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Determination of Geoduck Harvest Rates Using Age-structured Projection Modelling

Détermination des taux de capture de la panope du Pacifique à l'aide d'un modèle de projection structuré en fonction de l'âge

Zane Zhang and Claudia Hand

Shellfish Stock Assessment Section
Pacific Biological Station
3190 Hammond Bay Road
Nanaimo, B.C. V9T 6N7

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Abstract

An age-structured projection model was used to study the impacts of alternative exploitation intensities on geoduck populations, based on a large accumulation of survey data, age composition data and published estimates of natural mortality. Historic recruitment patterns were back-calculated using an age-structured model and future recruitment was simulated from the historic pattern. The fishing patterns examined were combinations of different instantaneous mortality rates (0.016 or 0.036) and different periods of historical recruitment (beginning in 1940 or 1960). For each simulation year, in each set of 1000 runs, the ratio of current biomass to virgin biomass was calculated and compared to the management objective of not allowing the biomass to fall below 50% of the virgin biomass within 50 years of initial harvest on a bed. Data were analyzed and results presented by geographic region.

Trends in recruitment were independent of the value of *M* used, although rates were higher when *M* of 0.036 was applied compared to *M* of 0.016. Historic recruitment rates were found to be highly variable in the pre-fishery state: rates increased from the early 1930’s to 1950, decreased until early 1960, increased to another peak in the mid 1960’s declined until the mid 1980’s and have been increasing to present.

A precautionary and reasonable scheme appears to be Y40M0.036 (recruitment simulation year starting in 1940 and M 0.036) for the north coast, and Y60M0.016 for the central coast and Queen Charlotte Islands. For the west coast of Vancouver Island and Georgia Basin, Y60M0.036 is precautionary. Overall, an exploitation rate of 1.2% and 1.8% of estimated current biomass is recommended for the west coast of Vancouver Island and the rest of the coast respectively. Further suggestions for managers are made on limit reference points and the choice of exploitation rate from the range provided.

Résumé

Un modèle de projection structuré en fonction de l'âge a servi à étudier les répercussions de différentes intensités d'exploitation sur les populations de panopes du Pacifique, au moyen d'une grande quantités de données de relevés, de données sur la composition selon l'âge et d'estimation publiées de la mortalité naturelle. Les tendances historiques du recrutement ont été rétrocalculées à l'aide d'un modèle structuré en fonction de l'âge et le recrutement futur a été simulé à partir des tendances historiques. Les tendances de la pêche examinées étaient des combinaisons de différents taux de mortalité instantanée (0,016 ou 0,036) et de différentes périodes de recrutement historiques (commençant en 1940 ou en 1960). Pour chaque année de simulation et dans chaque ensemble de 1000 passages du modèle, le rapport de la biomasse actuelle et de la biomasse vierge a été calculé et comparé à l'objectif de gestion qui consiste à ne pas permettre que la biomasse chute sous les 50 % de la biomasse vierge dans les 50 ans suivant le début de l'exploitation d'un gisement. Les données ont été analysées et les résultats, présentés par région géographique.

Les tendances du recrutement étaient indépendantes de la valeur de *M* utilisée, bien que les taux aient été supérieurs quand *M* de 0,036 était utilisé, comparativement à *M* de 0,016. Les taux de recrutement historiques se sont révélés hautement variables avant l'exploitation : ils ont augmenté à partir du début des années 1930 jusqu'aux années 1950, ont diminué au début de la décennie 1960, ont grimpé pour atteindre un autre sommet au milieu des années 1960 avant de baisser jusqu'au milieu des années 1980, puis de remonter jusqu'à aujourd'hui.

Un plan prudent et raisonnable serait de Y40M0,036 (année de début de la simulation du recrutement 1940 et *M* de 0,036) pour la côte nord et de Y60M0,016 pour la côte centrale et les îles Reine-Charlotte. Pour ce qui est de la côte ouest de l'île de Vancouver et du bassin de Georgia, Y60M0,036 semble prudent. Dans l'ensemble, un taux d'exploitation de 1,2 % et de 1,8 % de la biomasse actuelle estimée est recommandé pour la côte ouest de l'île de Vancouver et le reste de la côte respectivement. D'autres suggestions sont présentées à l'intention des gestionnaires au sujet des points de référence limites et du choix du taux d'exploitation, à partir de l'échelle fournie.

Introduction

Geoduck, *Panopea abrupta* (Conrad, 1849), are large hiatellid bivalves that thrive in un-consolidated substrates in the northern Pacific from California to southern Japan (Coan et al. 2000). The clams are extremely long-lived, with a maximum recorded age of 168 years (Bureau et al. 2002). They are slow-growing after an initial phase of fast growth during the first 10 years of life, and growth rate and maximum size varies along environmental gradients and between geographic regions (Hoffman et al. 2000, Bureau et al. 2002). Geoducks start to reach sexual maturity at age 2-3 years (Campbell and Ming 2003). Reproduction is through broadcast spawning during early summer months, followed by pelagic larval stage lasting 40 to 50 days (Goodwin et al. 1979, Goodwin and Shaul 1984). Postlarvae settle and move on the seafloor surface for several weeks (King 1986) until metamorphosis and the start of suspension feeding. The animals begin to dig, and reach their final refuge depth of up to 1 m in approximately 4 to 5 years, after which predation mortality is extremely low. An exception to low mortality is in regions of the British Columbia (BC) coast where the sea otter (*Enhydra lutris*) populations are recovering.

Geoducks are aggregated into beds, by virtue of their substrate requirements, and are thus structured as metapopulations, with population segments being inter-connected through the flow of planktonic larvae. No evidence has been reported of a relationship between the reproductive capacity of a population within a given location and subsequent recruitment to that location (Orensanz et al. 2004). Recruitment mechanisms operate differently during the periods of pre-settlement and post-settlement of larvae, and Orensanz et al. (2004) warn that key processes in the population dynamics may be completely blurred if analyzed at the wrong spatial scale.

Geoduck populations support lucrative dive fisheries in Washington State and BC. The average annual landed value was 38 million Canadian dollars over the last 5 years in BC alone. The BC fishery is managed through a combination of limited entry and individual quotas (Heizer 2000). Annual fixed quotas are set at 1% of estimated virgin biomass (B_0), the harvest rate being a result of initial yield models that were based on the limited biological information available at an early stage of fishery development. To date, B_0 has been estimated by adding fishery removals to the estimate of current biomass from transect surveys, while natural mortality and recruitment are assumed to be equal. Since the fishery is well into its third decade, it is becoming increasingly untenable to continue this practice of reconstructing virgin populations. Biological samples from commercial beds indicate that a high proportion of populations are comprised of animals that have recruited since the fishery began (Bureau et al. 2002, 2003). In addition, estimates of landings are not certain, especially for south coast waters in the early years of the fishery when catch reporting was often geographically vague, resulting in additional error to virgin biomass estimates. The accuracy of current biomass estimation is therefore expected to be greater than the accuracy of virgin biomass estimation.

The availability of a substantial amount of biological information warrants a new assessment of the geoduck stocks and re-evaluation of harvest rates in BC. Fishery-independent transect surveys have been conducted over all regions of the BC coast and, to date, include about 40% of the total estimated area of geoduck beds. Geoduck abundance, distribution and age composition have been collected from each surveyed location. Some important biological parameters of geoduck populations, such as growth and natural mortality rates, have also been estimated (Bureau et al. 2002, Zhang and Campbell 2004). In this paper, we study historic recruitment patterns through back-calculation, and investigate the impacts of alternative exploitation intensities on the geoduck populations through age-structured projection modelling. Advice is provided on choosing plausible and precautionary exploitation rates as applied to estimates of current biomass, and on how we may set up and use biological reference points in the management of this fishery. We also endeavour to provide answers to other questions posed by the managers (Appendix I).

Materials and Methods

We conducted this modelling study using biological information obtained from fishery-independent surveys and sampling, and fishery data obtained from log-books (Table 1). Historic recruitment patterns were back-calculated using an age-structured model, and we compared virgin geoduck densities estimated from this retrospective analysis with those estimated using the conventional method (survey-derived abundance + accumulated fishery removals). We simulated future recruitment from the estimated historic recruitment pattern, and examined the simulation accuracy by comparing projected abundances with observed abundances in four instances where repeat survey data were available. Through forward simulation, we evaluated the impacts of alternative fishing intensities on the stocks. Data were analyzed by survey location and the results grouped by geographic region. In this paper, we divide the BC coast into five geographic regions: North Coast (NC), Central Coast (CC), Queen Charlotte Islands (QCI), West Coast of Vancouver Island (WCVI), and Georgia Basin (GB) (Table 1, Fig. 1). In this study, CC also includes two surveyed locations in Queen Charlotte Strait. Analyses were also conducted by bed-productivity category, as approximated by estimated virgin density calculated in the conventional manner (Table 2).

In recent years, sea otter predation on geoduck has greatly increased in some parts of west coast of Vancouver Island. To aid in managing the geoduck fishery in the areas occupied by sea otters, we estimated predation rate in one localized area from which a time-series of survey and biological data were available.

1. Fishery-independent Surveys.

Each year, a number of geoduck beds are selected for surveying. Beds are chosen to be surveyed for a variety of reasons, including significant contributions to total landings in the fishery, disagreement in the quota recommended by DFO Science for a bed, or conservation concerns. If the selected location is comprised of many smaller beds, as opposed to beds that occur on large banks, the aggregate is partitioned into strata. For each strata, transect locations are selected randomly, following protocols described in

Campbell et al. (1998). A number of quadrats 2-metre wide and 10-metre long are set along each transect and SCUBA divers count the number of geoduck within each. Where appropriate, data are post-stratified for analysis and transects are excluded if the substrate was not suitable. Mean geoduck density and associated standard error were estimated for each bed using the two-stage random design estimator with transects as the primary sampling units and quadrats as the secondary sampling units (Thompson 1992). Biological samples were collected from the surveyed populations, from which length, weight and age data are obtained (Bureau et al. 2002, 2003). Age is determined using the acetate peel method (Shaul and Goodwin 1982) and, in most cases, estimated geoduck ages are provided with a range of uncertainty. Subsamples of approximately 150 animals each are collected from randomly-selected transects throughout the survey location and combined into one sample per location.

Density and biological information from 42 fishery-independent surveys was used in the modelling. The 42 surveys were conducted in 38 locations; four locations were surveyed in two different years (Table 1).The number of individual geoduck beds surveyed per location varies from one to eighteen (Table 1). From each surveyed location, between 186 and 580 geoduck were sampled for age determination.

2. Estimation of Historical Recruitments.

Recruitment age is defined to be 6 years, the age at which we assume geoducks to become fully vulnerable to harvesting (Campbell et al. 2004). Historical recruitment rates (recruits/m^2) were back-calculated for each survey location, using estimated geoduck density, the age structure of the bio-samples collected and fishery removals as inputs to the model. Estimated historic recruitment strength relies on the natural mortality rate, *M*, used in the back-calculation. *M* for geoduck populations appears to vary approximately between 0.01 and 0.04 (Breen and Shields 1983, Harbo et al. 1983, Sloan and Robinson 1984, Noakes and Campbell 1992, Bradbury and Tagart 2000). In a tagging experiment in Washington, *M* was estimated to be 0.016 with a standard error of 0.0046 (Bradbury et al. 2000). Using experimental data from WCVI, Zhang and Campbell (2004) estimated *M* to be 0.036 with a standard error of 0.003. These two estimates of *M* approximately cover the range of *M* found in the literature, and were utilized in this study to estimate historic recruitment patterns.

The youngest age considered in this paper is 6 years. The maximum age was set to be 80 years for the sampling year, and geoducks older than the maximum age were pooled to form a maximum-plus age group. The maximum age for previous years was one year younger than for the subsequent year. For instance, in the year prior to the sampling year, the maximum age was 79 years and geoducks older than age79 were pooled into the 79+ age group. In the sampling year, the abundance of geoducks for each surveyed bed is calculated as the product of mean density and the bed area, and the total abundance for each surveyed location is simply the sum of abundances for all the surveyed beds in the location. Abundance at each age during the sampling year was estimated as the product of the total geoduck abundance and the proportion of geoduck at that age in the bio-sample. Abundance of geoduck at age a in year y (earlier than the sampling year), $N_{y,a}$, for each survey location was estimated as:

$$N_{y,a} = N_{y+1,a+1} \times \exp(M) + C_{y+1} \times P_{y+1,a+1} \quad (1)$$

where C_{y+1} is the number of commercial removal of geoduck in year y+1, and $P_{y+1,a+1}$ is the estimated proportion of geoduck at age $a+1$ in year y+1. Thus, the proportion-at-age in the bio-samples was carried backwards in the retrospective analysis as the proportion at each age-class. Where commercial landings were only reported in weight, C_{y+1} was estimated by dividing the reported landings in weight by mean weight for the location. Mean weight for a bed is estimated from the landed weight and number of geoduck, where number is reported in logbooks, over the period 1997 to present. Mean weight estimates from nearby beds may be applied if no estimate for a given bed exists.

Annual recruitment rate for an individual survey location, which usually includes several beds, was expressed as recruitment density by dividing the estimated abundance of age-6 in each year by the summed area over all the surveyed beds. Annual recruitment rate for a geographic region was calculated as:

$$R_y = \sum_{location} \frac{N_{y,6}}{A} \quad (2)$$

where $N_{y,6}$ represents the estimated abundance of age-6 geoducks in year y in a location, and A represents the summed area over all the surveyed beds in the location .

To evaluate uncertainties in the estimation, 999 simulations were conducted. In each simulation, the starting age composition of the bio-samples was bootstrapped by re-sampling with replacement to produce a simulated sample of the same size. A further step incorporated the uncertainty in ageing; the actual age for each sample was randomly generated from a normal distribution, with the estimated age as the mean and one half of the error-range as the standard deviation. Geoduck densities in the sampling year were also randomly regenerated from a normal distribution with the mean and standard deviations estimated from survey results. The value of M was also randomly regenerated from a normal distribution with the designated mean and standard error (0.016 $\pm$ 0.0046 or 0.036 $\pm$ 0.003). The simulated data sets were used to estimate the recruitment patterns as described above.

3. Projection Simulations.

We assume that recruitment in the future will reflect what has occurred in the past. We fitted the 1000 back-calculated recruitment data to the gamma probability distribution for each surveyed location using the least square error method, and used the fitted distribution to describe the likelihood of recruitment rates for the location. In each simulation year, the number of recruits was randomly generated from the gamma distribution. For each survey location, population abundance (number of animals per square metre) and biomass were projected onwards for 50 years from the sampling year under a given exploitation rate (E), which varies from 0 to 4% with an interval of 0.5%.

We examined the impact of alternative harvesting intensities on the surveyed stock biomass and abundance in order to find plausible and precautionary *E*'s for the fishery. Population abundance at age $a+1$ in year y + 1 was estimated to be:

$$\begin{cases} N_{y+1,a+1} = N_{y,a} \times (1-E) \times \exp(-M) & (a < 80) \\ N_{y+1,a+} = (N_{y,a} + N_{y,a+}) \times (1-E) \times \exp(-M) & (a = 80) \end{cases} \quad (3)$$

We used the weight-age conversion equations, which were established for each surveyed location by Bureau et al. (2002, 2003), to convert abundance to biomass. For each simulation year, a performance index was calculated as the ratio of current biomass (B_c) to the virgin biomass (B_v), the latter being the back-calculated biomass in the year just before the beginning of the commercial fishery in the location. The performance index (as biomass or abundance) for each geographic area or productivity group was calculated by dividing the sum of current biomass (or abundance) by the sum of virgin biomass over all the surveyed locations in the geographic area. Among the nine surveyed locations in WCVI, four have been affected by sea otter predation (Table 3). We therefore calculated the ratio of B_c to B_v by using only the five unaffected locations.

Four possible simulation schemes were considered: recruitment simulation year starts from either 1940 or 1960, and the mean value of *M* used in the simulation is either 0.016 or 0.036. The four simulation schemes are thus denoted as Y40M0.016, Y60M0.016, Y40M0.036 and Y60M0.036. In general, future recruitment is more optimistic when the recruitment simulation year starts in 1940 than in 1960 because estimated recruitment is high during the period 1940-1960.

To evaluate uncertainties in the estimation, 999 simulations were conducted. In each simulation, age composition of the bio-samples, geoduck density in the sampling year, and value of *M* were randomly regenerated as described in the previous section.

