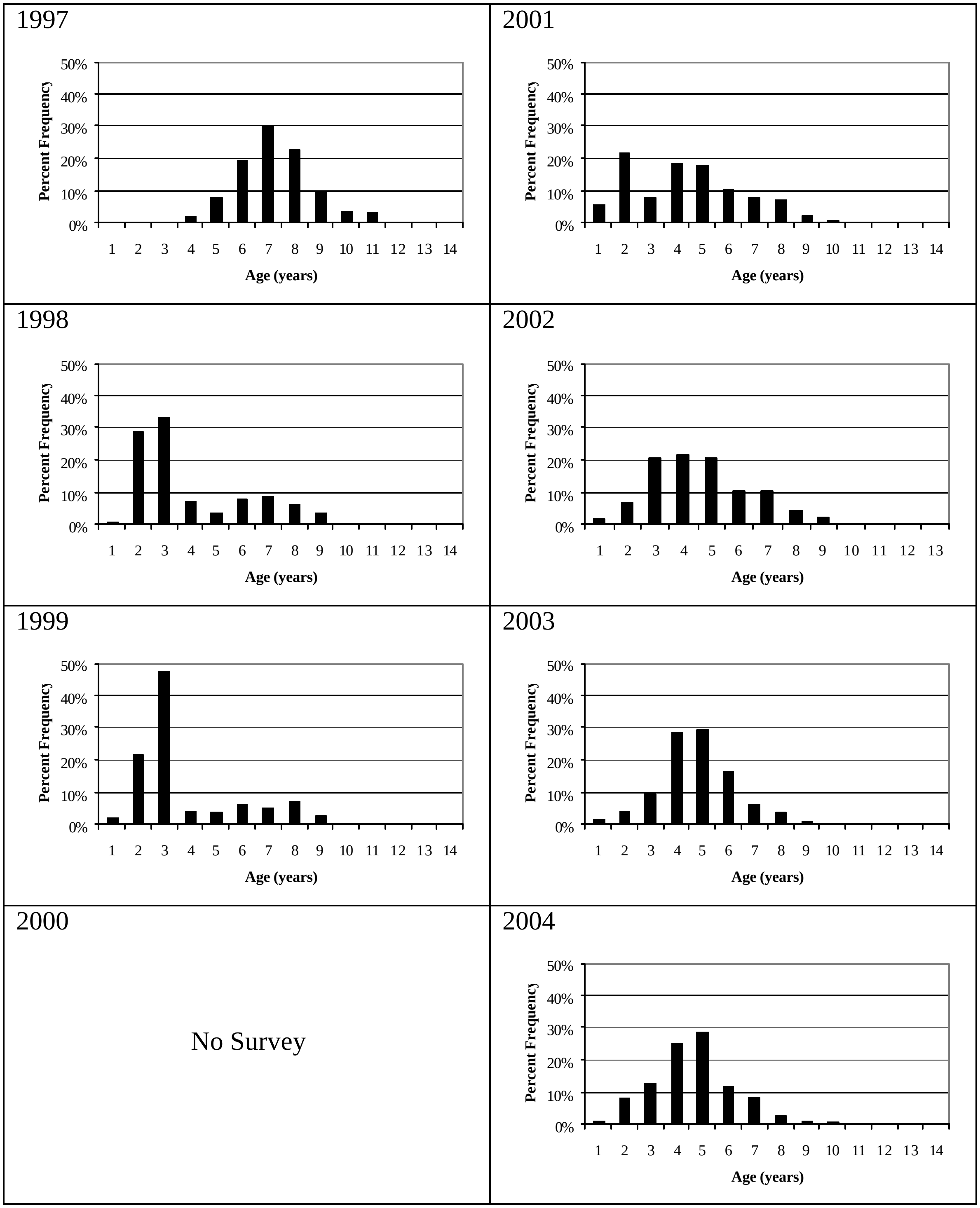
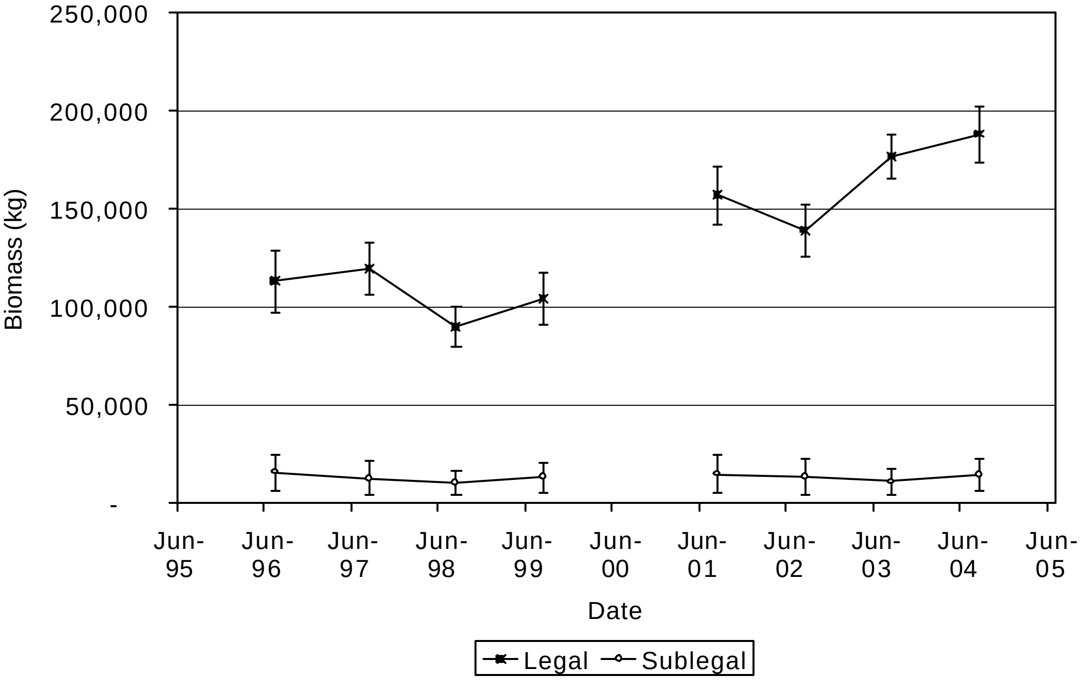


Figure 7. Age structure of Manila clams from Wall Beach, 1997-2004.



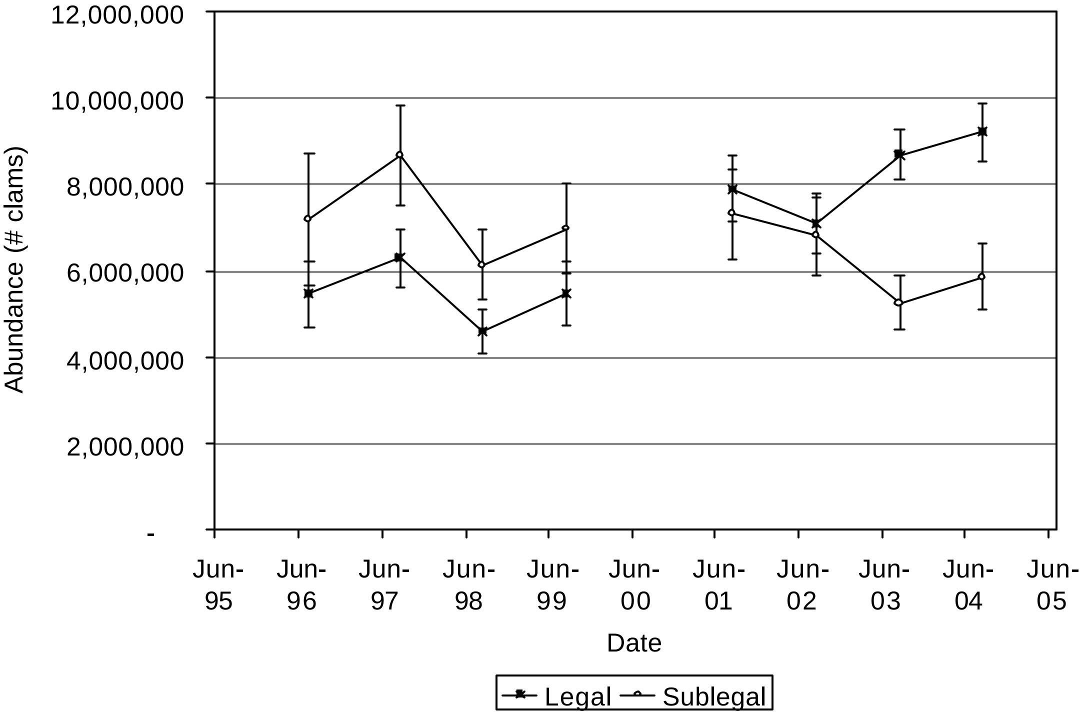


Figure 8. Manila clam stock trajectory at Booth Bay, 1996-2003.

Error bars are 95% confidence intervals.