4. Comparison of Projected and Survey-derived Geoduck Densities.

Surveys were conducted in two different years in each of the four locations: Comox Bar, Goletas Channel, Mission Group, and Winter Harbour (Table 1). This provides an opportunity to examine the location of the observed mean density within the range of the model-projected densities, which is helpful in selecting a percentile level for determining harvest rates. Except in Comox Bar, different sets of geoduck beds were surveyed on the two survey occasions; we used only the data obtained from beds which were surveyed on both occasions. We used results from the first survey to predict geoduck densities in the year of second survey. In each of the simulation years, recruitment was randomly generated from the gamma distribution, as described earlier. Population abundance at age a+1 in year y+1, $N_{y+1,a+1}$, was calculated by rearranging Equation 1. To incorporate uncertainties in estimated parameter values, 999 simulations were conducted.

5. Sea Otter Predation Rate.

Sea otter predation on geoduck appears to be severe in the Mission Group (Table 3). Model projection results for Mission Group also revealed that a considerable amount of geoduck were likely consumed by sea otters during 1998-2003. To estimate this predation rate, an extra mortality rate was added to *M*. Geoduck abundance in the second sampling year (2003) was then predicted based on the first survey information in 1998 in the same manner as described above. Various sea otter predation rates were trialed until the projected abundance mostly agreed with the survey-derived one. To assess the uncertainties, 999 simulations were conducted, in which age composition, *M* and geoduck densities were randomly generated, as described earlier. In addition, geoduck abundance in the second survey year (2003) was also randomly generated based on the second survey results.

Results

1. Historic Recruitment Pattern.

Trends in recruitment over time are comparable, irrespective of the value of *M* used in the back-calculation (Fig.2), whereas the magnitude of estimated historic recruitment rates are affected by the value of *M* used. Recruitment rates in the past were estimated to be higher when *M* of 0.036 was applied compared to a value of 0.016 (Fig. 2). Recruitment appears to have fluctuated appreciably in the virgin state in years prior to 1975 when the fishery began. Overall, recruitment in the BC coast increased from at least 1930, and reached the highest around 1950. It then decreased until the early 1960s, before it started to increase again. Recruitment reached another peak in the mid-1960s, and then declined until mid-1980s. Recruitment has been increasing since mid-1980s. In general, recruitment rates in 1940-1960 constituted the highest peak, and recruitment rates in 1960-1975 constituted a second, lower, peak. With application of *M* of 0.016, recruitment rates in recent years appear to be as high as in the highest historic period of 1940-60. With application of *M* of 0.036, recruitment rates in recent years appear to be approaching the lower level in 1960-1975. The apparent decline in the most recent years is most likely due to under-sampling of young geoduck in the bio-samples.

Among the five geographic regions, average recruitment rates are the highest in NC and CC, and intermediate in QCI and WC VI, and the lowest in GB (Fig. 3). Recruitment patterns in NC, CC, and QCI generally conform to the overall pattern for the entire coast. Recruitment patterns in WCVI and GB also resemble the overall pattern except that they lack the highest peak around 1950 (Figs. 3, 4). Mean recruitment rates in recent years are the highest for the period studied in GB (Fig. 4).

Despite apparent differences in the overall mean recruitment rates between some geographic regions, ranges of mean recruitment rates (extent of minimum and maximum mean recruitment rates) over individual locations within a region are wide, and there are substantial amounts of overlap in these mean recruitment rates (Fig. 5).

2. Comparisons of Virgin Geoduck Densities.

We estimated geoduck densities just before the onset of commercial fisheries, defined as the virgin densities, using both the age-structured model and the conventional method. With application of *M* of 0.016 in the age-structured model, estimated virgin geoduck densities are comparable to those estimated by the conventional method (Table 4). Pair-wise t-test indicates no significant difference (p=0.1), although the overall mean density estimated by the age-structured model is slightly lower than that of the conventional method (Fig. 6A). With application of *M* of 0.036 in the age-structured model, estimated mean virgin geoduck densities are, in general, higher than those estimated by the conventional method. Pair-wise t-test indicates the difference is highly significant (p<0.001) (Table 4, Fig. 6B).

3. Comparison of Estimated Recruitment Rates.

Independent surveys were conducted in two different years in each of the four surveyed locations, Comox Bar, Goletas Channel, Mission Group, and Winter Harbour. Recruitment densities estimated from the two independent surveys agree with each other reasonably well (Figs. 7, 8). XY plots of each pair of estimated mean recruitments, however, show that the estimations are most in agreement for Goletas Channel and Winter Harbour, and less so in Mission Group and Comox Bar (Figs. 9, 10). The XY plot is useful for determining relationships between two sets of data. When the points of the XY plot form a straight line with a high correlation coefficient, there is a highly correlated linear relationship between the two data sets. Figs 9A, 9B, 10A and 10B show that the correlation coefficient is high, indicating that the two estimated recruitment densities agree with each other well. On the other hand, Figs 9C, 9D, 10C and 10D show that the correlation coefficient is relatively low, indicating that the two estimated recruitment densities do not agree with each other well. It was noted that sample sizes for the surveys in Goletas Channel and Winter Harbour are either close to 450 or above 450, whereas the sample size for one of the two surveys in Mission Group or Comox Bar is either close to 300 or below (Table 1).

4. Projection Simulations.

For a given exploitation rate, stock biomass generally declines more quickly or increases more slowly when the recruitment simulation starting year is 1960 rather than 1940, and when *M* used in the modelling is 0.036 rather than 0.016. All projection results are presented in Tables 5-7.

With Y60M0.036, the population would decrease in NC, CC, and QCI even without exploitation, as recruitment would not be sufficient to compensate for the loss due to natural mortality (Figs 11 and 12). The geoduck stocks on WCVI could be harvested at 1.7% to have a 50% calculated chance of achieving the management goal of maintaining the biomass above one-half of the virgin biomass at the end of 50 years (Fig. 11C, Table 5). *E* would be reduced to 1.1% if we want to raise the chance of achieving the goal to 90% (Fig. 12C, Table 5).When we consider only the areas without sea otter predation, the corresponding E's would be 1.9% and 1.2% (Figs. 11D, 12D, Table 5).

The geoduck stocks in GB could be harvested at 2.7% to have a 50% calculated chance of achieving the management goal (Fig. 11F, Table 5) and 2.0% if we want to increase the chance to 90% (Fig. 12F, Table 5).

With Y40M0.036, *E* could be set between 2.5% and 3.6% over all the regions to have a 50% calculated chance of achieving the management goal (Fig. 13, Table 5) and would be reduced to 1.7-3.0% if we want to increase the chance to 90% (Fig. 14, Table 5). With Y60M0.016, the population would decrease in NC even without exploitation, as recruitment would not be sufficient to compensate for the natural loss due to mortality (Figs 15A, 16A). *E* could be set to 1.8-3.5% to have a 50% calculated chance to achieve the management goal for CC, QCI, and WCVI (Fig. 15, Table 5) and would be reduced to 1.6-2.8%, if we want to raise the chance to 90% (Fig. 16, Table 5). Geoduck stocks in GB seem to be able to sustain an exploitation rate around 4.0% (Table 5). With Y40M0.016, *E* could be set to 2.4-3.6% for NC, CC, QCI and WCVI to have a 50% calculated chance of achieving the management goal (Fig. 17, Table 5) and would be reduced to 2.0-3.0% if we want the calculated chance to increase to 90% (Fig. 18, Table 5). Stocks in GB again seem to be able to sustain higher harvest rates at 4.0% and 3.7% for 50% and 10% percentiles, respectively (Table 5).

Impacts of harvesting intensities on geoduck density are very similar to the impacts on geoduck biomass, in terms of trajectory of the ratio of current level to the virgin level. Differences in critical exploitation rates between the two evaluation criteria are small, usually within ± 0.3% (Tables 5, 6).

When geoduck beds are grouped into productivity categories, based on estimated virgin densities, it appears that slightly higher harvesting rates may, in general, be applied to beds with lower virgin densities, contrary to expectations (Table 7). As with geographic groupings, with Y60M0.036, recruitment barely compensates for the natural mortality for beds with intermediate and high virgin densities (Fig. 19). Geoduck stocks from beds with low virgin density could be harvested with 1.4% to have a 50% calculated chance of achieving the management goal. *E* would be reduced to 1.0% if we want to increase the chance to 90% (Fig. 19A-B, Table 7). With Y40M0.036, *E* could be set to 2.8-3.3% to have a 50% calculated chance to achieve the management goal, and *E* would be reduced to 2.3-2.7% if we want to raise the chance to 90% (Fig. 20, Table 7). With Y60M0.016, *E* could be set to 2.3-3.3% to have a 50% calculated chance to achieve the management goal, and *E* would be reduced to 2.0-2.9% if we want to raise the chance to 90% (Fig. 21, Table 7). With Y40M0.016, *E* could be set to be 3.0-3.5% to have a 50% calculated chance to achieve the management goal, and *E* would be reduced to 2.7-3.1% if we want the calculated chance to increase to 90% (Fig. 22, Table 7). Estimated virgin biomass is apparently not a useful index for bed productivity.

5. Comparison of Projected Densities with Observed Densities.

In Goletas Channel and Winter Harbour, model-projected geoduck densities agree generally well with the survey-derived mean densities, the latter being located between the median and 10^{th} percentile when the recruitment simulation year starts in 1960 and close to the 10^{th} percentiles when recruitment simulation year starts in 1940 (Fig. 23A,B).

The 10th percentile appears to be a precautionary choice within the suite of simulation schemes for setting up exploitation rates. In Comox Bar, the survey-derived mean density is either close to or above the 90th percentiles of the model-projected densities (Fig 23C), supporting the result of our recruitment back-calculation that recruitment was particularly strong in the 1990s in GB (see Fig. 4). Since recruitment simulation relies on estimated recruitment in the past, the model is incapable of accurately projecting the abundance or biomass trends when there is a persistence of especially high or low recruitment. In Mission Group, the observed mean density from the 2nd survey is considerably lower than the 10th percentiles (Fig. 23D), probably because a substantial amount of geoduck were consumed by sea otters. Sea otters are also known to reside in Winter Harbour, but their impact on geoduck appears to have been considerably less severe (Table 3). The measured density in Winter Harbour was not much lower than the predicted one.

6. Sea Otter Predation Rate

Sea otter predation rate on geoduck in the Mission Group was estimated to be between 0.15 and 0.17, depending on the simulation scheme used, with standard errors of 0.09 to 0.13 (Table 8).

Discussion

This study provides a revealing glimpse at possible historic recruitment trends for geoduck populations in BC, and presents a method of evaluating impacts of alternative harvesting intensities on the geoduck stocks. Features related to the study and implications of our findings to the assessment and management of the geoduck fishery are discussed.

Geoducks are only visible to divers when their siphons extend above the substrate surface and the proportion of geoducks that are visible to divers during a single observation is known as the “show factor”. In this study, show factors were not applied in the estimation of geoduck densities, because we are mainly interested in the consequences in terms of ratio of biomass to the virgin biomass. Consequently, estimated and back-calculated densities are likely to be slightly lower than actual ones. However, show factors are typically in the order of 90-95% (DFO, unpublished data) and corrections applied to the observed data are not significant.

Geoduck quotas have been based on virgin biomass. The conventional method of calculating virgin biomass is to add accumulated fishery removals to the survey-derived biomass and assume that recruitment and mortality are in balance. Virgin abundances estimated in this manner are not significantly different from those estimated using the age structured-model with M of 0.016, but are significantly lower than those estimated using the age structured-model with M of 0.036. It appears that the conventional method would result in estimates in the right ball park in cases where M is low, and produce conservative estimates in cases where M is high.

Estimated recruitment rates were based on age structures obtained from bio-samples. Sample size appears to be an important factor in the accuracy of recruitment determination. Historic recruitment rates based on two independent sets of samples agree reasonably well when both sample sizes are around or above 450, however when even one sample size is as low as around 300 animals, the historical trends diverge. A sample size of at least 450 animals in each survey is apparently required to determine the age-structure well. This sample size appears to be theoretically acceptable as well. Thompson (1987) demonstrated that sample sizes of 403 and 510 are required if we want to achieve at least 90% and 95% chance, respectively, to have errors of all estimated age proportions within 5%.

Our calculations show that recruitment appears to have been strong in recent years throughout the BC coast, likely because of some favourable environmental conditions prevailing in these years (Valero et al. 2004). Overall historic recruitment trends appear to be similar for NC, CC, QCI and, to a large extend, WCVI and GB as well, suggesting that geoduck recruitment may be regulated by some common oceanic factors. However, within each geographic region, recruitment variation is large, which may preclude using regional index sites to represent recruitment trends in any given area.

Geoduck stocks form metapopulations. There is no stock-recruitment relationship in the traditional sense, as recruitment to one location is unlikely associated with the reproductive capacity in the same location (Orensanz et al. 2004). Unless and until we could model the larval movement, we are not able to link recruitment in one spot to stock biomass in another. We are also currently unable to predict future recruitment rates based on environmental factors, although it is recognized that recruitment is likely related to the geographic and oceanic features in the immediate area. For instance, recruitment is higher in locations where water currents are of medium velocity (Goodwin 1990, Bureau et al. 2002). To conduct the recruitment simulations, we follow the advice of Maunder and Driso (2003), and assume that future recruitment will occur with a similar distribution as historical recruitment. Positive relationships between model-projected and observed abundances suggest that this approach is reasonable for geoduck populations in the absence of extraordinary recruitment or predation events.

Geoducks are long-lived animals, and natural mortality for geoduck populations must, therefore, be low. M has been estimated in the approximate range of 0.01-0.04 (Bradbury and Tagart 2000, Breen and Shields 1983, Noakes and Campbell 1992, Orensanz et al. 2004, Zhang and Campbell 2004). We chose to use a small value of M (0.016) and a large value of M (0.036) in the simulation model to evaluate impacts of fishing intensities on the stocks. As actual M is likely to vary between the two values, the real impact of fishing intensities on stocks is likely to be between the two estimated extremes. Thus, choosing the more conservative exploitation rate from within the range is likely to adequately precautionary.

The simulation model generates a wide range of exploitation rates over the four simulation schemes, each rate having an associated calculated risk of failing the management goal. To be precautionary, exploitation rates at the 10^{th} percentiles may be used instead of mean or median exploitation rates. This would reduce the calculated risk below 10%. As well, the comparison of model-projected and survey-derived densities in locations that were surveyed on two separate occasions indicates that the 10^{th} percentile is a precautionary choice and more appropriate than the mean or median exploitation rates.

Geoduck abundance trends are mainly regulated by the balance of recruitment and mortality. The simulation scheme of Y60M0.036 seems to be unrealistic for NC, CC, and QCI, and Y60M0.016 also seems to be unreasonable for NC. Population would be decreasing even without fishing, as recruitment would not be able to compensate for natural mortality. A precautionary and reasonable simulation scheme appears to be Y40M0.036 for NC and Y60M0.016 for CC and QCI. For WCVI and GB, the most precautionary results are from the simulation scheme of Y60M0.036. Based on these precautionary simulation schemes, exploitation rates would be set at 1.7%, 1.8%, 1.6%, 1.2% and 2.0% for NC, CC, QCI, WCVI and GB respectively. For simplicity, managers may opt to use a single exploitation rate of 1.8% for the entire coast except for WCVI. Results of simulation studies for geoduck beds grouped by estimated virgin density over the entire coast, as a surrogate for productivity, suggest that exploitation rates could be set to approximately 2.0%, which supports the exploitation rates proposed for geographic areas as being precautionary.

Once exploitation rates are selected, they should be applied to estimates of current biomass in order to derive quotas. Flexibility in choosing the most appropriate quota for a given bed can come from choosing different percentile points of the estimated biomass. If practical observations suggest that the actual biomass is lower than the estimated mean or median level, estimated biomass at a lower percentile point may be used in quota setting. This offers a practical and effective way of guarding against over-fishing in a localized region, and allows harvesters to achieve the set quota more effectively.

Estimates of current biomass must be updated to account for changes that will have occurred since the survey year. To estimate current biomass for beds where the latest survey was conducted a few year earlier, we may either use the simulation modelling presented in the paper, which includes a recruitment component and assumptions of M, or the conventional method previously used for calculating virgin biomass which assumes recruitment and natural mortality are in balance. In using the latter method, estimates of current biomass are obtained by subtracting accumulated fishery removals since the last survey from the estimated biomass in the last survey year. The advantage of this method is simplicity and practicality. Geoduck population dynamics are slow paced, due to high longevity and low natural mortality and recruitment rates, and for a short interval, this conventional method should provide estimates in the right ball park. When the interval is long, a lower percentile estimate of biomass may be chosen, especially if harvesters feel that geoduck abundance is lower than estimated. Alternatively, we may use the simulation modelling to generate several probability distributions for current biomass, and then choose an estimate in a precautionary manner. To estimate current biomass for beds which have never been surveyed, it will be necessary to extrapolate biomass estimates from "similar" beds, which might be neighbouring beds or beds sharing the same characteristics such as substrate type or oceanic conditions.