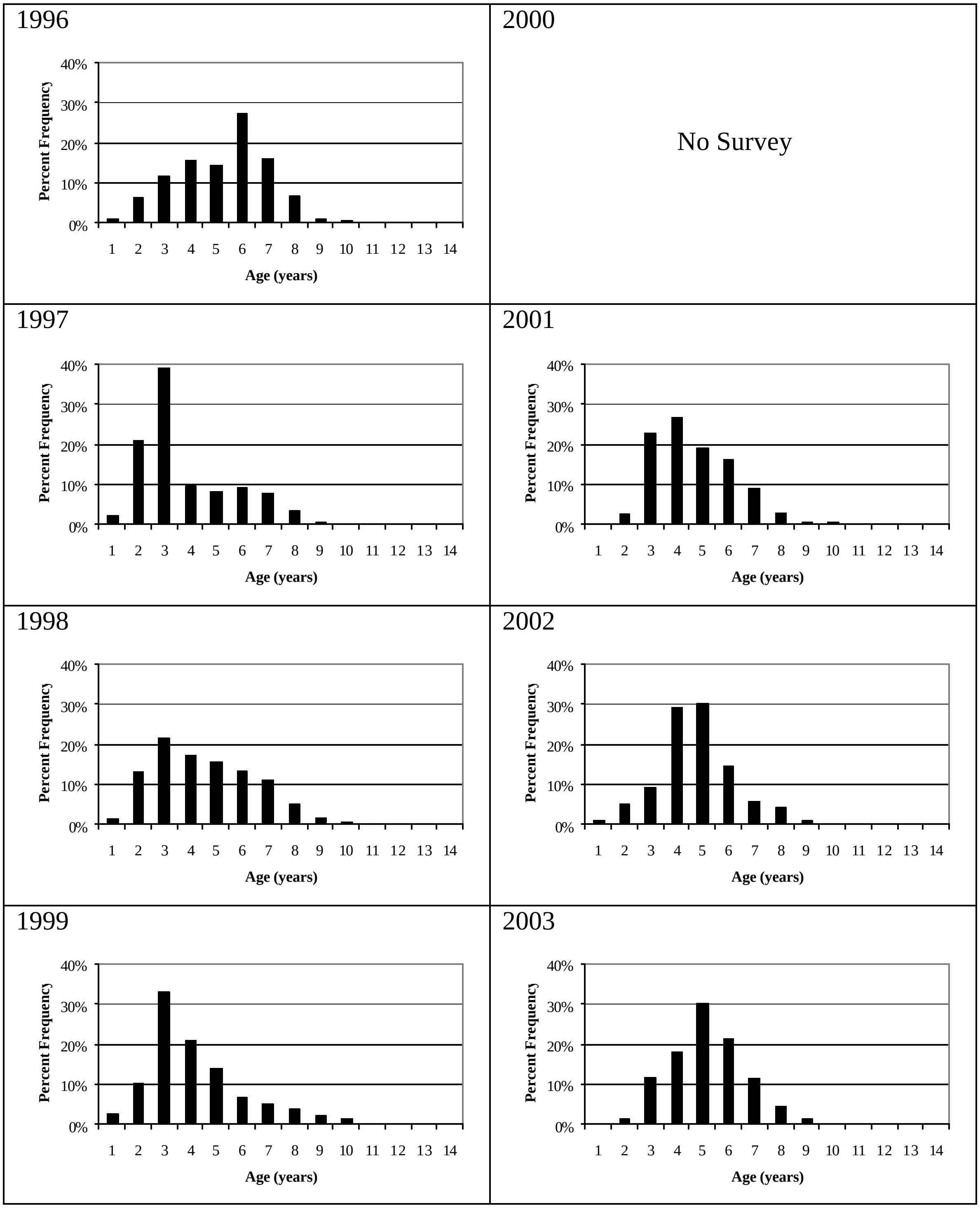


Figure 9. Age structure of Manila clams from Booth Bay, 1996-2003.

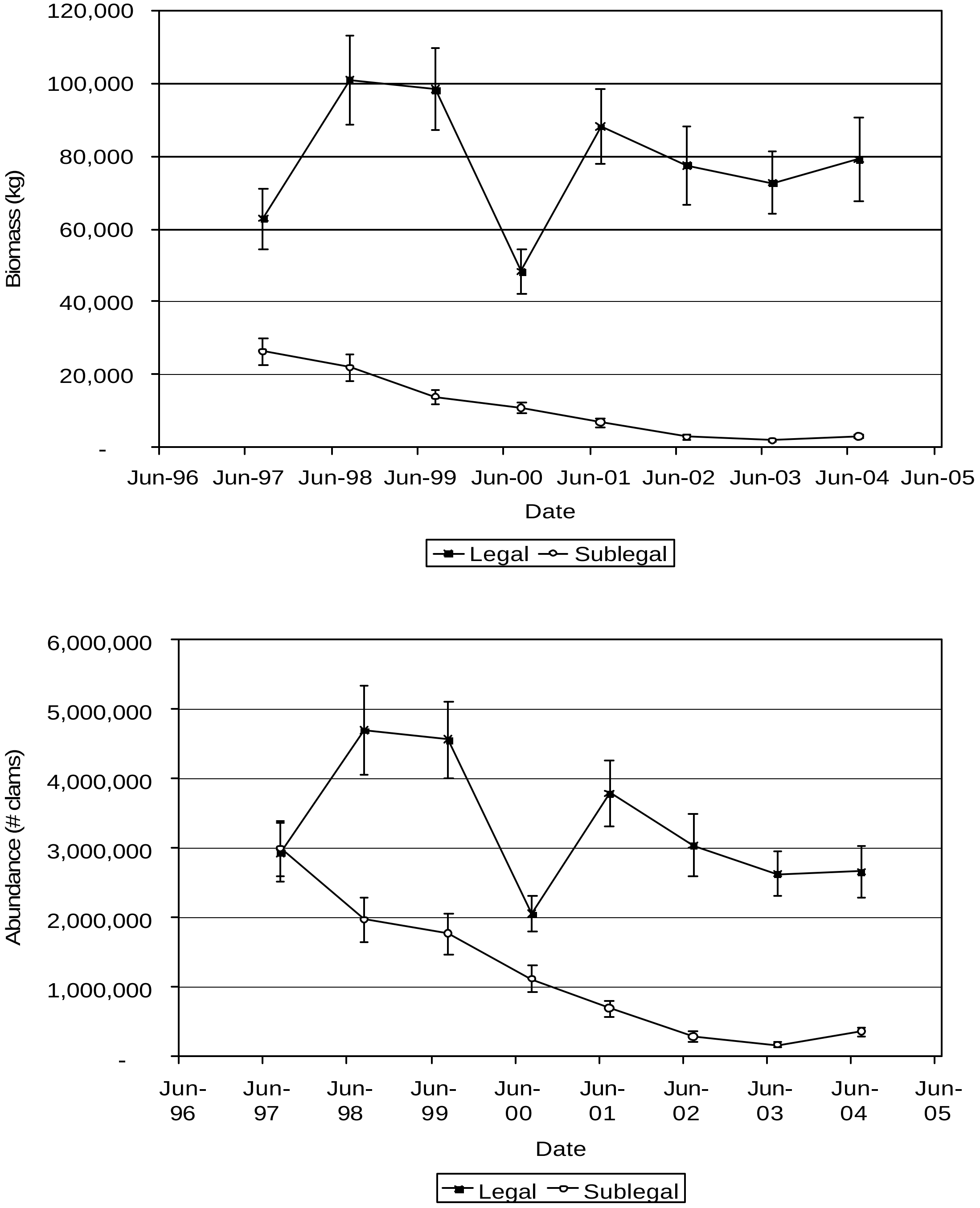


Figure 10. Manila clam stock trajectory at Goldstream, 1996-2004.

Error bars are 95% confidence intervals.

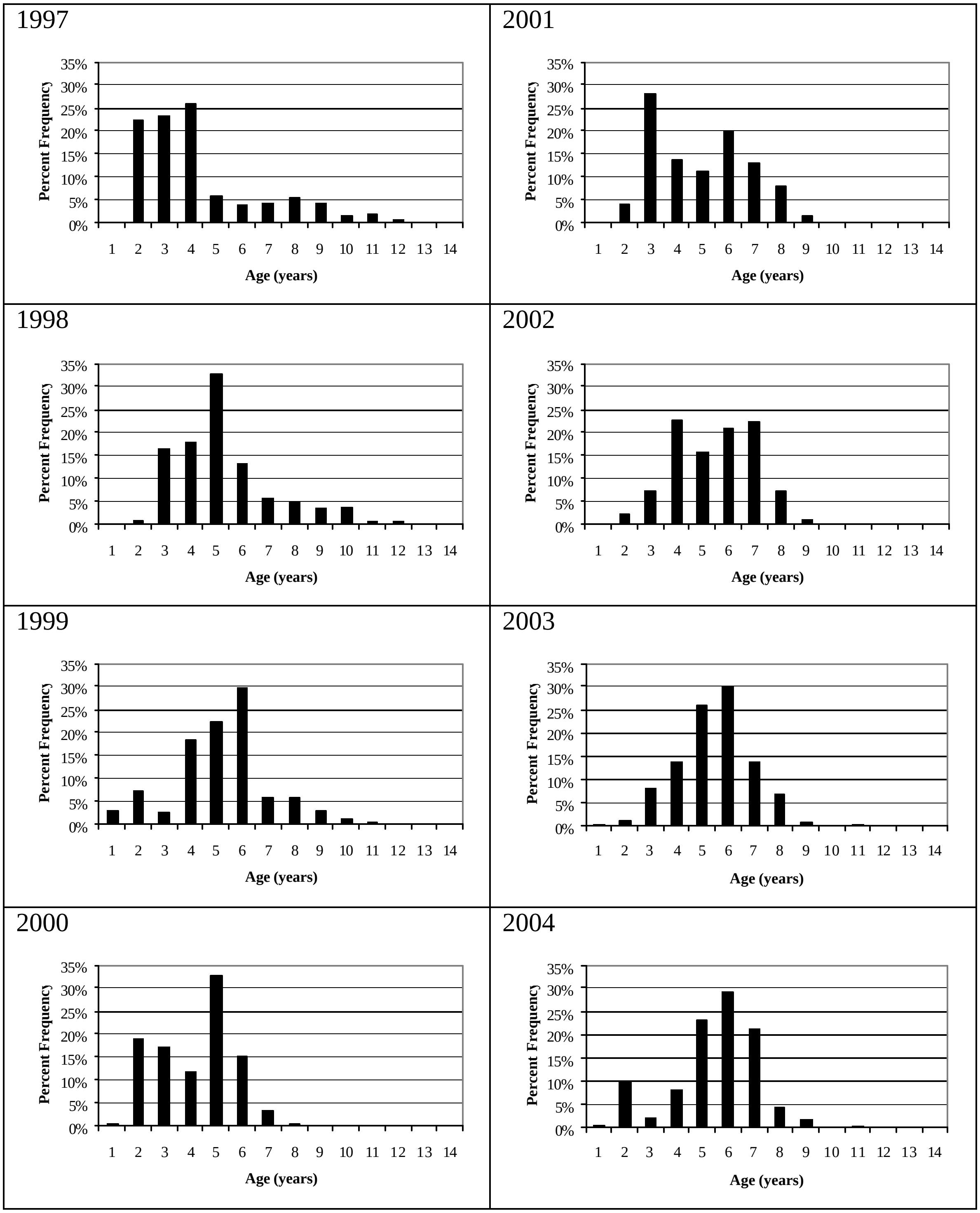


Figure 11. Age structure of Manila clams from Goldstream, 1997-2004.

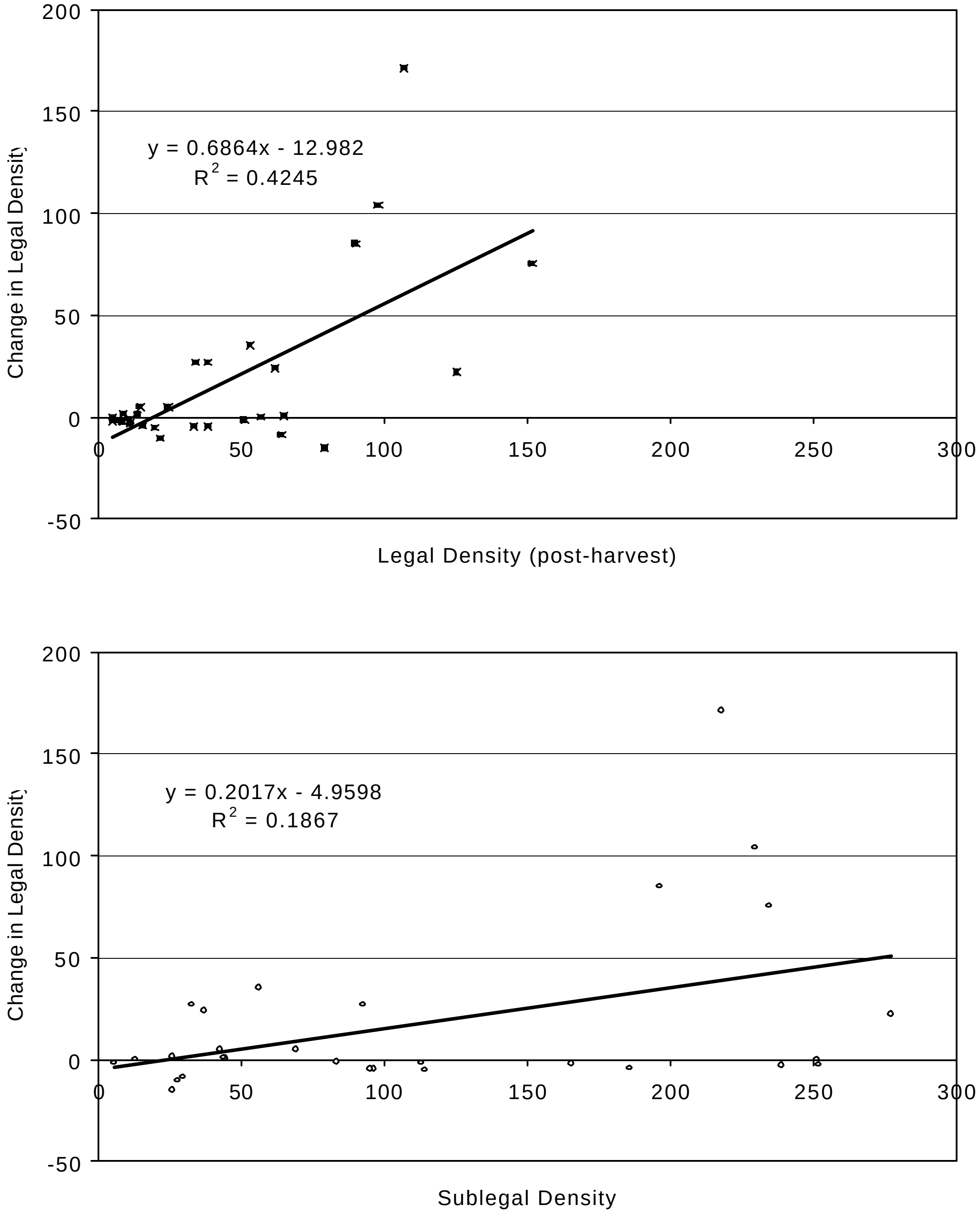


Figure 12. Simple production models relating change in legal density (clams m^{-2}) to post-harvest legal density (top panel) and sublegal density (bottom panel) for the previous year from beaches in the experimental harvest program.

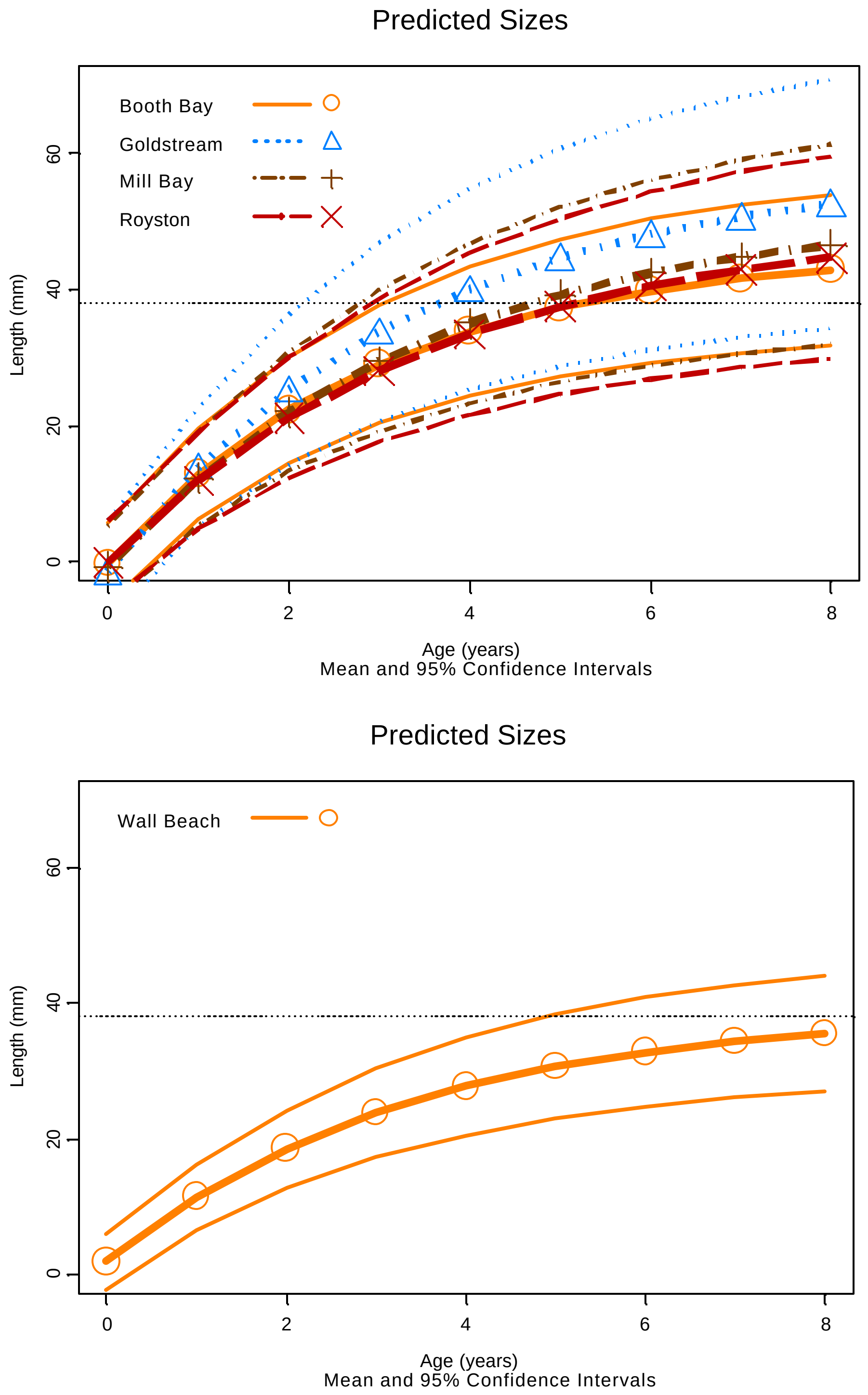


Figure 13. Predicted size at age of Manila clams at selected beaches used in population modelling (top panel) and at Wall Beach (bottom panel).

The dotted line at 38 mm represents the legal size limit.