To give an indication of the impact of adopting new exploitation rates and different estimates of biomass on quota recommendations, a comparison of mean quota options as calculated to date, and as revised, is presented for surveyed beds in the Queen

Charlotte Islands (Fig. 24). The ‘old’ quota estimates were calculated as 1% of virgin biomass and reduced with a factor that attempts to distribute catches evenly over a 50-year time horizon (Hand and Bureau 2000). Revised quota estimates are calculated as 1.6% of current biomass estimates. Most revised quotas are above the line of equality, and, overall, are higher by an average of approximately 50%.

Due to relatively slow rate of change in abundance of geoduck populations, it is not necessary to re-run the model annually for deriving new harvesting rates. We believe that a minimum of 5 years are needed before harvesting rates may be updated, which would also provide the time interval required to evaluate the model performance. Such an evaluation would require re-surveying select beds and examining where the new estimated mean lies in the confidence interval for projected density or biomass. The closer the mean and the model-projected median are, the better the model would seem to be working. Because biomass estimates are usually estimated with large uncertainties, we may pool beds with similar features such as geoduck density in order to increase the precision of biomass estimates. This would allow a more confident comparison of survey-derived biomass to model-projected estimates.

Sea otters are now residing in areas of WCVI and in portions of the Central Coast, and their predation on geoduck is severe in some locations. The predation rate in Mission group was estimated to be around 0.16, more than ten times as high as the recommended harvesting rate. In the parts of WCVI with no sea otters, the current biomass appears to be slightly above 50% of the virgin level under the simulation scheme of Y60M0.036 (see Figs. 11, 12). A lower exploitation rate of 1.2% is necessary. However, sea otter populations may expand to these parts of WCVI and predate on geoduck in the future. If this occurs, no matter how precautionary the exploitation rate is, it is unlikely that the management goal to maintain the biomass above the 50% of the virgin level can be achieved.

The current limit threshold is defined to be 50% of the virgin biomass level. In Washington, harvesting rate was calculated based on the $F_{40\%}$ criterion (Bradbury and Tagart 2000). Clark (1993) proposed that a target reference point can be set to $F_{40\%}$ based on simulations of stock-recruitment relations of a variety of groundfish. Mace (1994) also recommended the use of $F_{40\%}$ as a target fishing rate when the stock and recruitment relationship is unknown. Our threshold point appears to be more precautionary by comparison. However, the virgin biomass level that has been adopted as the benchmark for thresholds and for performance indicators in the projection modelling (i.e. the back-calculated biomass just before harvest in any given location) happened to be relatively low in late 1970s. From this prospect, the threshold point does not seem to be overly conservative. On the other hand, there are likely significant geoduck populations living in un-fishable water depths, in substrates where harvest is impractical, in contaminated waters or in marine reserves and parks. Although their contribution to recruitment in the fishable beds is unknown, it is conceivable that some amount of larvae will successfully settle in the fishable beds. Thus, we suggest that target and limit reference points may be set to 50% and 40%, respectively, of virgin biomass at the onset of commercial fishery. Thus, if the geoduck population in a bed is approaching the limit reference point, fishing should stop. Fishing should not resume until the population has increased above the target reference point and there are indications or evidence that the population is not likely to decrease towards the limit reference point under a chosen exploitation rate. Note, however, that these threshold points are still reliant on estimates of virgin biomass. Investigations of alternative reference points should be undertaken, with the view to moving away from the need to estimate virgin biomass and discovering a fixed reference biomass density that would be able to support viable geoduck populations.

Most of the geoduck fishery in BC is rotational, where only one third of the geoduck beds are harvested in any one year, at three times of the annual exploitation rate. The rationale for such a rotational fishery is purely logistic: easy monitoring, reduced number of landing ports, and concentration of the assessment effort (Orensanz et al. 2004). The optimal rotational period is unknown because biological implications of pulse fishing on geoduck population dynamics are poorly understood. Age-structured models were developed in 1992 with assumed relationships between juvenile survival and fishing activity, and stock and recruitment relationships (Campbell and Dorocicz, 1992, Breen 1992). These studies suggested that rotational fishing has no obvious biological benefit, but confers some economic advantage over annual fisheries. An increase in the rotation period would further reduce management and assessment demands. Furthermore, with a longer rotation, higher exploitation rates would be applied to fewer beds, which might permit a more timely evaluation of the accuracy of biomass estimates. In cases where biomass is overestimated, harvesters would likely face immediate difficulties in achieving the quota and feedback would be quickly received. This may lead to in-season management difficulties, however. A longer rotational period may also cause negative impacts on geoduck recruitment. As dioecious broadcast spawners, geoducks need to live close enough for successful fertilization. With a higher exploitation rate, risk of over-harvesting the local stock would increase, especially in cases where biomass is over-estimated. If the local stock happens to be a source bed, a contributor to recruitment in the general area, the population productivity would decrease. To evaluate the impacts of different years of rotation, we ideally need to better understand the dynamics of density-dependence for spawning, for larval settlement, and for growth and survival, as well as estimates of harvesting-induced mortality on pre-recruited geoduck. In the absence of this biological information, hypothetical situations may be modelled and possible consequences examined, which could lead to testable theories. At the least, extreme cases can be eliminated and precautionary rotational periods identified, based on common sense.

Fishermen have consistently reported that geoduck beds vary in productivity. For geoduck, productivity is mainly a function of the magnitude and frequency of recruitment, since growth in body weight is negligible beyond age-10. Although analytical trials using categories of virgin biomass as a surrogate for productivity did not produce meaningful or logical results, further attempts to categorize and analyze beds using a suite of characteristics, including anecdotal reports from industry and biological parameters calculated from survey sampling, should be attempted. A database housing this information is currently being assembled.

Recommendations

(1) Set quotas at 1.8% of estimated current biomass for NC, CC, QCI and GB, and 1.2% of estimated current biomass for WCVI for a period of at least five years. For flexibility in quota setting, choose biomass estimates at different percentiles of the estimated biomass distribution.

(2) Set the target and limit biological reference points to be 50% and 40% of the virgin biomass, which is the biomass just before the fishery started. Therefore, when biomass of a geoduck bed is approaching the limit reference point, harvesting shall stop. Harvesting should not resume until the biomass rises above the target reference point and evidence shows that there is only a small chance that the biomass will decrease again towards the limit reference point under the resumed harvesting intensity.

(3) Calculate current biomass by subtracting accumulated fisheries removals since the last survey from the estimated biomass in the last survey year.

(4) The size of bio-samples collected from a survey for age determination should be at least 450 animals.

(5) Continue to develop indices to categorize geoduck beds by productivity, for future modelling.

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References

Bradbury, A. & J. V. Tagart. 2000. Modeling geoduck, *Panopea abrupta* (Conrad, 1849) population dynamics. II. Natural mortality and equilibrium yield. *J. Shellfish Res.* 19: 63-70.

Bradbury, A., D. P. Rothaus, R. Sizemore & M. Ulrich. 2000. A tag method for estimating the natural mortality rate of geoducks (*Panopea abrupta*). *J. Shellfish Res*. 19: 690.Bradbury, A. & J. V. Tagart. 2000. Modeling geoduck, *Panopea abrupta* (Conrad, 1849) population dynamics. II. Natural mortality and equilibrium yield. *J. Shellfish Res.* 19: 63-70.

Breen, P. A. & T. L. Shields. 1983. Age and size structure in five populations of geoduck clams (*Panope generosa*) in British Columbia. *Can. Tech. Rep. Fish. Aquat. Sci.* 1169. 62 pp.

Breen, P. A. 1992. Sustainable fishing patterns for geoduck clam (*Panopea abrupta*) populations in British Columbia. PSARC Working paper I93-10. Summarized *In* Irvine, J. R., R .D. Stanley, D. McKone, S. M. McKinnell, B. M. Leaman and V. Haist (eds). 1993. Pacific Stock Assessment Review Committee (PSARC) Annual Report for 1992. Can. MS Rep. Fish. Aquat. Sci. 2196: 199 p.

Bureau, D., W. Hajas, N. W. Surry, C. M, Hand, G. Dovey & A. Campbell. 2002. Age, size structure and growth parameters of geoducks (*Panopea abrupta* Conrad, 1849) from 34 locations in British Columbia sampled between 1993 and 2000. *Can. Tech. Rep. Fish. Aquat. Sci.* 2413. 84 pp.

Bureau, D., W. Hajas, C. M, Hand & G. Dovey. 2003. Age, size structure and growth parameters of geoducks (*Panopea abrupta* Conrad, 1849) from seven locations in British Columbia sampled between 2001 and 2002. *Can. Tech. Rep. Fish. Aquat. Sci.* 2494. 29 pp.

Campbell, A. and J. Dorociez. 1992. Yield and risk analysis for the geoduck fishery in two areas of southern British Columbia. PSARC Working Paper I93-2. Summarized *In* Irvine, J. R., R. D. Stanley, D. McKone, S. M. McKinnell, B. M. Leaman and V. Haist (eds). 1993. Pacific Stock Assessment Review Committee (PSARC) Annual Report for 1992. Can. MS Rep. Fish. Aquat. Sci. 2196: 199 p.

Campbell, A., C. M. Hand, C. Paltiel, K.N. Rajwani & C.J. Schwarz. 1998. Evaluation of some survey methods for geoducks, pp. 5-42. In: G.E. Gillespie & L.C. Walthers [eds.] Invertebrate Working Papers reviewed by the Pacific Stock Assessment Reviesw Committee (PSARC) in 1996. *Can. Tech. Rep. Fish. Aquat. Sci*. 2221.

Campbell, A. & M.D. Ming. 2003. Maturity and growth of the Pacific geoduck, *Panopea abrupta*, in southern British Columbia, Canada. *J. Shellfish Res*. 22: 85-90.

Campbell, A., C. W. Yeung, G. Dovey & Z. Zhang. 2004. Population biology of the Pacific geoduck clam, *Panopea abrupta*, in experimental plots, southern British Columbia, Canada. *J. Shellfish Res.* 23: 661-673.

Clark, W.G. 1993. The effect of recruitment variability on the choice of target level of spawning biomass per percruit. pp. 233-246. In: G. Kruse, D.M. Eggers, R.J. Marasco, C. Pautzke, & T.J. Quinn II (eds.). Proceedings of the International Symposium on Managmenet Strategies for Exploited Fish Populations. Alaska Sea Grant College Program Report No. 93-02, University of Alaska, Fairbanks.

Coan, E.V., P.H. Scott, and F.R. Bernard. 2000. Bivalve seashells of western North America. Santa Barbara: Santa Barbara Museum of Natural History Publication. 566p.

Goodwin, C.L. 1990. Commercial geoduck dive fishery. pp. 24-31. In: J.W. Armstrong & A. E. Copping (eds). Proceedings of a Forum on Puget Sound's Biological Resources – Status and Management, Seattle, Wash..

Goodwin, C. L. & W. Shaul. 1984. Age, recruitment and growth of the geoduck clam (*Panope generosa*, Gould) in Puget Sound, Washington. *State Wash. Dep. Fish. Progr. Rep*. 215. 30 pp.

Goodwin, C. L., W. Shaul & C. Budd. 1979. Larval development of the geoduck clam (*Panope generosa* Gould). *Proc. Nat. Shellfish Assoc*. 69: 73-76.

Hand C.M. & D. Bureau. Quota options for the geoduck clam (*Panopea abrupta*) fishery in British Columbia for 2001 and 2002. Can. Stock Assessment Secretariat Research Document 2000/163: 53p.

Harbo, R. M., B. E. Adkins, P. A. Breen & K. L. Hobbs. 1983. Age and size in market samples of geoduck clams (*Panope generosa*). *Can. MS Rep. Fish. Aquat. Sci.* 1714. 77 pp.

Heizer, S. 2000. The commercial geoduck (*Panopea abrupta*) fishery in British Columbia, Canada – an operational perspective of a limited entry fishery with individual quotas, pp. 226-233. In: R. Shotton (ed). Use of property rights in fisheries management. Proceedings of the FishRights99 Conference, Freemantle, Western Australia, 11-19 November 1999. FAO Fish. Tech. Rap. No. 404/2

Hoffman, A., A. Bradbury & D.L. Goodwin. 2000. Modeling geoduck, *Panopea abrupta*, (Conrad, 1849) population dynamics. I. Growth. *J. Shellfish Res*. 19: 57-62.

King, J.J. 1986. Juvenile feeding ontogeny of the geoduck, *Panope abrupta* (Bivalvia: Saxicavacea), and comparative ontogeny and evolution of feeding in bivalves. M.Sc. thesis, University of Victoria, Victoria, B.C. pp. 281.

Mace, P.M. 1994. Relationships between common biological reference points used as thresholds and targets of fisheries management strategies. Can. J. Fish. Aquat. Sci. 51:110-122.

Maunder, M.N. & R.B. Driso. 2003. Estimation of recruitment in catch-at-age models. *Can. J. Fish. Aquat. Sci*. 60: 1204-1216.

Noakes, D. J. & A. Campbell. 1992. Use of geoduck clams to indicate changes in the marine environment of Ladysmith Harbour, British Columbia. *Environmetrics*, 3: 81-97.

Orensanz, J.M., C.M. Hand, A.M. Parma, J. Valero & R. Hilborn. 2004. Precaution in the harvest of Methuselah's clams — the difficulty of getting timely feedback from slow-paced dynamics. *Can. J. Fish. Aquat. Sci*. 61: 1355-1372.

Shaul, W. & L. Goodwin. 1982. Geoduck (*Panope generosa*: Bivalvia) age as determined by internal growth lines in the shell. *Can. J. Fish. Aquat. Sci.* 39: 632-636.

Sloan, N. A. & S. M. Robinson. 1984. Age and gonad development in the geoduck clam *Panope abrupta* (Gould) from southern British Columbia. *J. Shellfish Res*. 4: 131-137.

Thompson, S.K. 1987. Sample size for estimating multinomial proportions. The American Statistican. 41: 42-46.

Thompson, S.K. 1992. Sampling. John Wiley and Sons.

Valero J. L., C. Hand, J. M. Orensanz, A. M. Parma, D. Armstrong, R. Hilborn. 2004 Geoduck recruitment in the Pacific Northwest. Cal. COFI Rep. Vol. 45.

Zhang, Z. & A. Campbell. 2004. Natural mortality and recruitment rates of the Pacific geoduck clam, *Panopea abrupta*, in experimental plots. *J. Shellfish Res*. 23: 675-682.

Appendix I

PSARC INVERTEBRATE SUBCOMMITTEE
Request for Working Paper

Date Submitted: **May, 2005**

Individual or group requesting advice:

- Geoduck managers (R. Harbo, J. Rogers, E. Wylie, J. Toole)- Resource Management; in support of requests from the Underwater Harvester's Association

Proposed PSARC Presentation Date: November 2005

Subject of Paper (title if developed): Determination of geoduck harvest rates using age-structured projection modelling

Science Lead Authors: Zane Zhang, Claudia Hand

Resource Management Lead Author: R. Harbo / J. Rogers

Rationale for request:

- The current assessment framework calculates virgin biomass in each bed by adding cumulative bed landings to estimates of current biomass from survey data, and assuming that recruitment and natural mortality rates are equal. Estimates of density are extrapolated to un-surveyed beds using a proximity-similarity rule. A fixed harvest rate of 1% is applied coastwide to a range of virgin biomass estimates. Back-calculating virgin density after 30 years of the fishery is becoming untenable: the fishery is now largely targeting recruits. The accuracy of current biomass estimates is expected to be greater than the accuracy of virgin biomass estimates.
- The current management/assessment frameworks use a limit reference limit point of 50% of the estimated virgin biomass, which is assumed to be the time at which 50-years worth of quota, at 1% of Bv, have been harvested. Many beds have been closed under this limit and this has contributed to quota reductions. Currently there is no clear strategy on how and when to re-open beds and how to set new quotas.
- Harvesters feel that the north coast stocks are being underutilized, but agree that the stocks have declined on the west coast of Vancouver Island (WCVI) and in many Inside areas. This is likely a result of a combination of prior overestimation of stocks. On the WCVI, and in the Central coast, Bcurrent is more meaningful than original biomass, with the increased predation by sea otters.

Objectives of Working Paper:

1. Provide recommendations for changes to the management of geoduck beds based on results of simulation modelling using survey information and biological samples to date. Provide recommendations for the selection within a range of quotas options available, including variable harvest rates applied to estimates of *current biomass*. Determine appropriate bed groupings (e.g. geographical, beds of similar recruitment history, or bed categories) which

could share the same harvest rate.

2. Evaluate current limit reference point (50% virgin biomass) and recommend new alternate reference points for current biomass, relative to estimates of virgin biomass, if appropriate. Recommend a strategy for re-opening geoduck beds that close after they fall under the new limit reference point.

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

1. What are historic recruitment patterns in sampled geoduck populations and is there a stronger relationship with geographical area or with habitat features? How should data be pooled in the modelling exercises and at what scale are the stock units to be assessed and modelled; i.e. polygons, beds, and metapopulations?
2. How should data be pooled from surveys and biological samples (currently 42 beds) in the modelling exercises?
3. How do estimates of virgin biomass compare between back-calculated (B0=BS+BR), survey estimates and reconstructed from simulation modelling, for surveyed beds. (e.g. Rolling Roadstead).
4. How are the model results best expressed, as changing biomass or density? Presentations of both are requested.
5. What is the *accuracy* of the model predictions? Do the survey results over time match the model density and biomass predictions?
6. What is the *precision*, i.e. variation in age structure from site to site within a geographical area and from samples collected at the same site over time? Should collection protocols (location, sample size) be modified to improve this data source? Is there potential for index sites that may represent recruitment patterns in a larger geographical area or is each site very unique
7. What is the impact of sea otters on current biomass? Should survey sites and samples from areas impacted by otters be pooled with sites without otters? This issue should be at least acknowledged, and there should be some discussion about the dramatic change in natural mortality in areas occupied by sea otters. Should these areas be isolated with unique calculations of Bcurrent and exploitation?
8. How often will *Bcurrent estimates* for beds be updated? How will landings be treated in the update (will the model be run annually to revise estimates based on the fishery landings?) The model will predict biomass for a number of years (How many?) after the survey. How long are current biomass estimates from surveyed beds valid? It has been suggested that beds with surveys older than 5 years will be treated as non-surveyed.
9. How often should the parameters of the model be updated (e.g. Exploitation rate)? As new data becomes available each year, will *exploitation rates* be revised for quota calculations? It has been suggested that exploitation rates be fixed for a period of time, and then evaluated.
10. A discussion and recommendations for target and limit reference points._Do we want to maintain populations at or above the current threshold of 50% virgin biomass or a new threshold (e.g. 50% target reference point and 40% limit reference point.) If a bed falls below the limit reference point, would it have to recover above the target ref. point of 50%, before fishing would recommence?
11. A discussion of risks of using different percentiles for setting exploitation rates. Given the variability in the exploitation rates, what are the risks of a declining population from choosing a given rate? For example, should managers use the 10 percentile, where there is a 90%

chance that the biomass will be 50% or greater after 50 years of harvest?

12. What criteria are important to evaluate if the model is working? Survey intensity (# of transects) may have to be increased or vary by bed, according to the bed category and/or the expected geoduck density, to detect the small changes (3 to 6%) expected over a relatively short period of time. Is it appropriate to use changes in the mean densities as an index, knowing that the changes are not be statistically significant?
13. The new proposed framework will result in a greater range of quota options and require managers to develop new decision rules for assigning bed quotas. What are recommendations for choosing within the wide range of quota options that result from incorporating the full range of data uncertainty in model results? Development of quota options. A discussion of the following frameworks would be useful:
    i.) Use a *fixed exploitation rate* for beds in a geographical area/ bed category grouping and a range of biomass estimates (lower 95%CI up to the mean biomass estimate) for surveyed beds. Should the mean biomass estimate be a limit reference point? A discussion/ decision rules need to be developed for extrapolation of Bcurrent to unsurveyed beds. This could follow the same process of extrapolating Bvirgin for unsurveyed beds.
    ii.) Use a *fixed Bcurrent estimate* (mean biomass for surveyed beds) and have a range of quota options based on different exploitation rates. Unsurveyed beds could be treated in the current manner -1% of Bvirgin or decision rules developed for the best estimate of biomass and the options calculated from different exploitation rates.
14. Discuss the general implications of longer rotational periods on the geoduck fishery

Timing issues related to when Advice is necessary:

- The results of the paper will not be available for the 2006 fishery. However, some initial pilots have been initiated at the Mission Group and Goletas Channel and are proposed for 2006 at Marina Island, Houston-Stuart Channel, QCI and possibly a surveyed site in Clayoquot. Precautionary exploitation rates, from preliminary modelling, are proposed for a number of possible pilots in 2006: Inside Waters use 2%of Bcurrent (Marina I., Comox Bar), WCVI use 1.2% - 2.8%(Mission Group, Forward Harbour, Elbow Bank, Diplock-Chain Islands), and QCI use 1.6% Bcurrent (Houston-Stewart)

Approval as appropriate:

Head, Shellfish & Marine Mammals Assessment	Date
Regional Resource Manager – Invertebrates	Date

Table 1. Information on fishery-independent surveys.

Geographic Region	Survey Location	Fishery Starting Year	Survey and Sampling Year	Number of Beds	Biological Sample Size
CC	Anderson/Laredo	1987	1997	10	293
CC	Goose/Wurtele/Seaforth	1981	1995	9	460
CC	Hakai Passage	1982	1998	14	292
CC	Kitasu Bay[2]	1989	1994	5	434
CC	Price Island	1987	1993	3	455
CC	S Bardswell/Prince Group	1985	1996	11	427
CC	West Higgins Pass[2]	1985	1994	2	474
CC	Duncan Island	1984	1995	13	468
CC	Goletas Channel, 1994[2]	1984	1994	5	447
CC	Goletas Channel, 2003	1984	2003	8	459
NC	Dundas Island	1986	1998	6	306
NC	Moore Islands	1996	1998	4	290
NC	Otter Pass	1981	1996	6	427
NC	Principe Channel	1996	1997	7	298
NC	West Aristazabal Island	1983	1996	15	395
QCI	Burnaby Island	1984	1994	7	431
QCI	Cumshewa Inlet	1980	1997	7	480
QCI	Gowgaia Bay[2]	1985	1999	8	270
QCI	Hippa Island[2]	1986	1999	6	432
QCI	Hotspring Island	1986	1995	10	385
QCI	Houston Stewart Ch.	1985	1996	14	453
QCI	Parry Passage	1987	2002	1	440
QCI	Selwyn/Dana/Logan Inlets	1988	1998	18	321
QCI	Tasu Sound[2]	2000	2001	12	446
GB	Boatswain Bank	1980	2001	1	536
GB	Comox Bar, 1993	1978	1993	1	440
GB	Comox Bar, 1998	1978	1998	1	289
GB	Marina Island	1978	2002	2	304
GB	Oyster River	1978	1996	1	466
GB	Round Island	1979	2000	1	322
GB	Thormanby Island	1978	1999	2	283
WCVI	Barkley Sound	1979	2000	9	301
WCVI	Elbow Bank	1978	1994	1	405
WCVI	Millar Channel	1979	1997	1	277
WCVI	Mission Group, 1998	1980	1998	5	304
WCVI	Mission Group, 2003[3]	1980	2003	7	456
WCVI	NE Barkley Sound	1982	2002	8	501
WCVI	Nootka Sound[3]	1985	2000	7	311
WCVI	Rolling Roadstead[2,3]	1980	2001	1	418
WCVI	Winter Harbour, 1996	1983	1996	10	580
WCVI	Winter Harbour, 2002[3]	1983	2002	6	495
WCVI	Yellow Bank	1980	1997	1	186

[1]Central Coast (CC), North Coast (NC), Queen Charlotte Island (QCI), Georgia Basin (GB), West Coast of Vancouver Island (WCVI).
[2] Biological sampling was completed one year after the transect survey, for logistical reasons.
[3] Survey locations where geoduck populations have been impacted by sea otters.

Table 2. Virgin densities used to approximate three levels of productivity.

	Productivity		
	Low	Intermediate	High
Virgin Density (D)	$D < 1.15/m^2$	$1.15/m^2 <= D < 1.7/m^2$	$D >= 1.7/m^2$
Number of Locations	13	14	15

Table 3. Percentage of reported comments on sea otter holes and on presence of sea otter in the four surveyed locations of west coast of Vancouver Island which have been affected by sea otter predations.

		Sea Otter Holes						Sea Otters		
Survey Location	Number of Reports	NA[1]	Too Many*	Many	Few	Present	Absent	NA[2]	Present	Absent
Winter Harbour	57	87.7%		7.0%	3.5%	1.8%		91.2%	5.3%	3.5%
Rolling Roadstead	23	78.3%		13.0%	8.7%			100.0%		
Mission Group	29	51.7%	6.9%	31.0%	3.4%	3.4%	3.4%	65.5%	34.5%	
Nootka Sound	16	50.0%	12.5%	18.8%	12.5%	6.3%		93.8%	6.3%	

NA[1] -- Comments not related to sea otter holes.
NA[2] -- Comments not related to presence or absence of sea otter.
* -- Too many sea otter holes to conduct geoduck harvesting.

Table 4. Comparison of back-calculated virgin geoduck densities (number/m^2) by the conventional method and by age-structured modelling, ratio of estimated current to virgin biomass and accumulated landings (thousands of animals) prior to the survey.

Area[1]	Location	Density from Conventional Method	Density from Age-structured Modelling		Bc/Bv[2]	Landings ('000's)
			M = 0.016	M = 0.036		
CC	Anderson/Laredo	1.51	1.32	1.62	0.92	219.1
CC	Goose/Wurtele/Seaforth	1.75	1.94	2.53	0.58	637.8
CC	Hakai Passage	1.64	1.48	1.96	0.63	597.6
CC	Kitasu Bay	2.43	2.48	2.80	0.93	1.2
CC	Price Island	1.19	1.16	1.31	0.67	230.3
CC	S Bardswell/Prince Group	2.36	2.69	3.37	0.73	195.1
CC	West Higgins Pass	3.32	3.56	4.08	0.48	146.9
CC	Duncan Island	1.31	1.25	1.50	0.56	430.6
CC	Goletas Channel, 1994	1.58	1.57	1.82	0.52	682.5
CC	Goletas Channel, 2003	1.64	1.18	1.47	0.65	933.8
NC	Dundas Island	1.85	1.99	2.53	0.72	319.1
NC	Moore Islands	4.97	5.19	5.51	0.94	12.1
NC	Otter Pass	1.89	1.30	1.69	0.85	279.8
NC	Principe Channel	2.26	2.33	2.42	0.95	13.3
NC	West Aristazabal Island	1.83	2.07	2.69	0.61	531.7
QCI	Burnaby Island	1.58	1.77	2.16	0.64	350.3
QCI	Cumshewa Inlet	0.65	0.52	0.72	0.88	323.9
QCI	Gowgaia Bay	0.72	0.76	1.01	0.73	38.7
QCI	Hippa Island	3.25	3.66	4.73	0.69	341.2
QCI	Hotspring Island	1.64	1.39	1.68	0.89	138.4
QCI	Houston Stewart Channel	1.70	1.76	2.16	0.65	877.1
QCI	Parry Passage	0.73	0.82	1.03	0.50	145.1
QCI	Selwyn/Dana/Logan Inlets	1.35	1.59	1.96	0.74	71.9
QCI	Tasu Sound	1.24	1.27	1.31	0.86	34.0
GB	Boatswain Bank	1.19	0.82	1.23	0.95	416.6
GB	Comox Bar, 1993	0.37	0.23	0.30	0.87	857.0
GB	Comox Bar, 1998	0.44	0.26	0.35	0.91	973.4
GB	Marina Island	0.95	0.48	0.57	0.60	792.7
GB	Oyster River	0.11	0.09	0.13	0.78	220.1
GB	Round Island	1.12	0.84	0.96	0.36	107.7
GB	Thormanby Island	0.52	0.62	0.96	0.65	950.5
WCVI	Barkley Sound	1.18	1.17	1.59	0.50	864.8
WCVI	Elbow Bank	1.46	1.37	1.66	0.31	869.3
WCVI	Millar Channel	2.00	1.88	2.65	0.76	948.6
WCVI	Mission Group, 1998	2. 21	1.63	1.96	0.51	2,344.6
WCVI	Mission Group, 2003	1.71	0.97	1.11	0.52	2,465.0
WCVI	NE Barkley Sound	1.04	1.21	1.65	0.41	556.3
WCVI	Nootka Sound	1.05	1.01	1.23	0.45	316.3
WCVI	Rolling Roadstead	1.19	0.93	1.04	0.23	1,800.0
WCVI	Winter Harbour, 1996	0.86	0.84	1.04	0.53	1,111.7
WCVI	Winter Harbour, 2002	1.11	0.89	1.13	0.52	1,043.2
WCVI	Yellow Bank	2.18	1.90	2.55	0.72	736.9

[1]Central Coast including Area 12 (CC), North Coast (NC), Georgia Basin (GB), Queen Charlotte Island (QCI), West Coast of Vancouver Island (WCVI)

[2] Average over the two natural mortality rates (0.016, 0.036).

Table 5. Exploitation rates to maintain stock biomass above one-half of the virgin biomass level at the end of 50 years for the five geographic areas: North Coast (NC), Central Coast (CC), West Coast of Vancouver Island (WCVI), Queen Charlotte Island (QCI) and Georgia Basin (GB).

Natural	Beginning year of		Geographic Area					
Mortality Rate	recruitment simulation	Percentile	NC	CC	WCVI	WCVI*	QCI	GB
0.036	1960	10th	0.0%	0.0%	1.1%	1.2%	0.0%	2.0%
	1960	50th	0.0%	0.3%	1.7%	1.9%	0.2%	2.7%
	1940	10th	1.7%	3.0%	2.2%	2.0%	2.0%	2.4%
	1940	50th	2.5%	3.6%	3.0%	3.0%	2.6%	3.3%
0.016	1960	10th	1.1%	1.8%	2.8%	2.8%	1.6%	4.0%
	1960	50th	1.3%	2.0%	3.3%	3.5%	1.8%	4.0%
	1940	10th	2.0%	3.0%	2.9%	2.9%	2.4%	3.7%
	1940	50th	2.4%	3.3%	3.4%	3.6%	2.7%	4.0%

* Only include the surveyed locations with absence of sea otter.

Table 6. Exploitation rates to maintain geoduck density above one-half of the virgin density at the end of 50 years for the five geographic areas: North Coast (NC), Central Coast (CC), Queen Charlotte Island (QCI), West Coast of Vancouver Island (WCVI) and Georgia Basin (GB).

Natural Mortality Rate	Beginning year of recruitment simulation	Percentile	Geographic Area NC	CC	WCVI	QCI	GB
0.036	1960	10th	0.0%	0.0%	0.9%	0.0%	1.7%
	1960	50th	0.0%	0.3%	1.4%	0.2%	2.4%
	1940	10th	1.9%	3.2%	2.1%	2.1%	2.2%
	1940	50th	2.7%	3.9%	2.9%	2.7%	3.1%
0.016	1960	10th	1.1%	1.8%	2.6%	1.6%	3.8%
	1960	50th	1.4%	2.0%	3.0%	1.8%	4.0%
	1940	10th	2.0%	3.0%	2.8%	2.3%	3.5%
	1940	50th	2.5%	3.4%	3.3%	2.7%	4.0%

Table 7. Exploitation rates to maintain stock biomass above one-half of the virgin biomass level at the end of 50 years for geoduck beds with three virgin density levels.

			Virgin Density		
Natural mortality rate	Beginning year of recruitment simulation	Percentile	Low $D<1.15/m^2$	Intermediate $1.15/m^2<=D<1.7/m^2$	High $D>=1.7/m^2$
0.036	1960	10th	1.0%	0.4%	0.4%
	1960	50th	1.4%	0.8%	0.7%
	1940	10th	2.3%	2.7%	2.3%
	1940	50th	2.9%	3.3%	2.8%
0.016	1960	10th	2.9%	2.1%	2.0%
	1960	50th	3.3%	2.3%	2.3%
	1940	10th	3.1%	2.9%	2.7%
	1940	50th	3.5%	3.2%	3.0%

Table 8. Annual instantaneous rates of sea otter predation on geoduck during 1998-2003 in Mission Group, west coast of Vancouver Island.