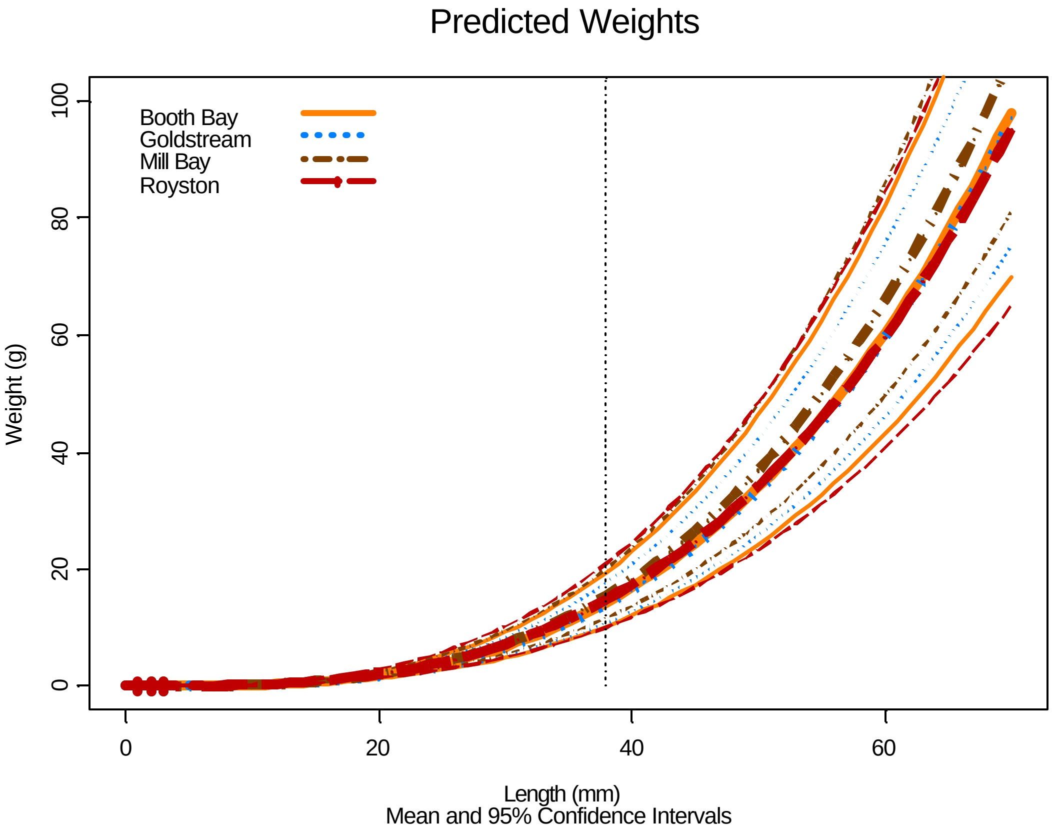


Figure 14. Predicted weight at length for Manila clams from selected beaches used in population modelling.

The dotted line at 38 mm represents the legal size limit.

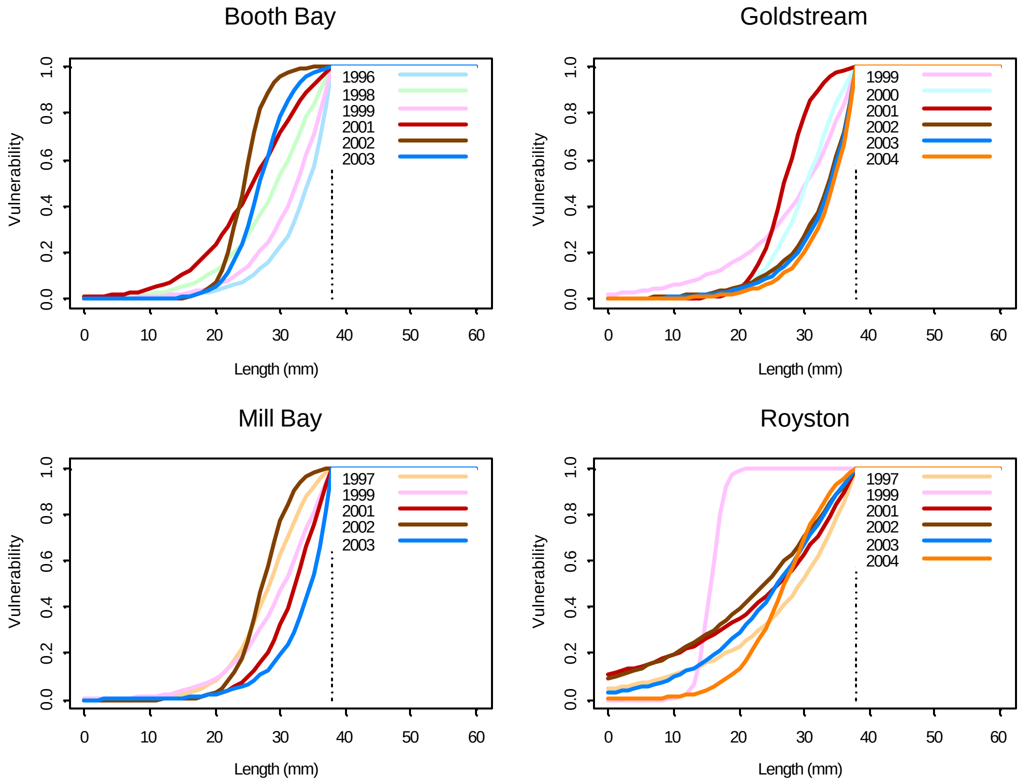


Figure 15. Estimated vulnerability at length for Manila clams by beach and survey year. The dotted line at 38 mm represents the legal size limit.

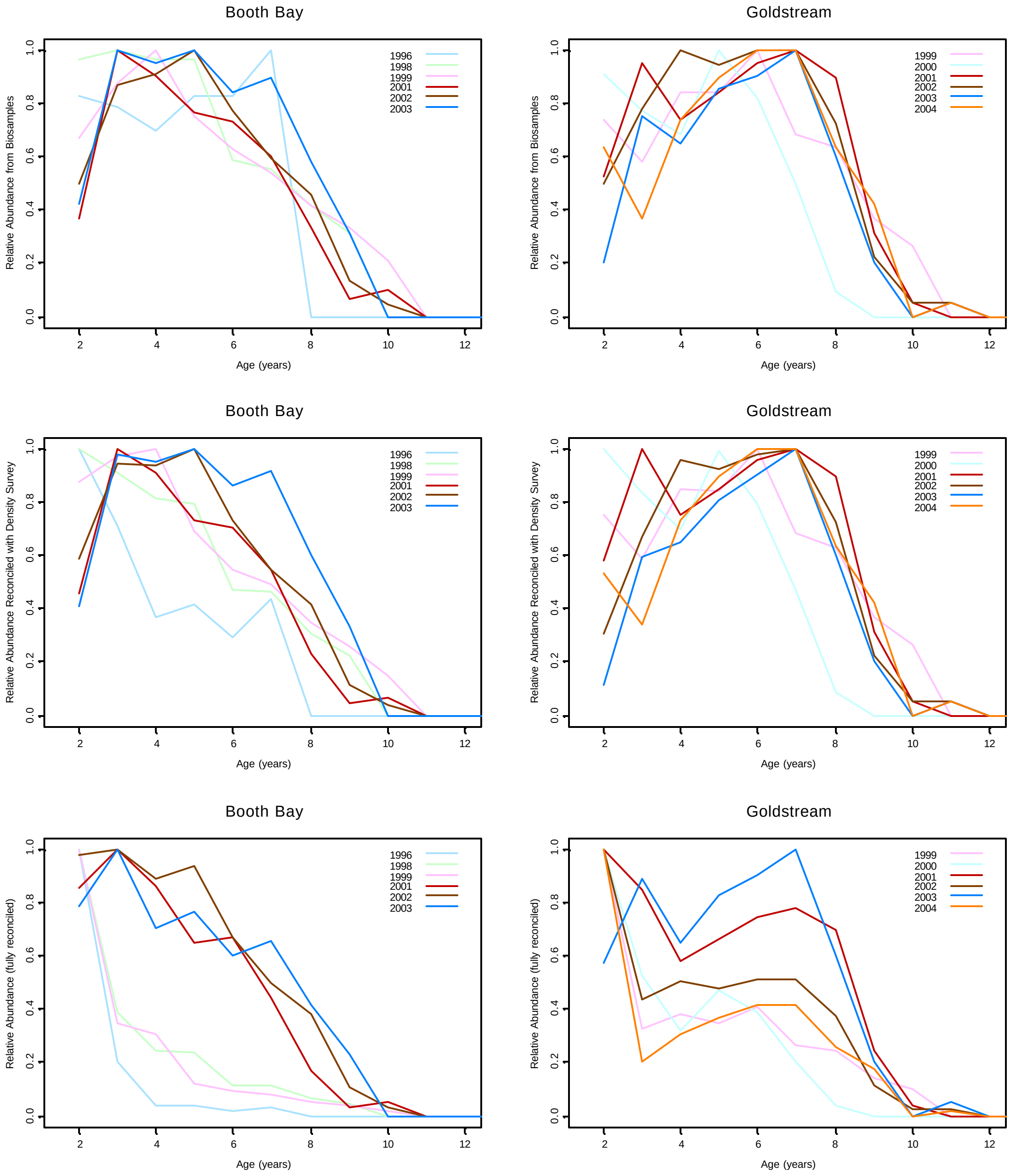


Figure 16. Impact of reconciliation of age distributions to survey estimates for Manila clams by beach.

Upper panels are data from biological samples, middle panels have been reconciled with density data and lower panels have been further reconciled using vulnerability parameters.