Simulation Scheme	Y40M0.016	Y40M0.036	Y60M0.016	Y60M0.036
Mean	0.15	0.17	0.15	0.17
Standard Deviation	0.10	0.13	0.09	0.12

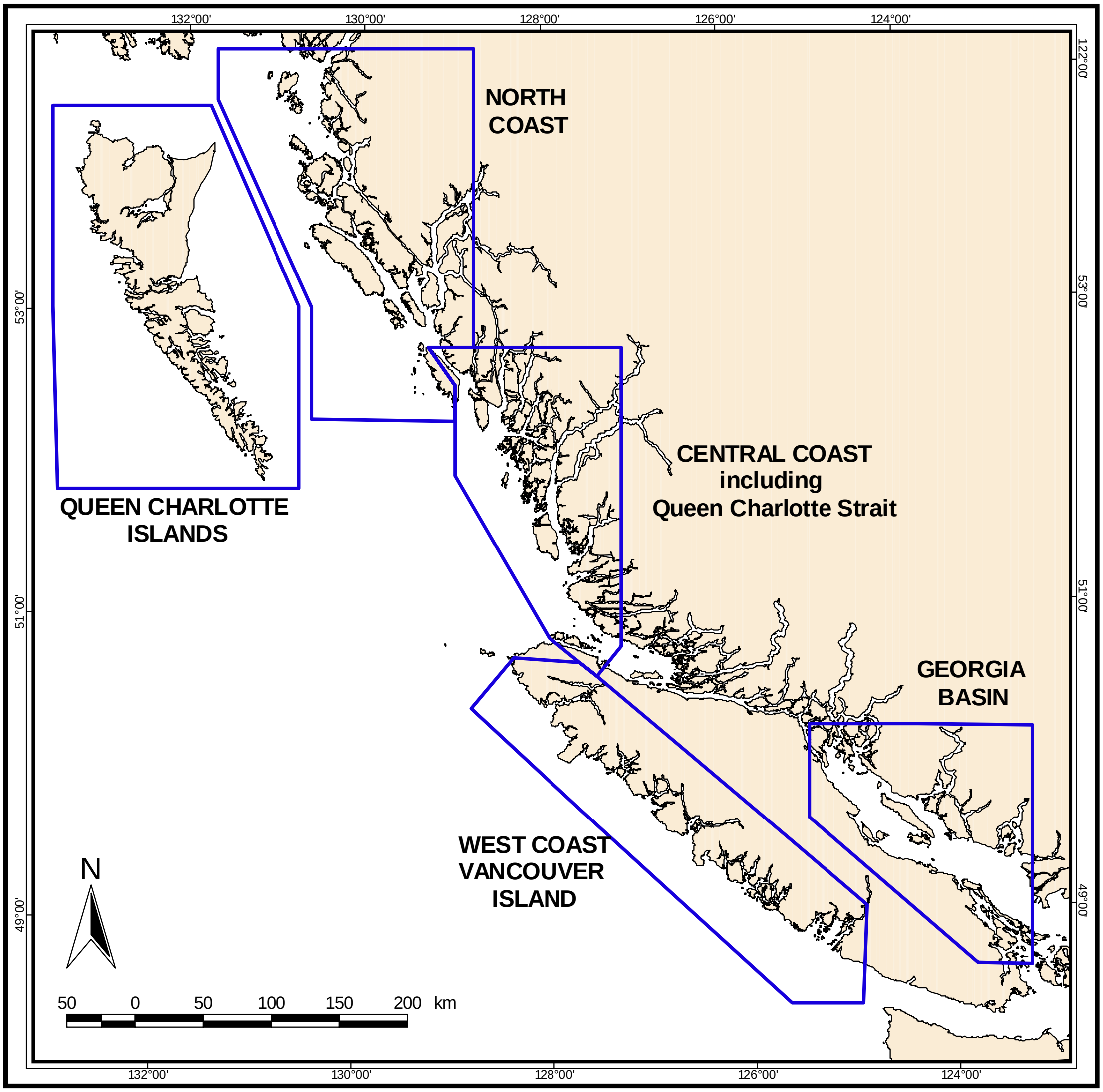

Fig. 1. British Columbia coast showing the five geographic areas.

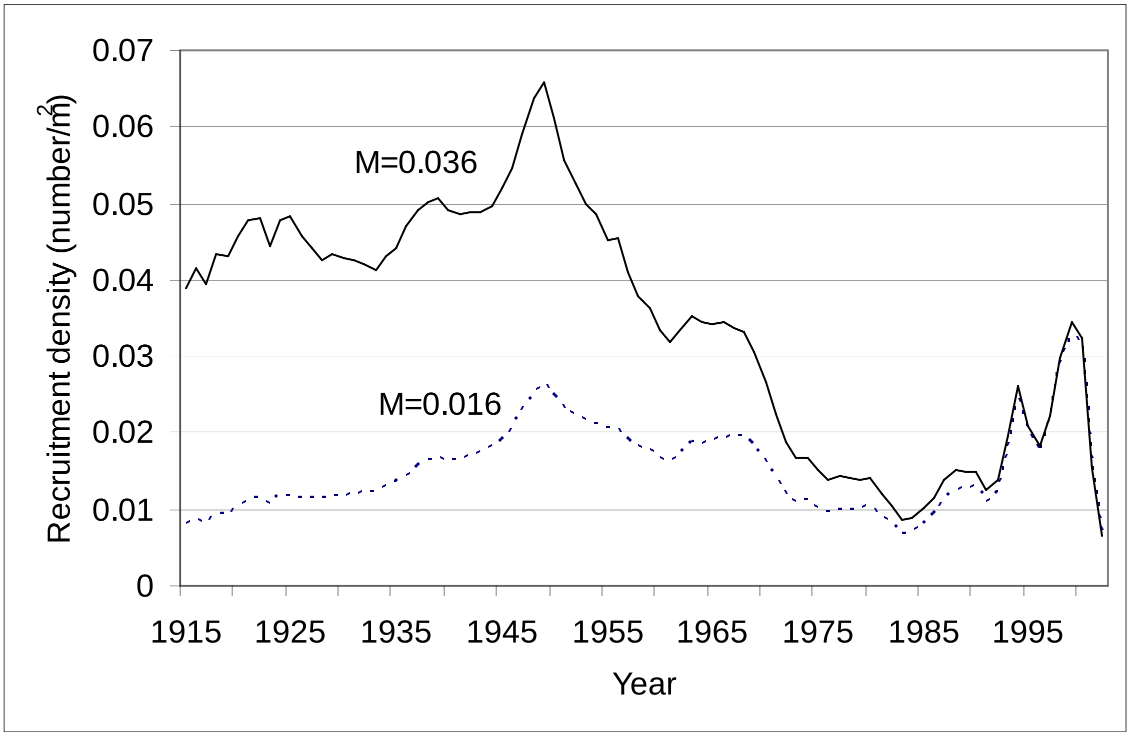

Fig. 2. Estimated mean recruitment rates for the entire BC coast.

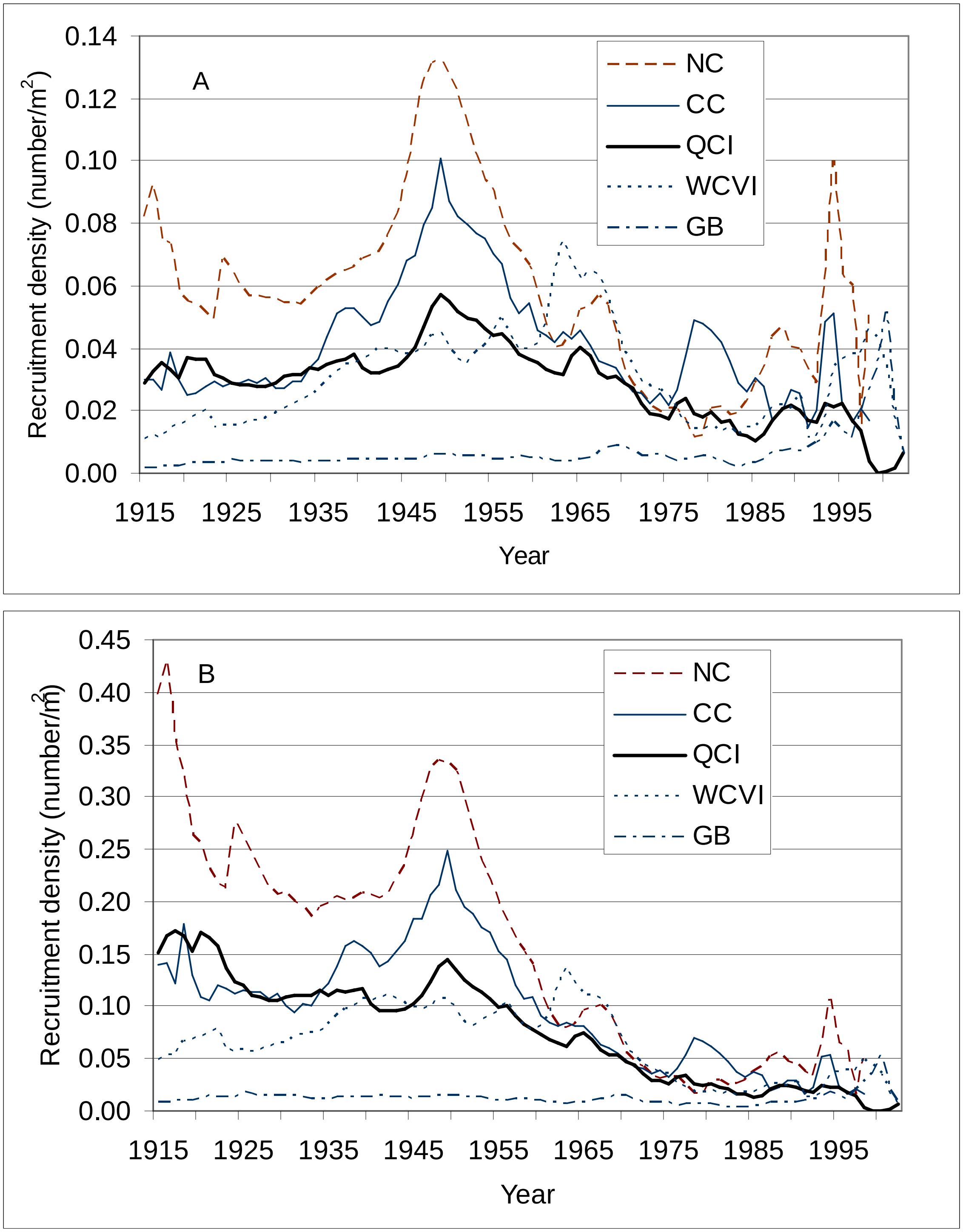

Fig. 3. Estimated mean historic recruitment rates for the five geographic areas: North Coast (NC), Central Coast (CC), Queen Charlotte Island (QCI), West Coast of Vancouver Island (WCVI), and Georgia Basin (GB). A: M=0.016, B: M = 0.036.

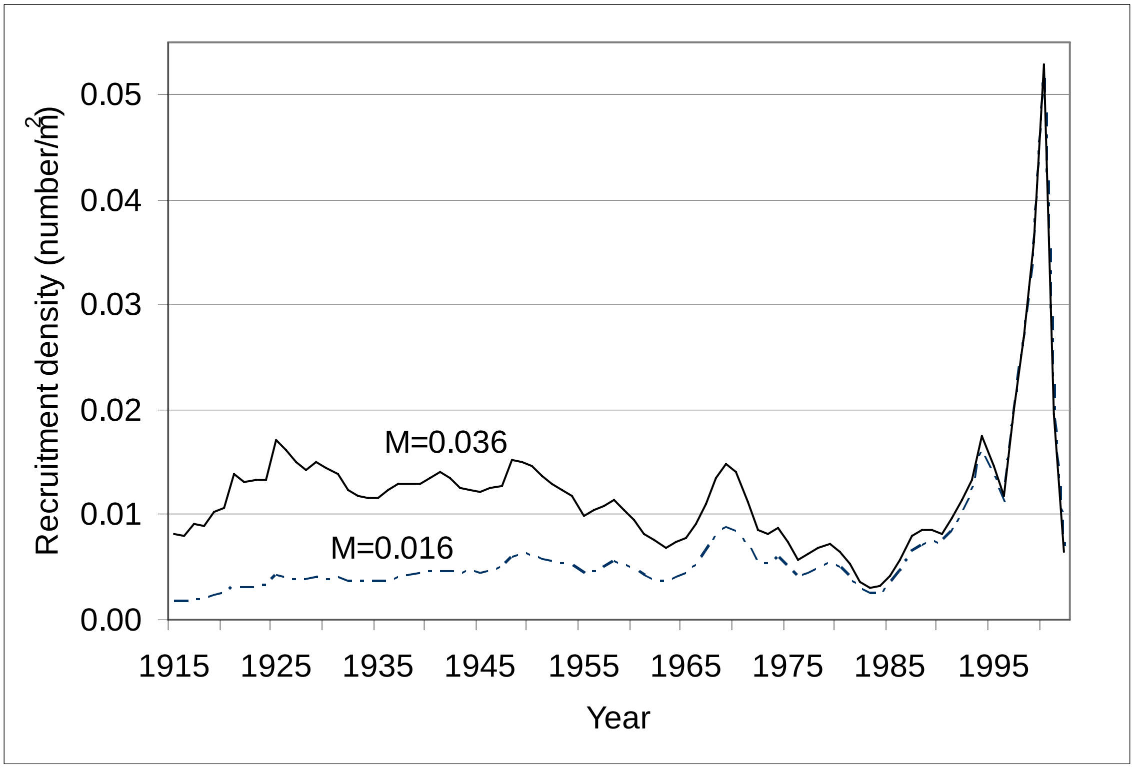

Fig. 4. Estimated mean historic recruitment rates for the Georgia Basin.

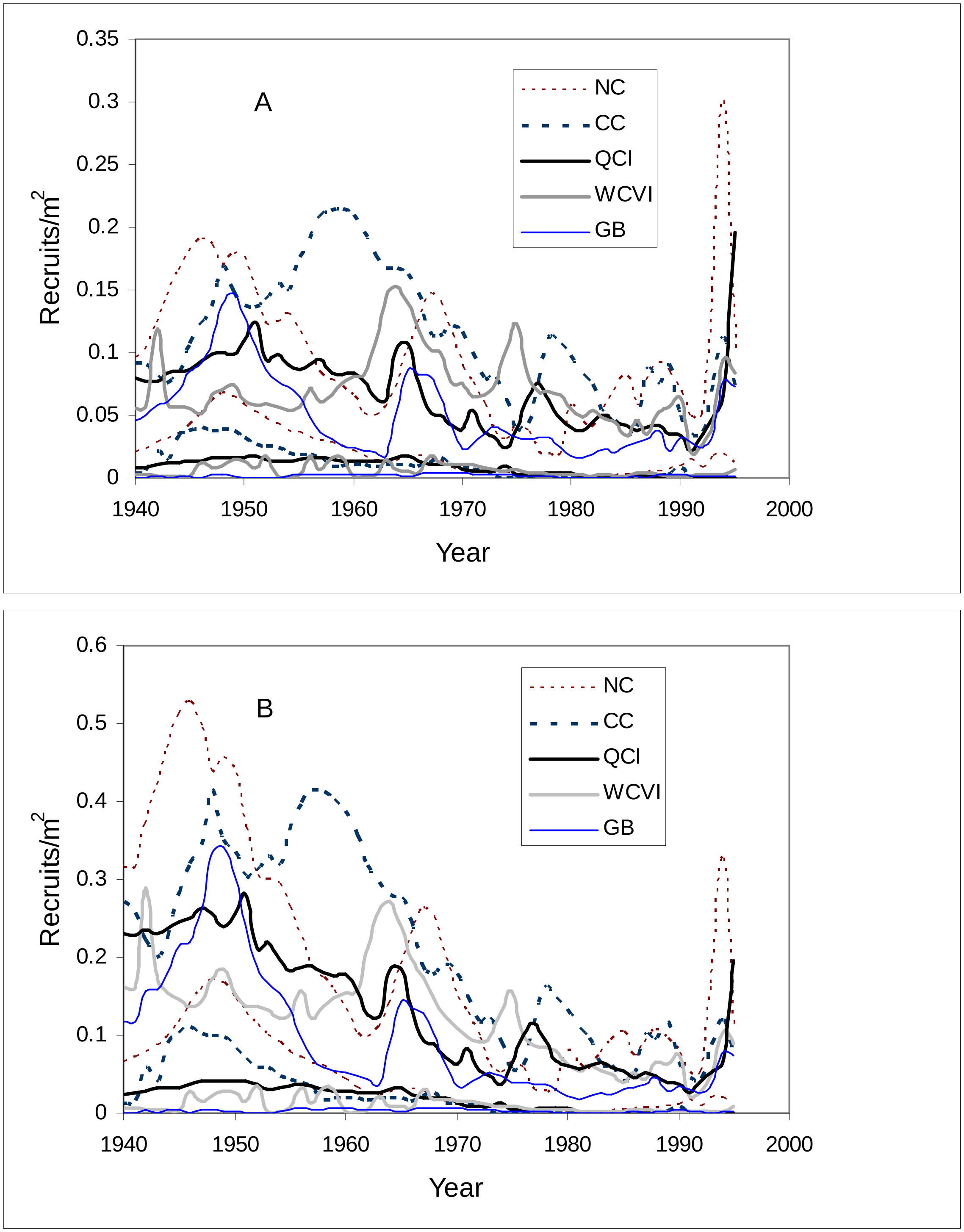

Fig. 5. Comparisons of estimated ranges of mean historical recruitment rates for individual locations in the five geographic areas. (A: $M = 0.016$; B: $M = 0.036$).