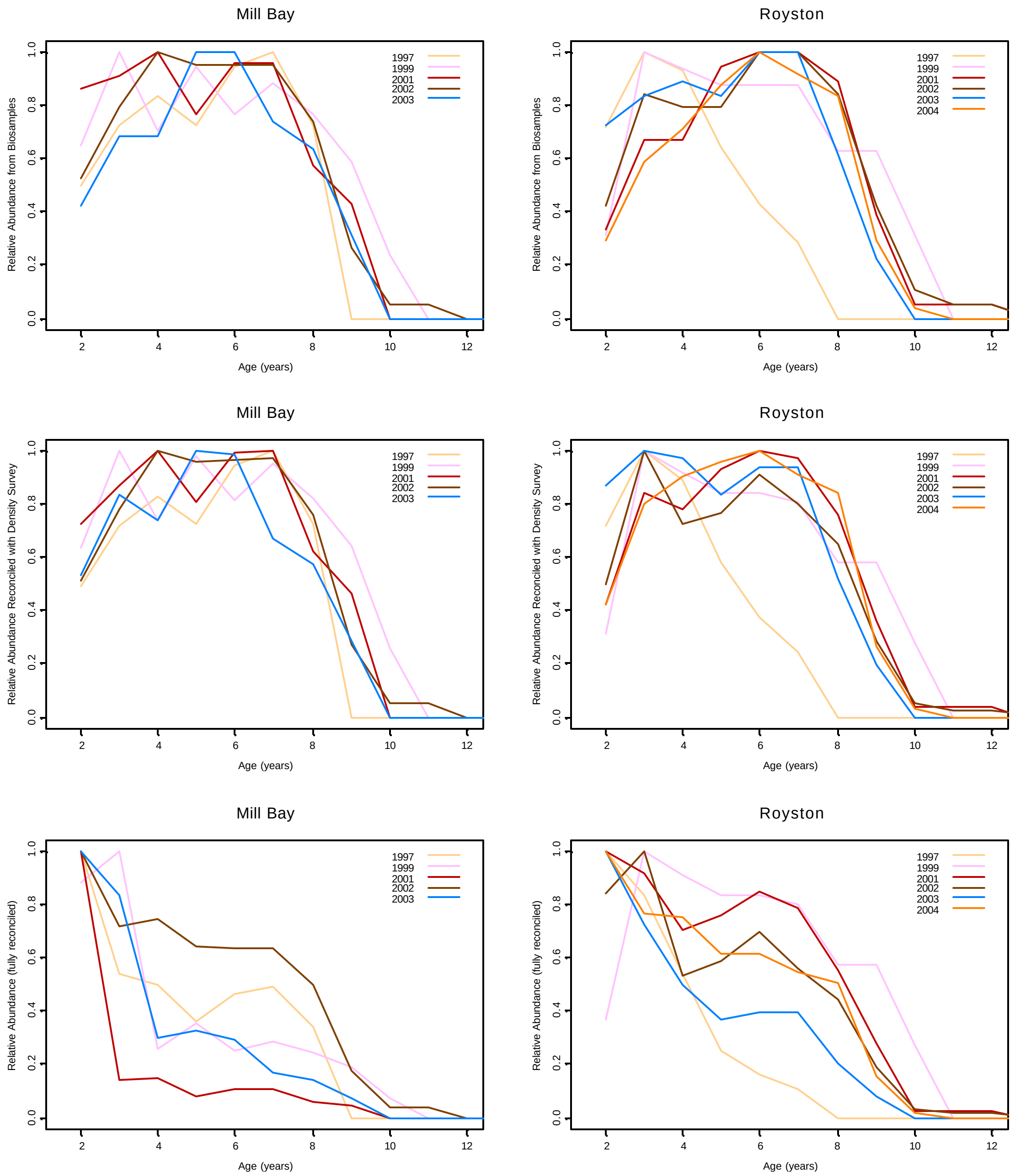


Figure 16. (continued).

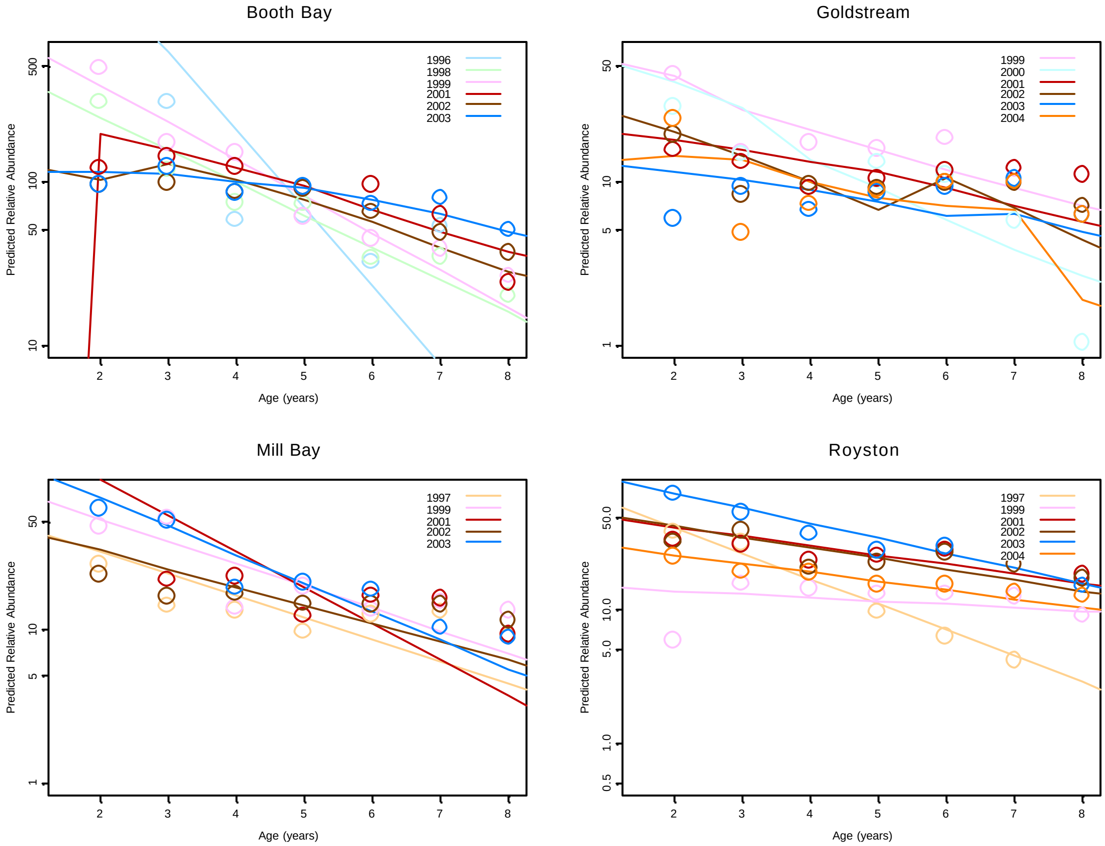


Figure 17. Reconciled results of snapshot surveys fitted to mortality estimates for Manila clams by beach and survey year.

Circles are survey results and lines are model results.

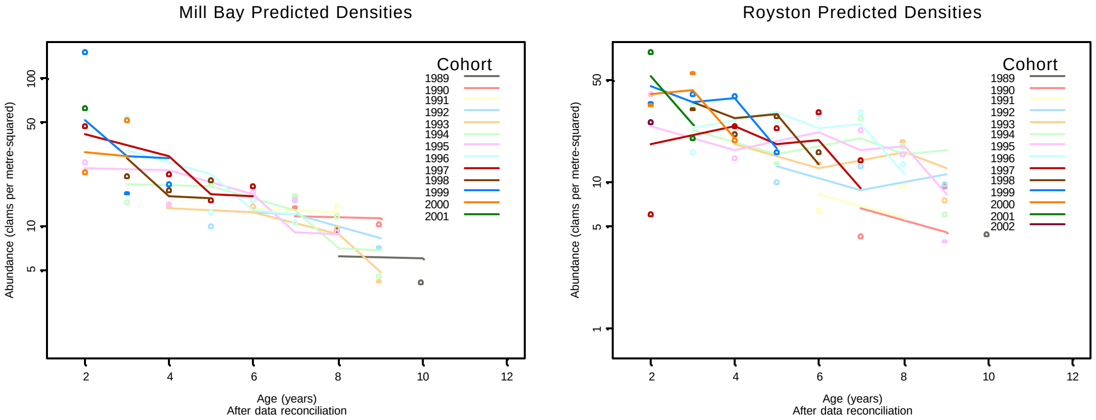


Figure 18. Model fits of survey series data for Mill Bay and Royston.

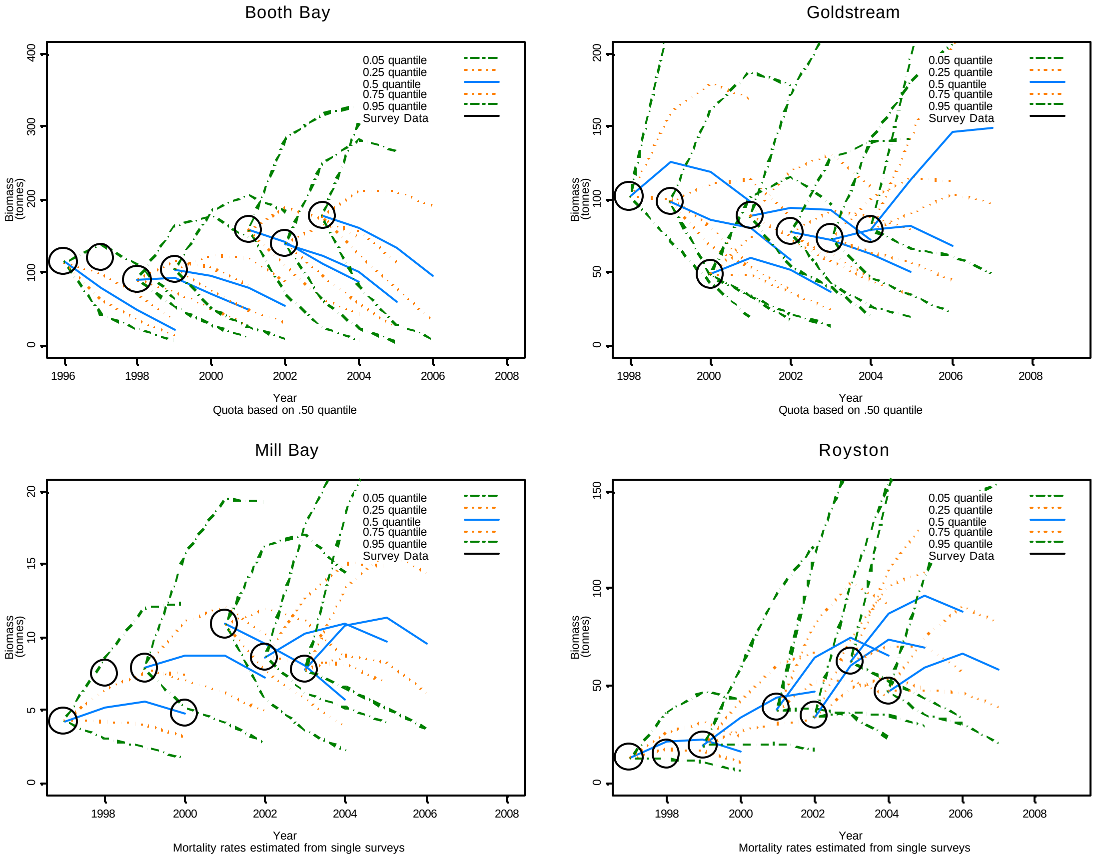


Figure 19. Projections of legal biomass from snapshot surveys using mortality rates from snapshot surveys and harvest rates based on the 0.50 quantiles of legal biomass and legal density.