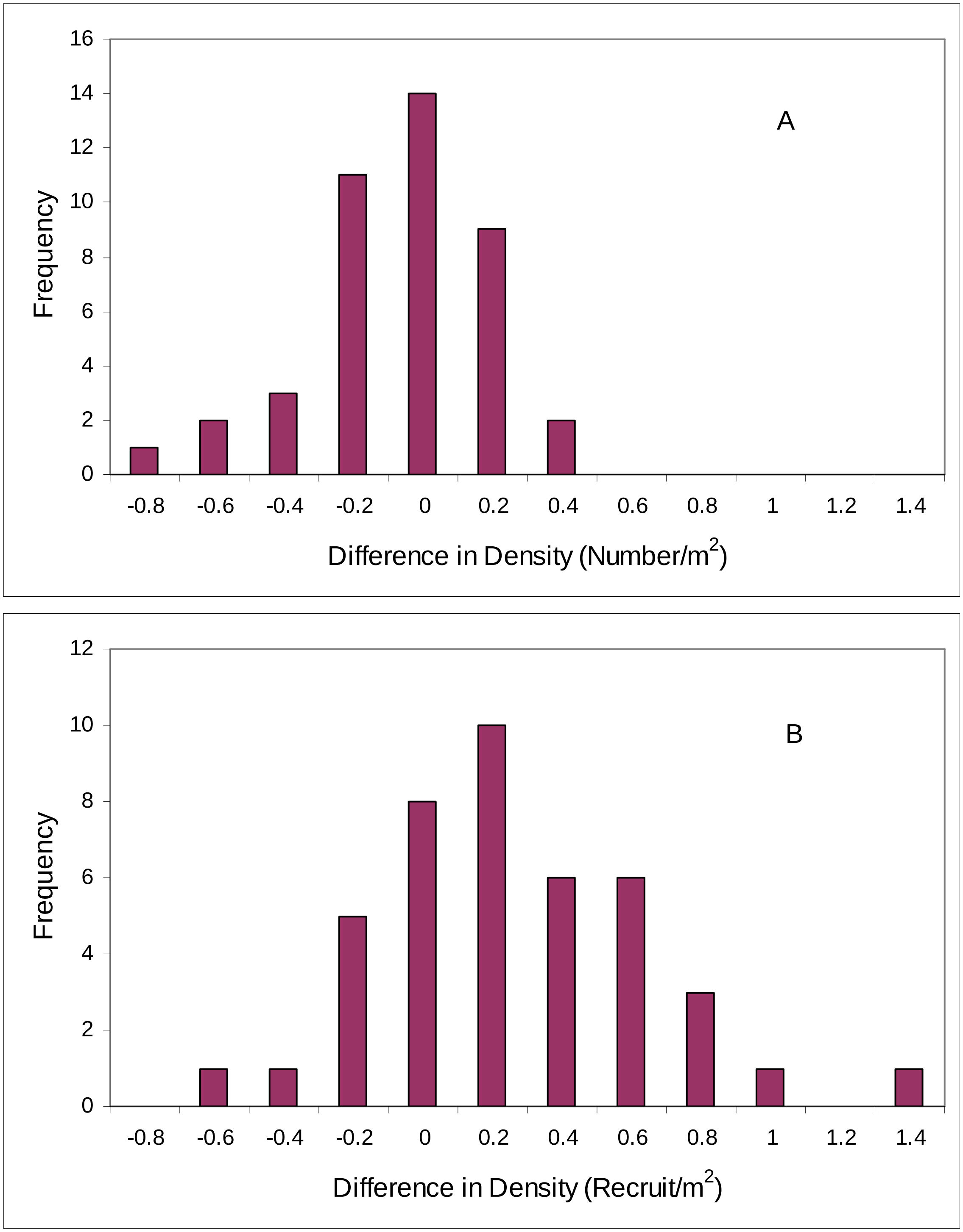

Fig. 6. Differences in virgin geoduck densities estimated by the age-structured model and the conventional method. (A: M = 0.016; B: M = 0.036).

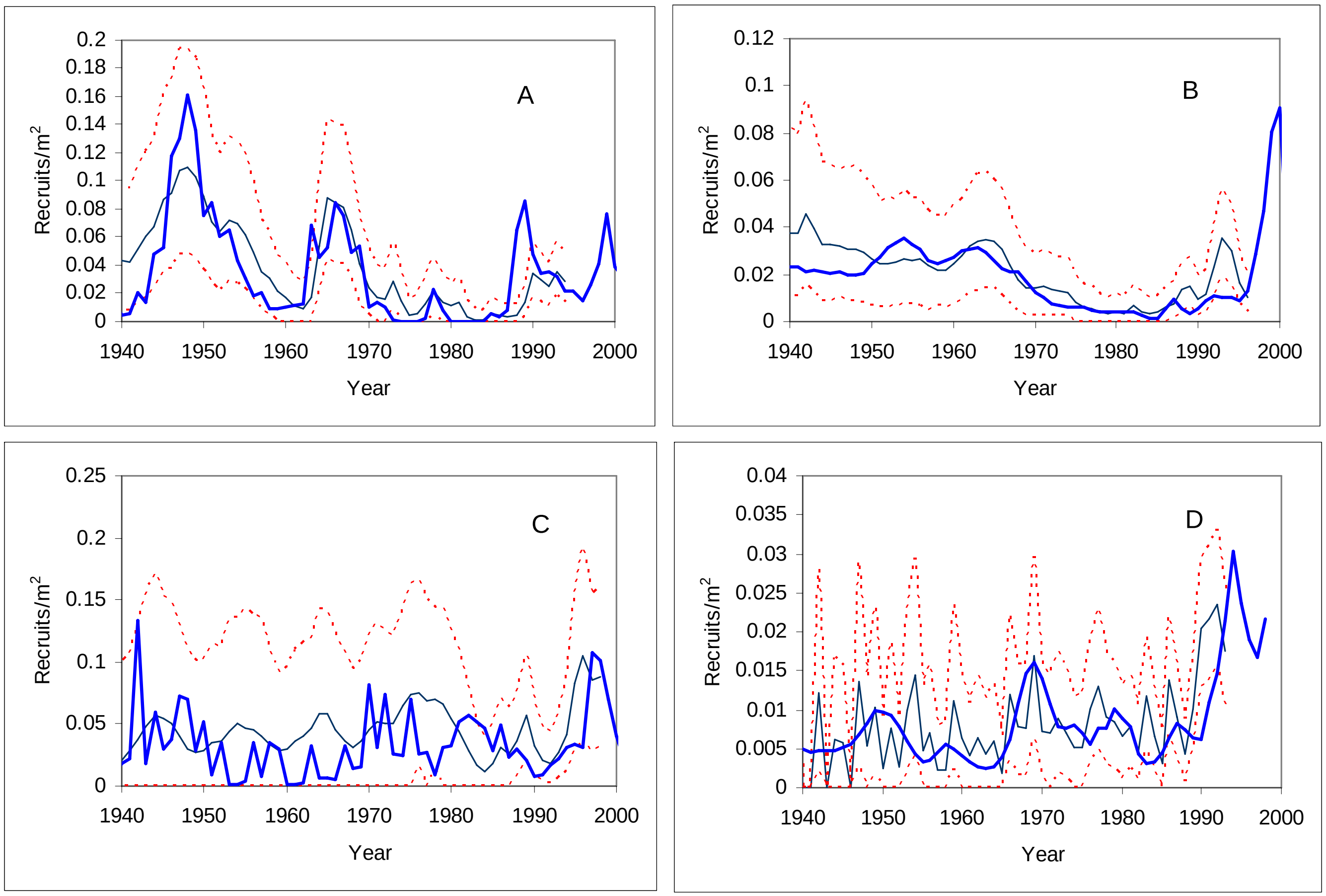

Fig. 7. Comparison of recruitments estimated from two surveys in different years (*M* = 0.016). The solid line represents the mean estimated based on the 1st survey, and the broken lines denote the 95% confidence limits. The bold line represents the mean estimated based on the 2nd survey. (A - Goletas Channel; B - Winter Harbour; C - Mission Group; D - Comox)

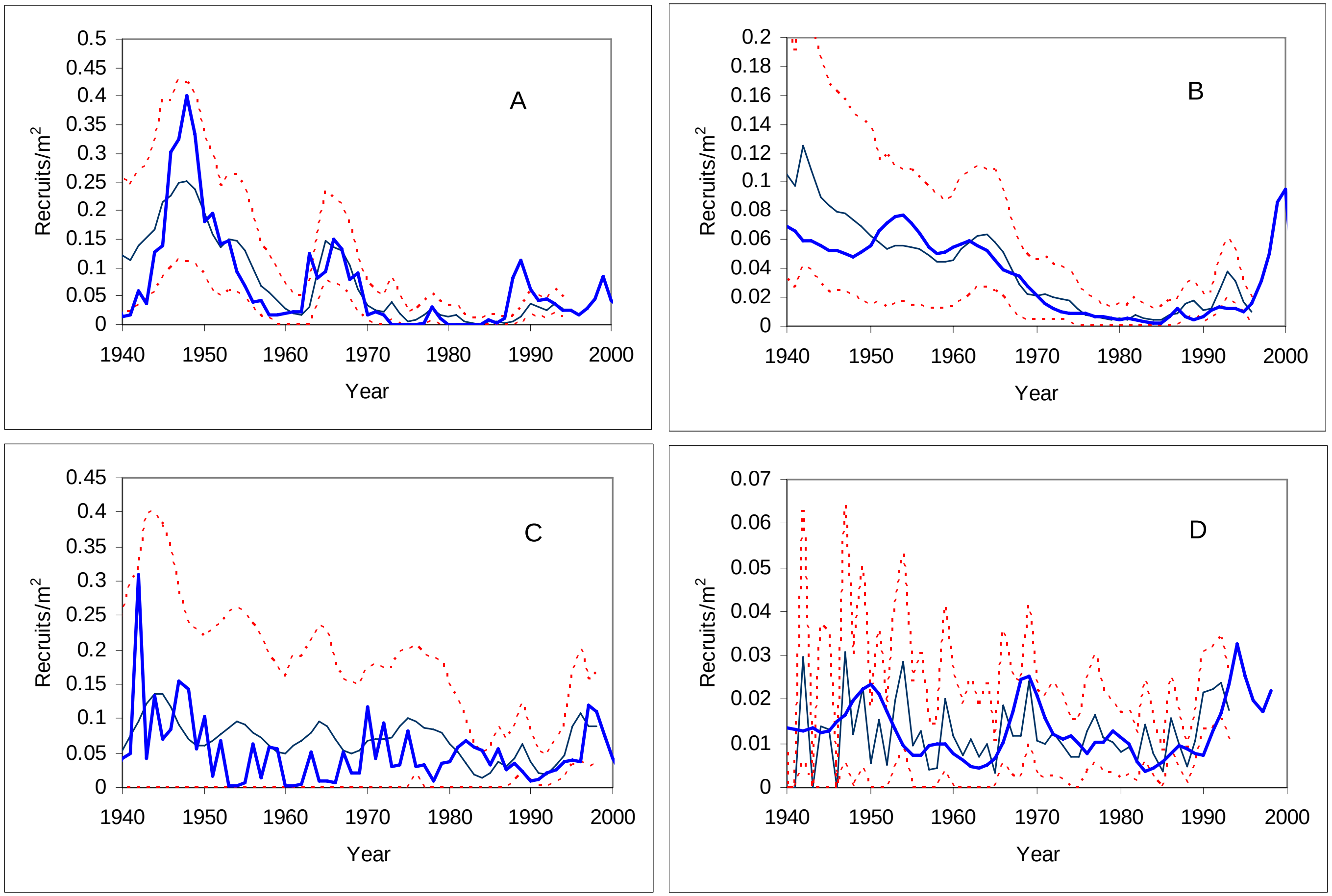

Fig. 8. Comparison of recruitments estimated from two surveys in different years (M = 0.036). The solid line represents the mean estimated based on the 1st survey, and the broken lines denote the 95% confidence limits. The bold line represents the mean estimated based on the 2nd survey. (A - Goletas Channel; B - Winter Harbour; C - Mission Group; D - Comox)

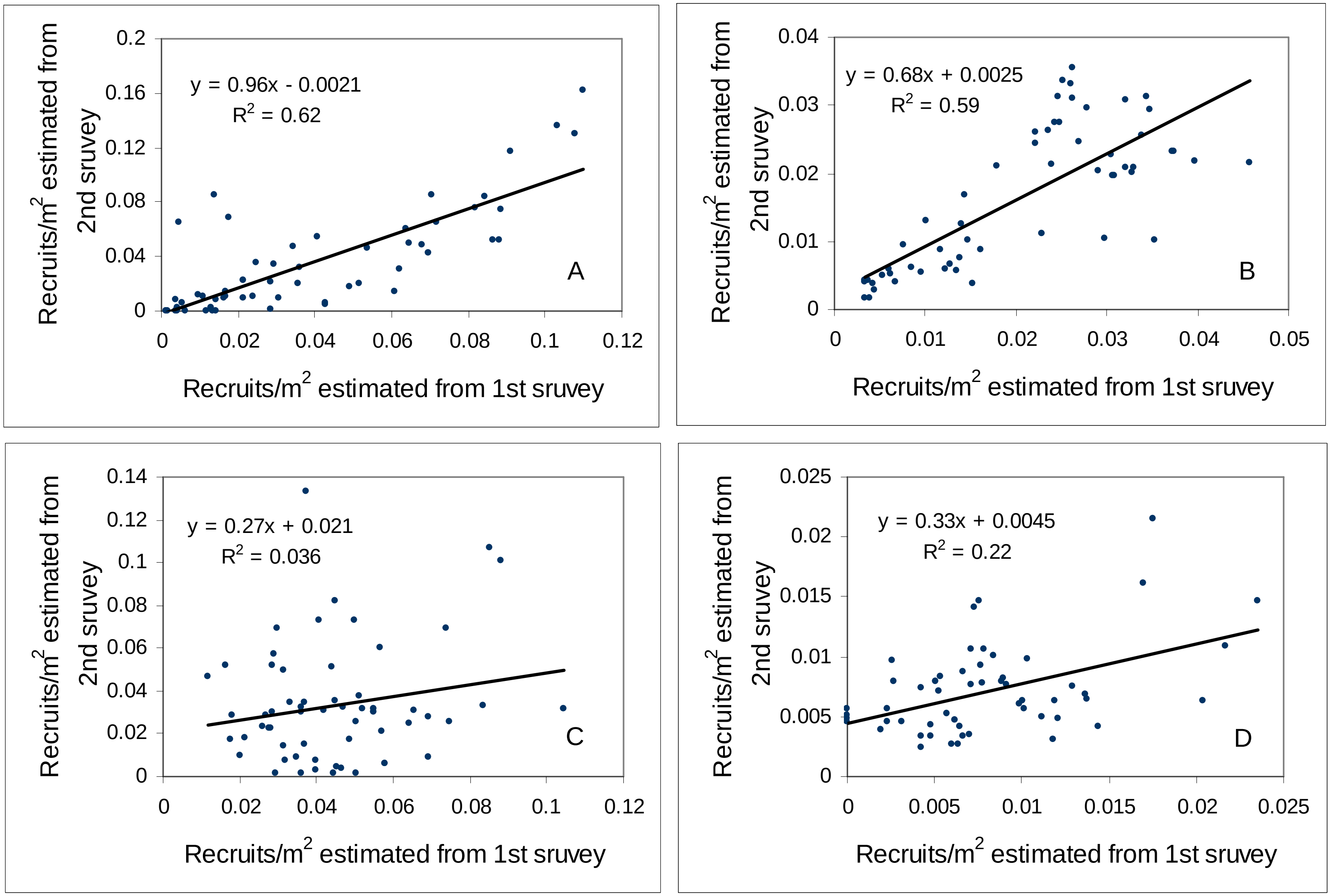

Fig. 9. XY plots of recruitment rates estimated from two independent surveys ($M = 0.016$).
(A - Goletas Channel; B - Winter Harbour; C - Mission Group; D - Comox)