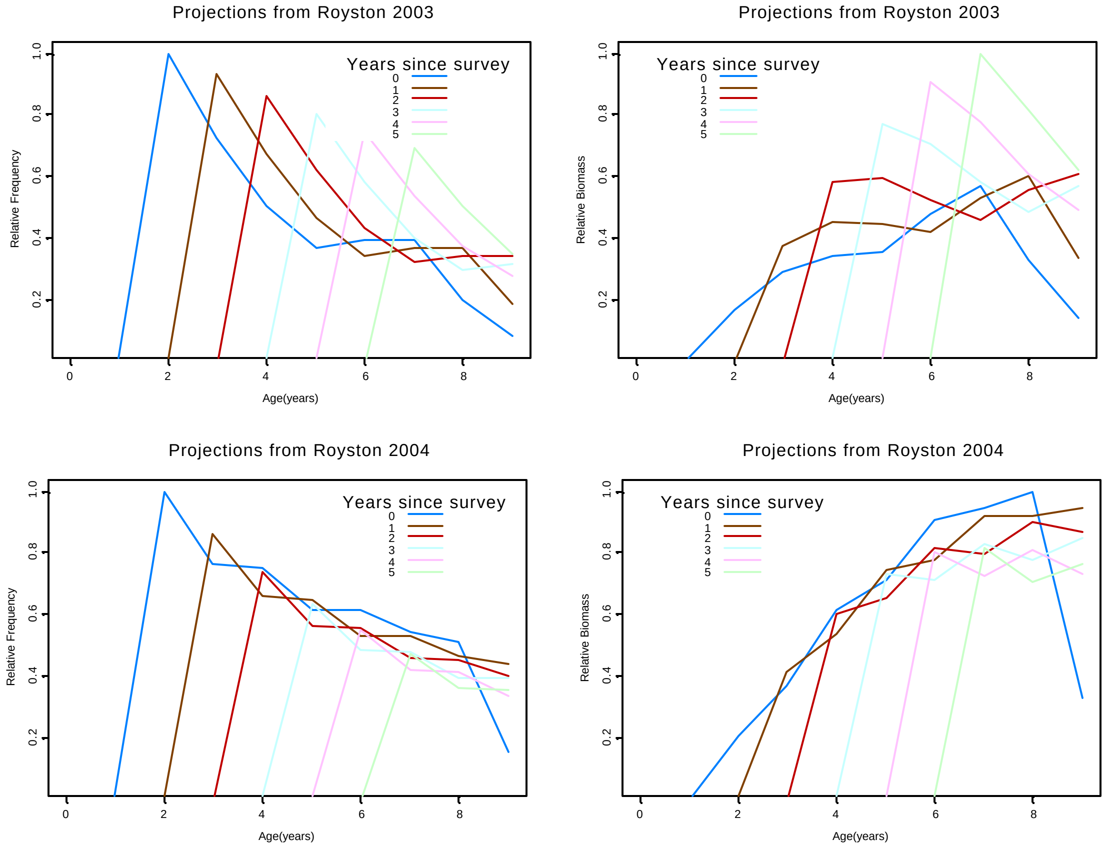


Figure 20. Deterministic projections of age structure using mortality rates from snapshot surveys for Royston, 2003 and 2004.

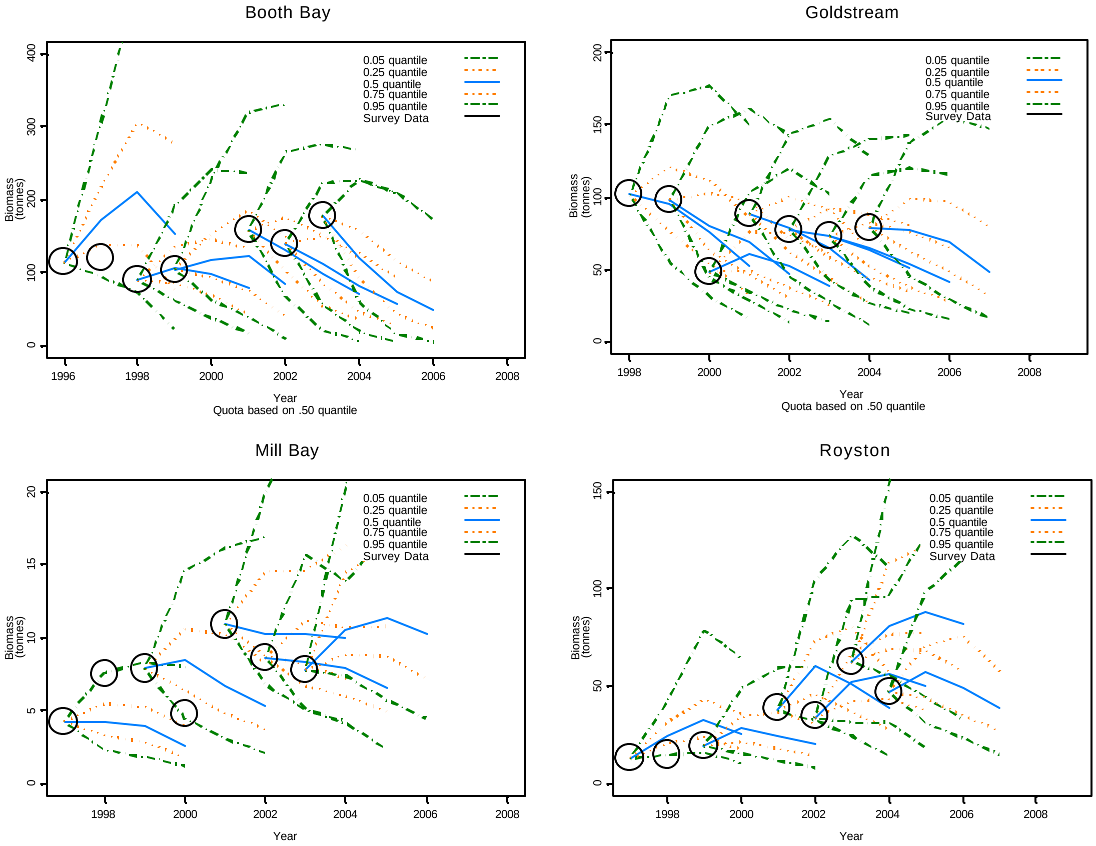


Figure 21. Projections of legal biomass by beach and survey year using M=0.3 and harvest rates determined using the 0.50 quantiles of legal biomass and legal density.

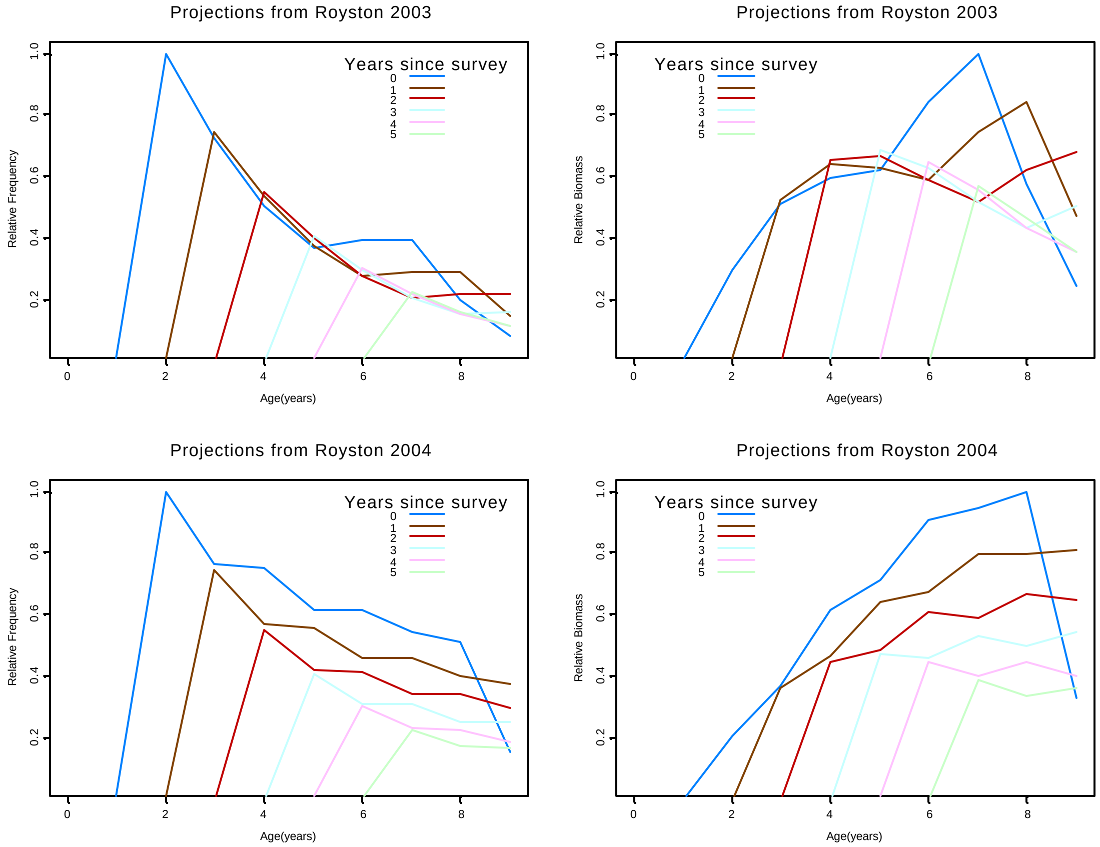


Figure 22. Deterministic projections of age structure using M=0.3 for Royston, 2003 and 2004.

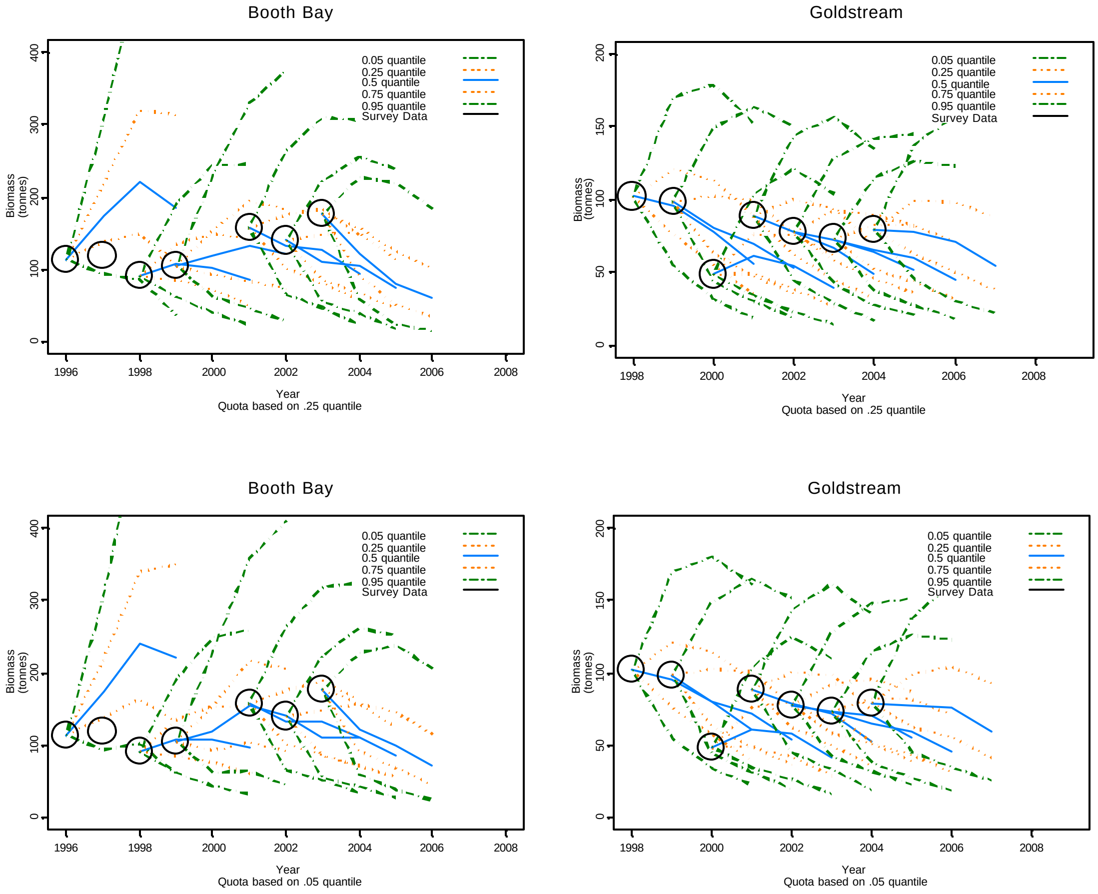


Figure 23. Projections of legal biomass by beach and year using q_{quota}=0.25 (top panel) and q_{quota}=0.05 (bottom panel) and M=0.3.

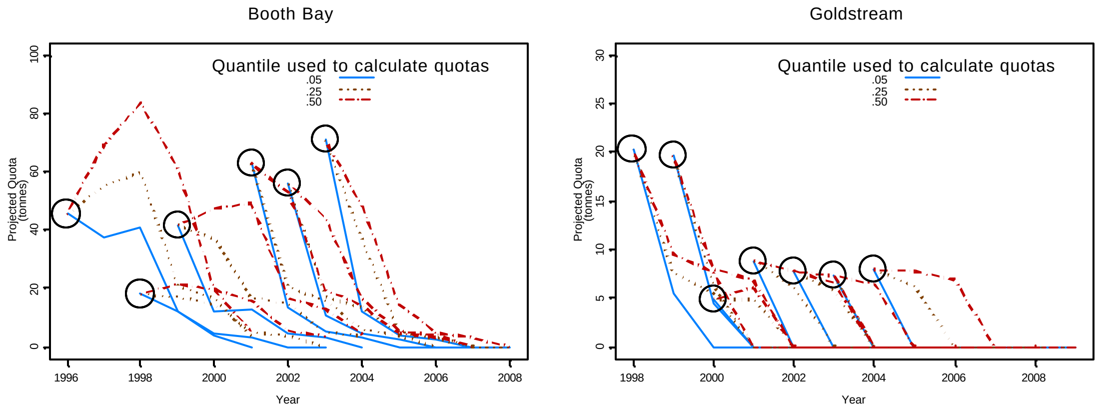


Figure 24. Effect on projected quotas by beach and year with three levels of q_{quota} and M=0.3.

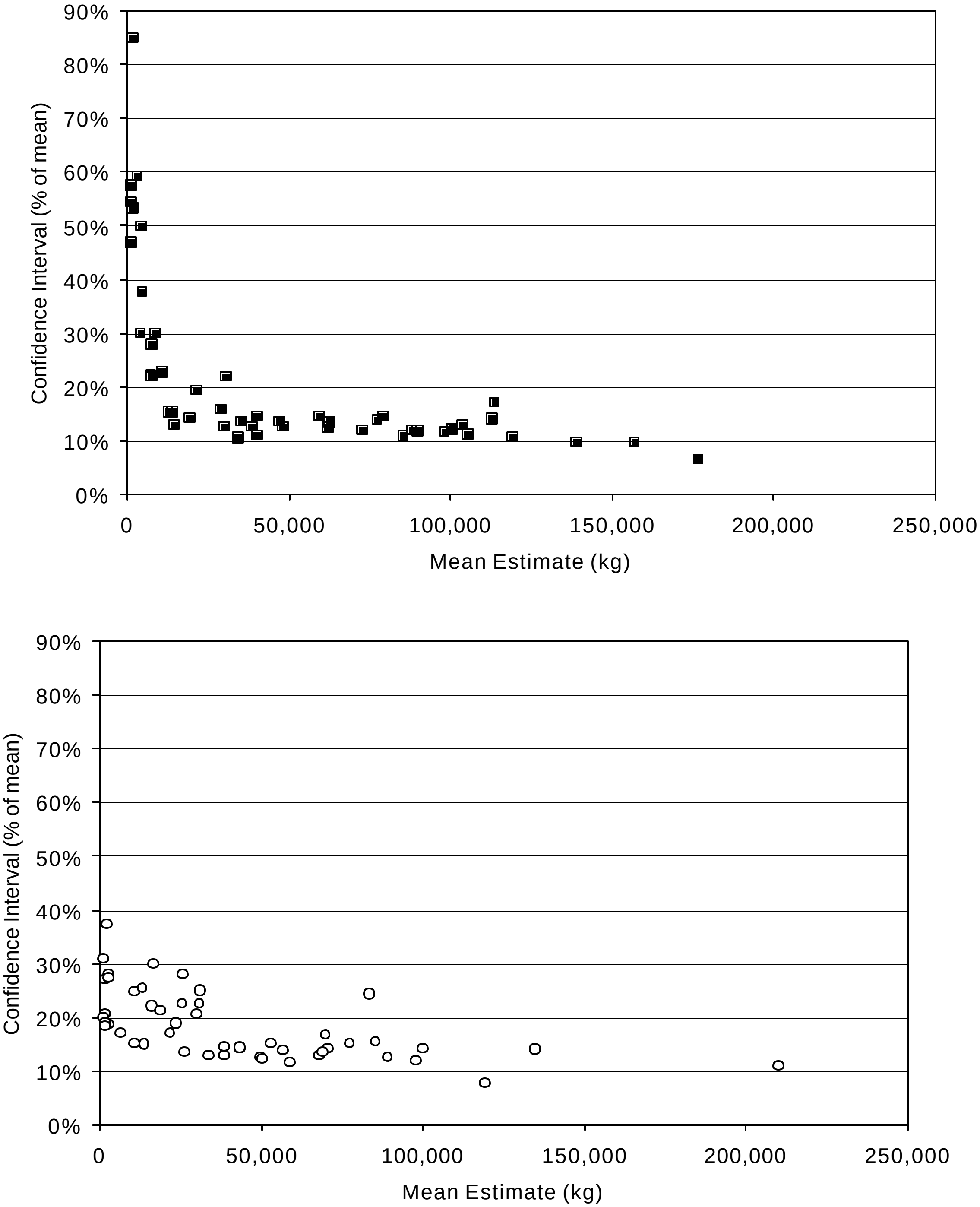


Figure 25. Relationships between estimated total legal (top panel) and sublegal (bottom panel) Manila clam biomass (kg) and width of the associated confidence interval for beaches in the experimental harvest program, 1997-2004.