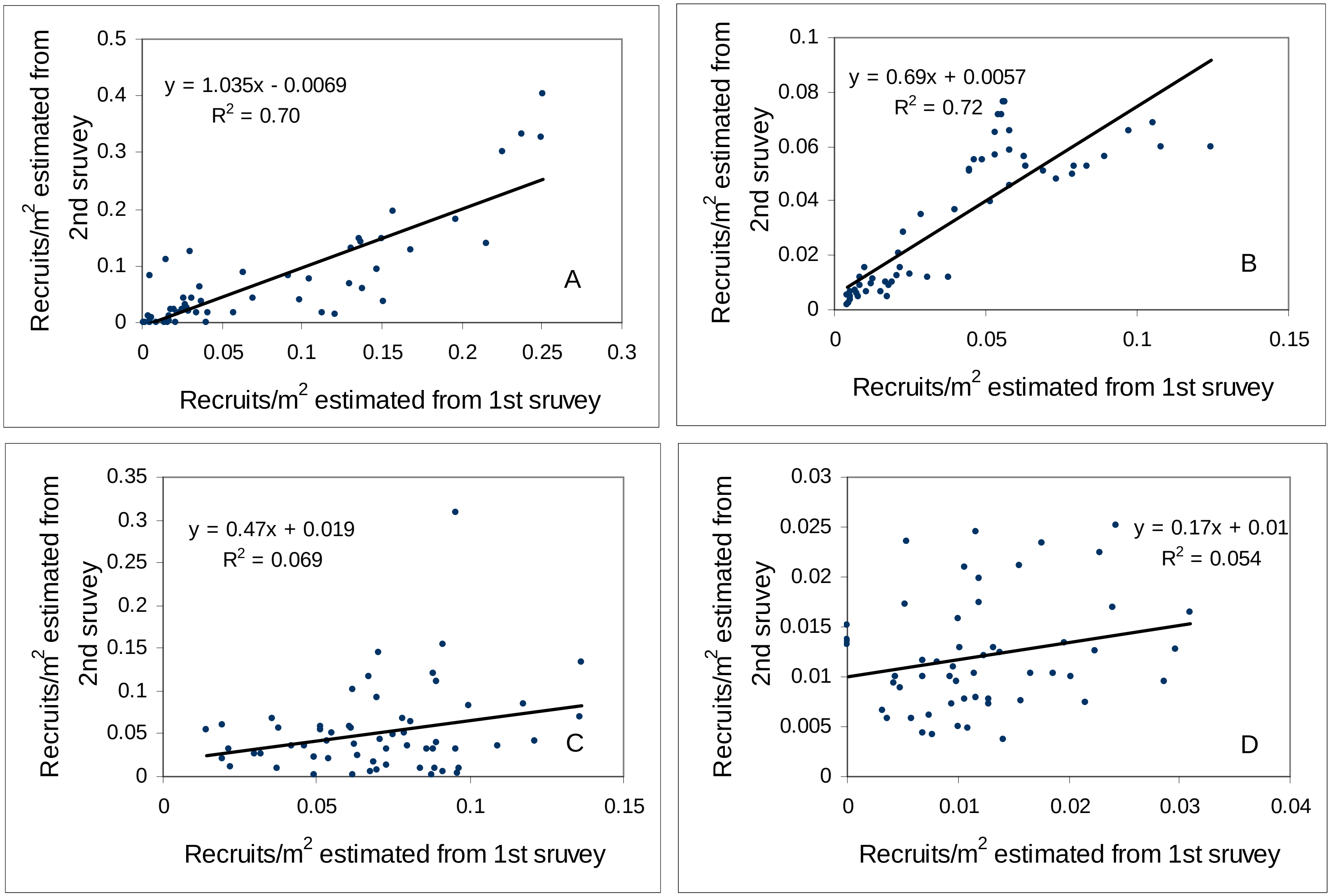

Fig. 10. XY plots of recruitment rates estimated from two independent surveys ($M = 0.036$).
(A - Goletas Channel; B - Winter Harbour; C - Mission Group; D - Comox)

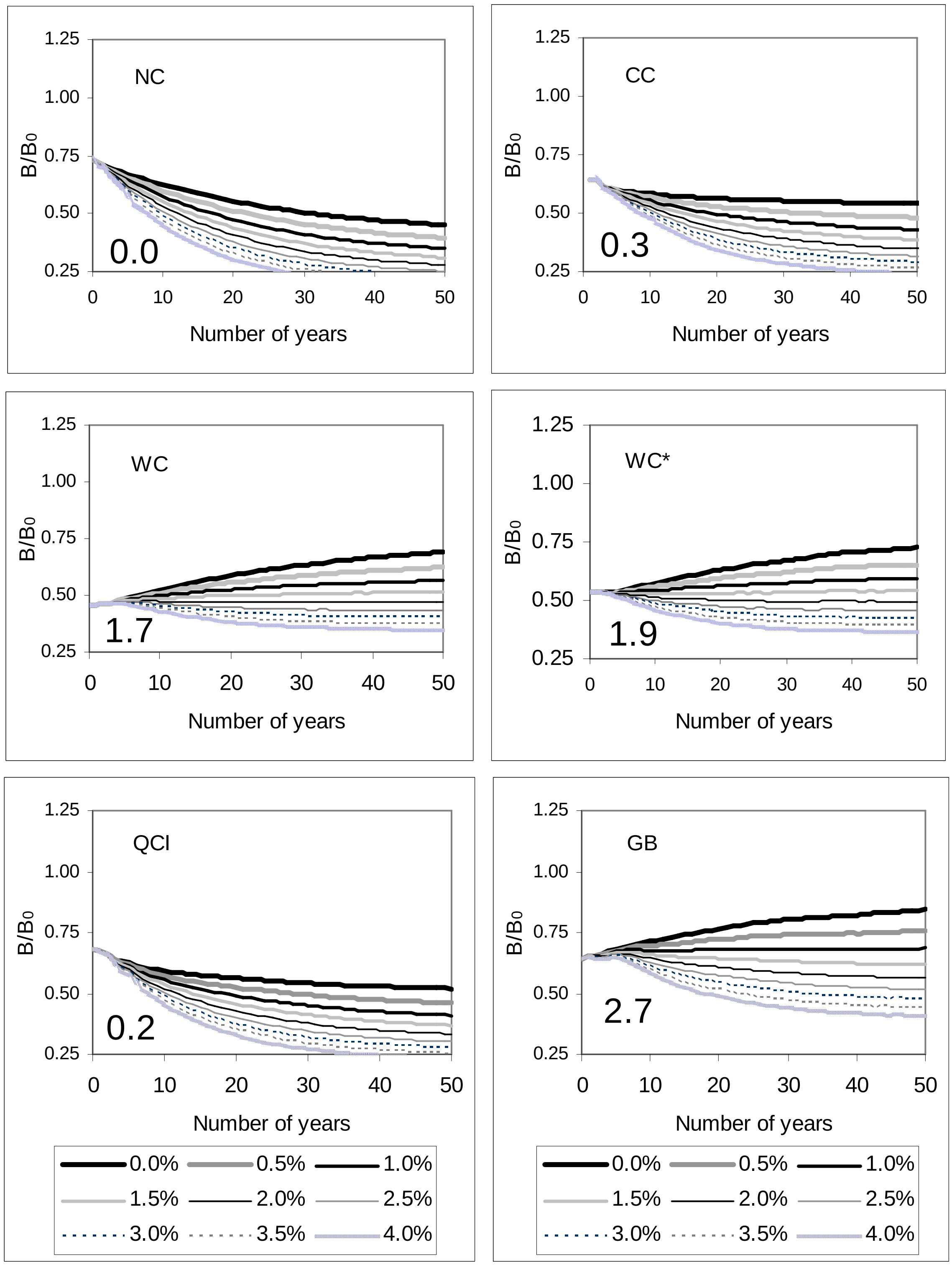

Fig. 11. Simulated changes in relative biomass at the 50th percentile with different exploitation rates. Recruitment simulation starting year is 1960 and *M* is 0.036. NC -- North Coast, CC -- Central Coast, WC -- West Coast of Vancouver Island, WC* -- West Coast of Vancouver Island without sea otter, QCI -- Queen Charlotte Island, GB - Georgia Basin.

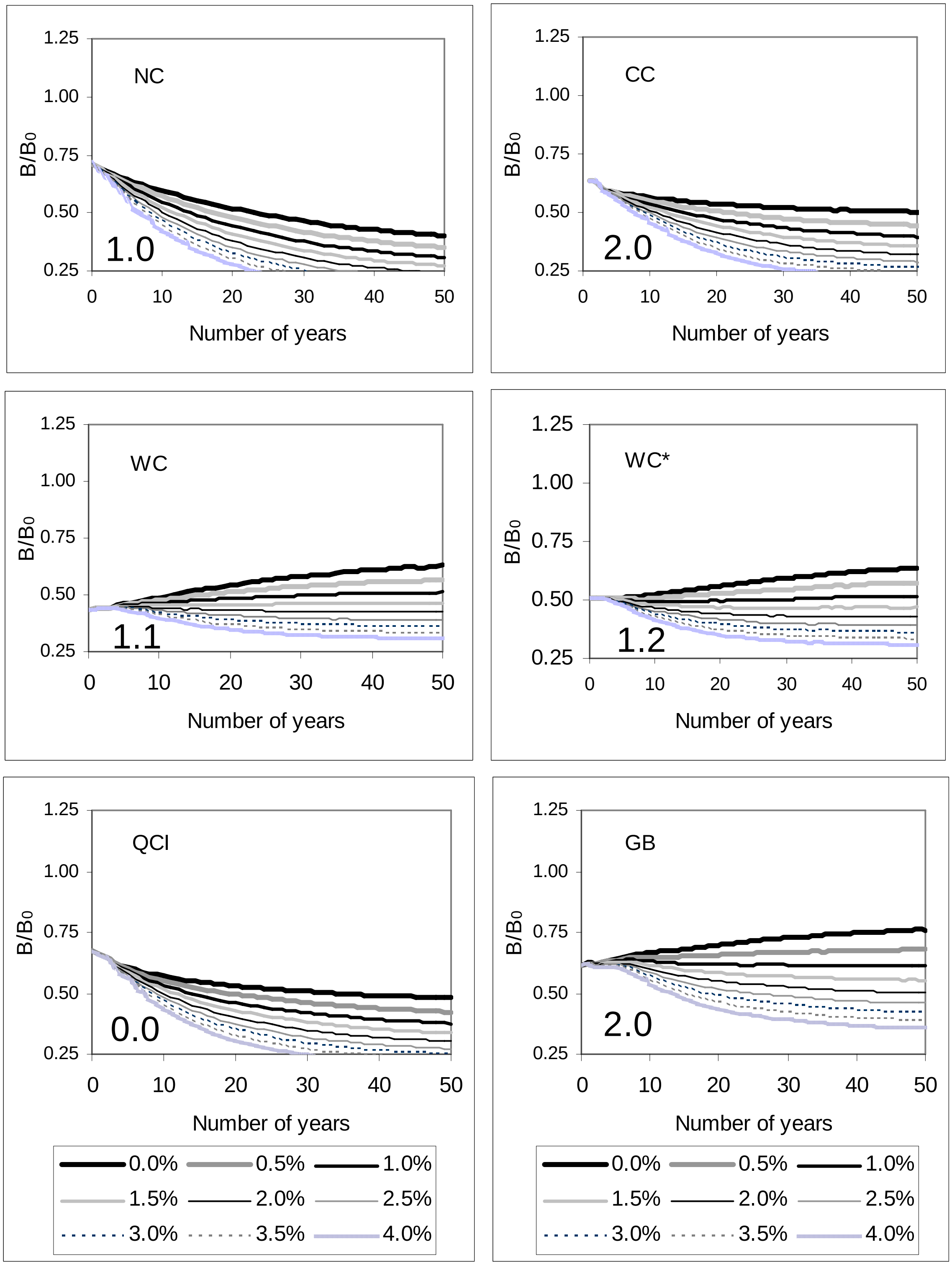

Fig. 12. Simulated changes in relative biomass at the 10th percentile with different exploitation rates. Recruitment simulation starting year is 1960 and *M* is 0.036. NC -- North Coast, CC -- Central Coast, WC -- West Coast of Vancouver Island, WC* -- West Coast of Vancouver Island without sea otter, QCI -- Queen Charlotte Island, GB - Georgia Basin.

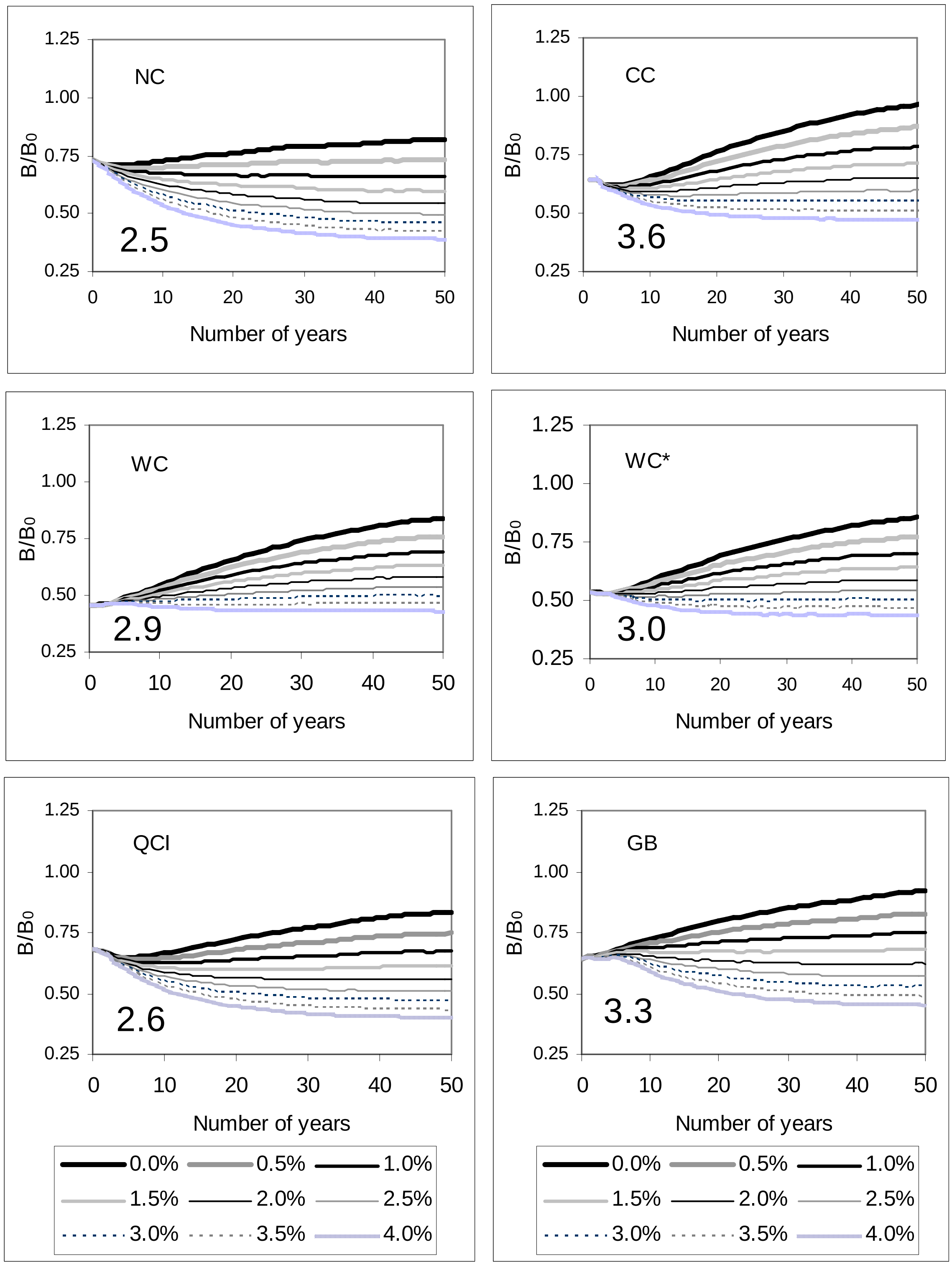

Fig. 13. Simulated changes in relative biomass at the 50th percentile with different exploitation rates. Recruitment simulation starting year is 1940 and *M* is 0.036. NC -- North Coast, CC -- Central Coast, WC -- West Coast of Vancouver Island, WC* -- West Coast of Vancouver Island without sea otter, QCI -- Queen Charlotte Island, GB - Georgia Basin.