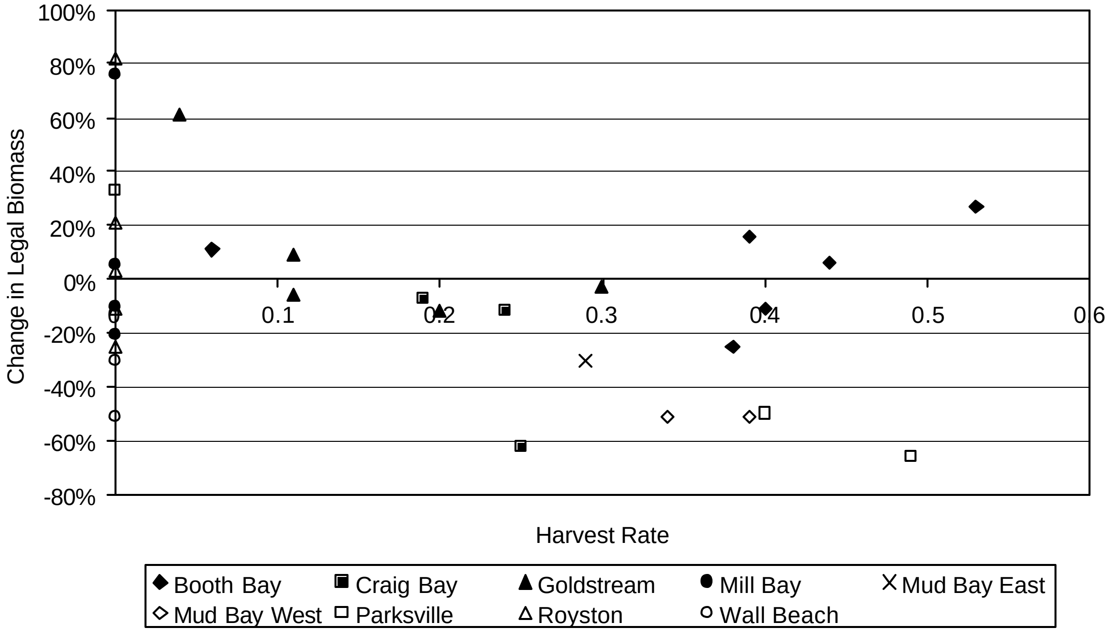


Figure 26. Relationship of harvest rate to change in biomass of legal Manila clams from experimental harvest program beaches, 1996-2004.

Appendix 1. Request for Working Paper.

Date Submitted: **April 26, 2004**

Individual or group requesting advice:

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Proposed PSARC Presentation Date:

- November 2004

Subject of Paper (title if developed): Review of Management Strategy and Assessment Framework in the Clam Depuration Fishery

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Rationale for request:

- Much of the survey work has been funded by industry
- Density based Harvest rates (0%-control beaches to 40% of the legal biomass) have been applied since 2001. Surveys have been undertaken since 1991 (see earlier PSARC WP).
- Review will allow refinement of a long term strategy utilising reference point management and rationalize the assessment framework.

Question(s) to be addressed in the Working Paper:

- Does additional information support current harvest rates for the Depuration fishery? (What are *ranges of sustainable harvest rates*?)
- How often do surveys need to be conducted to provide reliable fish management data? We currently have annual surveys at some beaches and others where only periodic surveys are required. We need to refine the current management and assessment frameworks.
- How does recruitment (do we also want to look at growth, knowing growth rates may change across the beach?) vary from location to location and from control beaches (0%) to heavily harvested beaches
- What are the criteria for closing a beach to harvest? What are minimum biomass thresholds or other biological reference points (e.g. signs of recruitment?) that should be used to close beaches? How long should a beach be closed for "rebuilding of stocks" and to what level?
- What stock information has been obtained from the existing strategy comparing control beach data to harvest beach data? Is control beach data to be continued or modified?
- What has been learned from " survey after harvest" beach sites in the fishery (i.e. Long Bay, Mud Bay Lasqueti Island)
- What other options exist, if any to beach surveys?

Objective of Working Paper: To refine and rationalize biological reference points and management strategy (in addition to size limits) for intertidal clam fisheries. What are sustainable harvest rates in the Depuration and “wild fisheries”? How often should beaches be surveyed?

Appendix 2. Equations and notation used in production modeling of Manila clam depuration harvests.

Equation numbers are those from the text.

	Equations
(1)	$D_{i'} = D_i * (1 - HR_i)$
(2)	$\Delta D = D_{i+1} - D_{i'}$

Symbol	Description
ΔD	Change in density of legal size clams.
D_i	Density of legal size clams in year *i* prior to harvest.
$D_{i'}$	Post-harvest density of legal size clams in year *i*.
HR_i	Harvest rate in year *i*.

Appendix 3. Equations describing dynamics for Manila clam population models.

Equation numbers are those from the text.

Growth

$$L(a)=(L_\infty+e_\infty)(f(a))+e_{meas} \tag{3}$$

$$f(a)=1-e^{-k(a-t_0)} \tag{4}$$

$$L_\infty+e_\infty=e^{mean\left(\log\left(\frac{L(a)}{f(a)}\right)\right)} \tag{5}$$

$$L(a+1)=\left(\frac{f(a+1)}{f(a)}\right)(L(a))+e_{growth} \tag{6}$$

$$SSQ(k,t_0)=\sum_{n=1}^{N}\sum_{a=1}^{a_{\max}}\left(L(a)-f(a)(L_\infty+e_\infty)\right)^2 \tag{7}$$

$$a_{recruit}\approx t_0-\log\left(\frac{L_\infty-L_{Legal}}{L_\infty}\right)$$

$$s_{growth}^{2}(a)^2=\left(1+\left(\frac{f(a+1)}{f(a)}\right)^2\right)\left(s_{meas}^{2}\right)$$

Weight per clam

$$W=aL^b\left(e^e\right)$$

$$\overline{W}(L)=aL^b\left(e^{\left(\frac{s_w^2}{2}\right)}\right) \tag{8}$$

$$SSQ(a,b)=\sum_{n=1}^{N}\left(\log\left(\frac{W}{aL^b}\right)\right)^2 \tag{9}$$

$$\overline{W}(a)=a\left(L_\infty(f(a))\right)^b\left(e^{\left(\frac{s_w^2}{2}\right)}\right) \tag{10}$$

$$s_w^2=\frac{\left(\log\left(\frac{W}{\hat{W}}\right)\right)^2}{n-2}$$

Appendix 3. (continued)

Vulnerability

$$V(L)=1, L \geq L_{Legal} \tag{11}$$

$$V(L)=\frac{1+e^{-v0\left(L_{Legal}-v1\right)}}{1+e^{-v0(L-v1)}}, L < L_{Legal} \tag{12}$$

$$P(L \mid L < L_{legal}, a) = y_{a} * V(L) * P(L \mid a) \tag{13}$$

$$MLE(v0, v1) = -\sum_{clam(L<L_{Legal})} \left(\log\left(P\left(L \middle| L < L_{Legal}, a\right)\right)\right) \tag{14}$$

$$A^{3}_{L,a} = A^{2}_{L,a} / V(L) \tag{15}$$

Estimating mortality from a snapshot

$$MLE(M) = -\sum_{a=2}^{A} A_a \left(\log\left(\hat{A}_a(M)\right)\right) \tag{17}$$

$$\mathrm{var}(\log(N_a)) = \left(\frac{1}{a_{\max}-3}\right)\left(\sum_{a=2}^{A}\sum_{n_a=1}^{N}\log\left(\frac{\hat{N}_a(M)}{N_a}\right)^{2}\right) \tag{24}$$

Estimating mortality from a series of surveys of unharvested beaches

$$\log\left(\hat{A}_{a,y}\right) = \log(A_0) - Ma + g_c + h_y + e_{A_{a,y}} \tag{18}$$

$$S_{xx} = \sum_{a=1}^{a_{\max}}\sum_{c=1}^{C}(a-\bar{x}_c)^2 \tag{19}$$

$$S_{xy} = \sum_{a=1}^{a_{\max}}\sum_{c=1}^{C}(a-\bar{x}_c)\left(\log(A_{a,c}) - \bar{y}_c\right) \tag{20}$$

$$\hat{M} = \frac{S_{xy}}{S_{xx}} \tag{21}$$

$$\log(A_0) + g_c = \bar{y}_c - M\bar{x}_c \tag{22}$$

$$h_y = mean\left(\log(A_{a,y}) - \log(A_0) + g_c + Ma\right) \tag{23}$$

Appendix 4. Notation used in Manila clam population models.

Symbol	Description
	Data
a	Age of a clam.
$L(a)$	Length of a clam at age a.
W	Weight of a clam.
year	Year of survey.
cohort	Year in which clam settled (year – age).
N	Total number of clams in a sample.
$a_{\max}$	Total number of age classes in a sample.
	Fixed Parameters
L_{Legal}	Minimum harvest size (38 mm for Manila clams).
	Estimated Parameters
L_∞	Mean asymptotic length of the von Bertalanffy growth model.
e_∞	A clam-specific random variation in asymptotic length. $e_\infty \sim N(0, s_\infty^2)$
∞_{meas}	Variance associated with measurement error and random variation in growth of individual clams. $\infty_{meas} \sim N\left(0, s_{meas}^2\right)$
$s_{growth}^2(a)$	Variance in estimated growth over one year.
k	Intrinsic rate of increase in the von Bertalanffy growth model.
t_0	Theoretical age at which length is zero in the von Bertalanffy growth model.
a , b	Non-random variable in length-weight relationship.
s_w^2	Variance associated with length-weight relationship.
V(L)	Vulnerability to survey.
v0,v1	Parameters of the vulnerability equation.
y_a	A normalizing constant. $\sum_{L=1}^{L_{Legal}-1} \Psi_a(V(L))(P(L\|a)) = 1$
M	Instantaneous natural mortality rate.

Appendix 4. (continued).

Symbol	Description
	Estimated Parameters (continued)
$A_{L,a}^{1}$	Abundance of clams of length *L* and age *a* as estimated from a biological sample.
$A_{L,a}^{2}$	Abundance of clams of length *L* and age *a* after data are adjusted to agree with estimates of biomass.
$A_{L,a}^{3}$	Abundance of clams of length *L* and age *a* after data are adjusted to agree with estimates of biomass and the estimated vulnerabilities of sublegal-sized clams.
A_{a}	Abundance (after reconciliation) of clams of age *a*.
$A_{a,y}$	Abundance (after reconciliation) of clams of age *a* in year *y*.
g_{c}	Relative strength (on a log scale) of a cohort. $g_{c} \sim N\left(0, s_{c}^{2}\right)$
h_{y}	Effect of survey-year on abundance. $h_{y} \sim N(0, s_{year}^{2})$
$e_{A_{a,y}}$	Random error in abundance not explained by age, cohort or year. $e_{A_{a,y}} \sim N\left(0, s_{A}^{2}\right)$
$\bar{x}_{c}$	Mean of the unique age values observed for the cth cohort.
$\bar{y}_{c}$	Mean of the log of abundance values observed for the cth cohort.
q_{quota}	Quantile of biomass and population density used to determine quota.