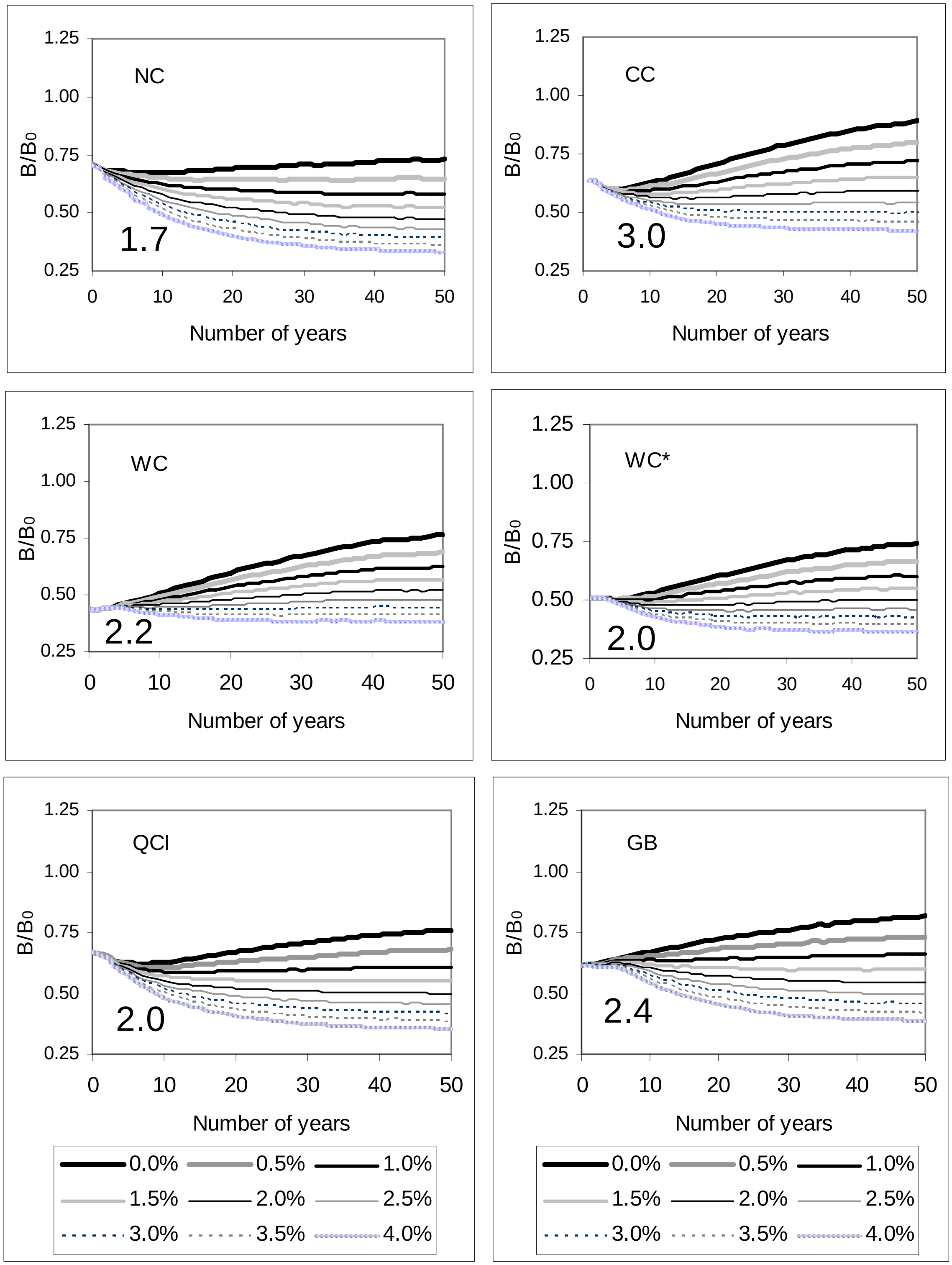

Fig. 14. Simulated changes in relative biomass at the 10th percentile with different exploitation rates. Recruitment simulation starting year is 1940 and M is 0.036. NC -- North Coast, CC -- Central Coast, WC -- West Coast of Vancouver Island, WC* -- West Coast of Vancouver Island without sea otter, QCI -- Queen Charlotte Island, GB - Georgia Basin.

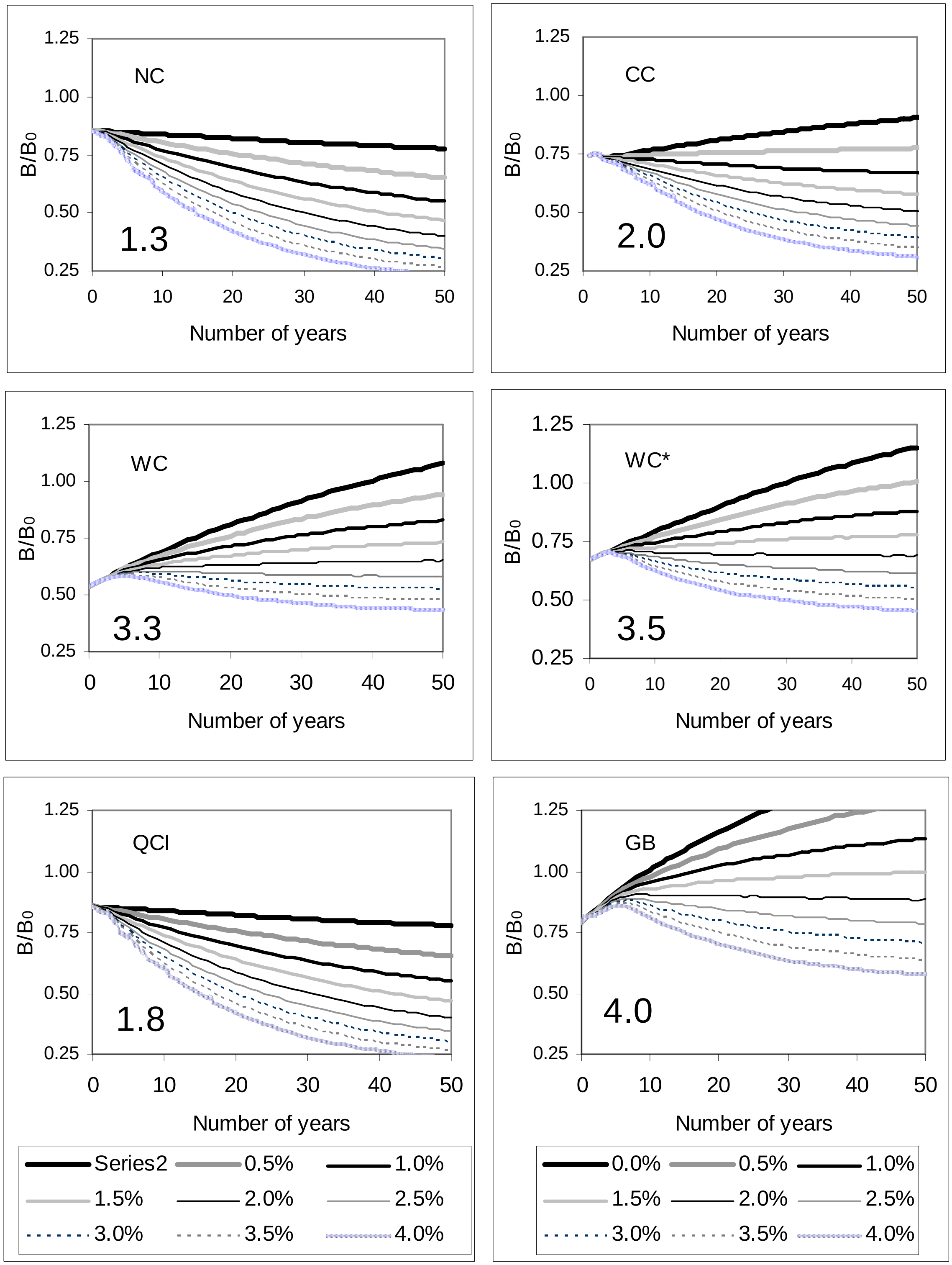

Fig. 15. Simulated changes in relative biomass at the 50th percentile with different exploitation rates. Recruitment simulation starting year is 1960 and *M* is 0.016. NC -- North Coast, CC -- Central Coast, WC -- West Coast of Vancouver Island, WC* -- West Coast of Vancouver Island without sea otter, QCI -- Queen Charlotte Island, GB - Georgia Basin.

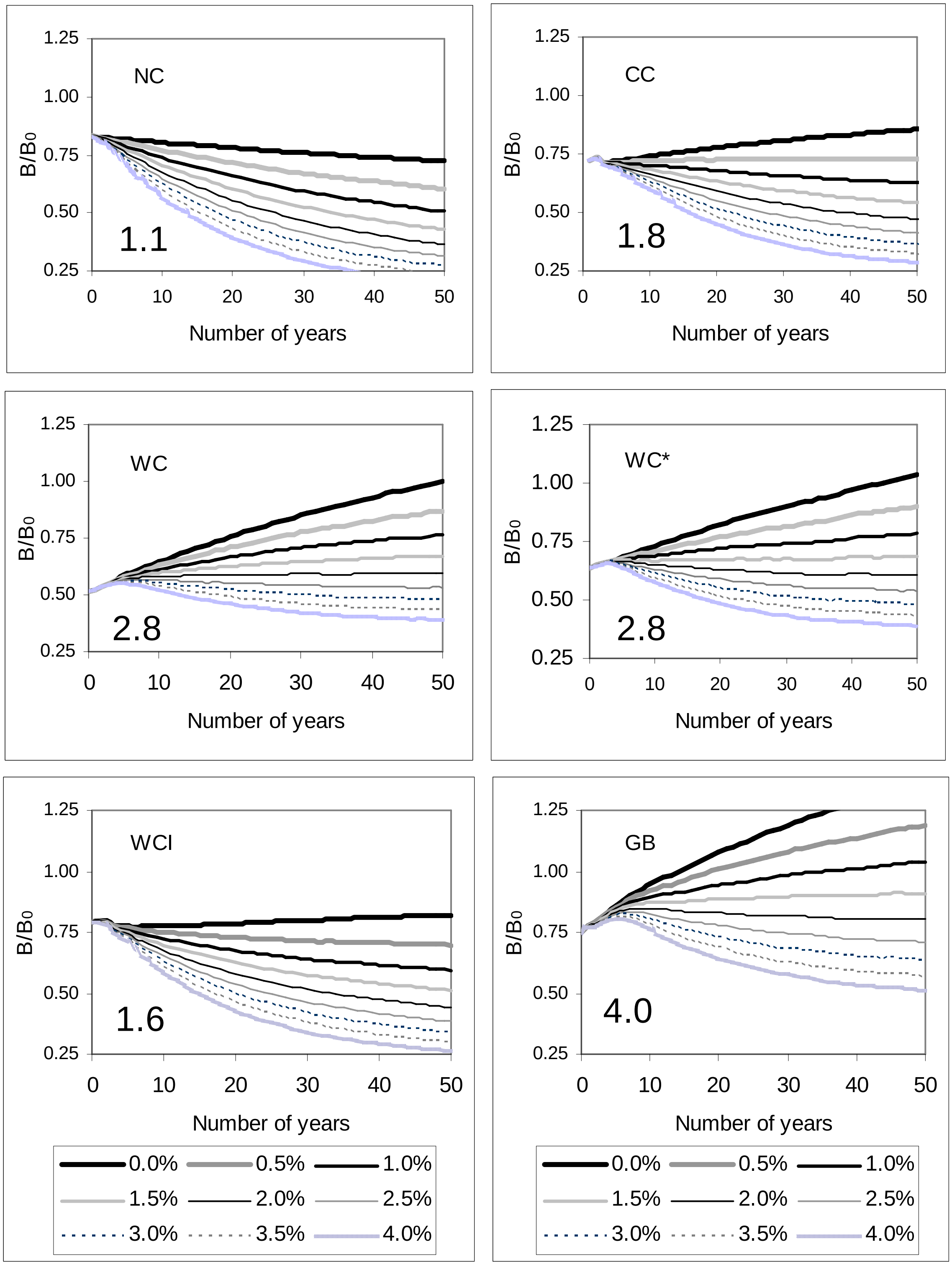

Fig. 16. Simulated changes in relative biomass at the 10th percentile with different exploitation rates. Recruitment simulation starting year is 1960 and *M* is 0.016. NC -- North Coast, CC -- Central Coast, WC -- West Coast of Vancouver Island, WC* -- West Coast of Vancouver Island without sea otter, QCI -- Queen Charlotte Island, GB - Georgia Basin.

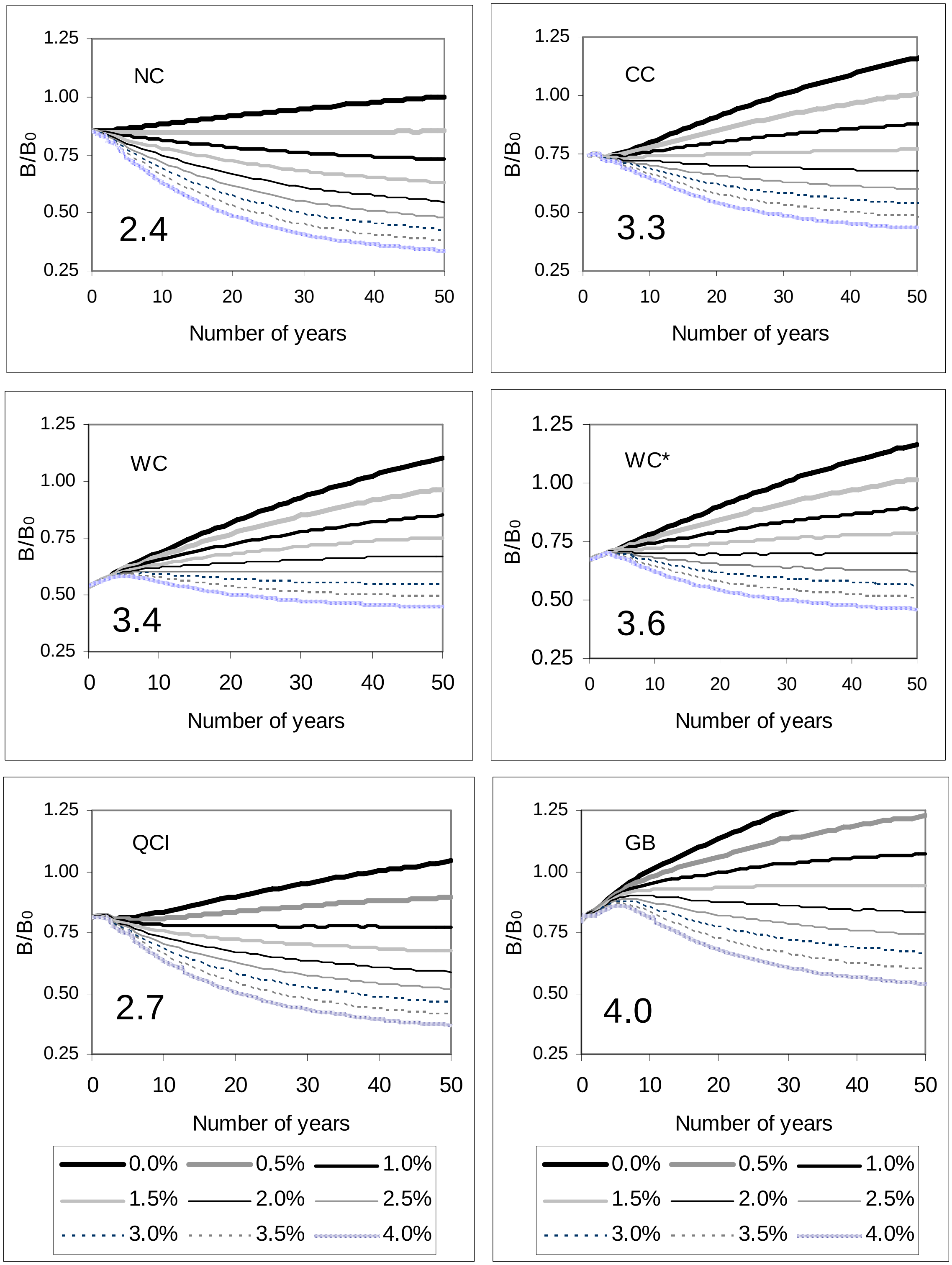

Fig. 17. Simulated changes in relative biomass at the 50th percentile with different exploitation rates. Recruitment simulation starting year is 1940 and *M* is 0.016. NC -- North Coast, CC -- Central Coast, WC -- West Coast of Vancouver Island, WC* -- West Coast of Vancouver Island without sea otter, QCI -- Queen Charlotte Island, GB - Georgia Basin.

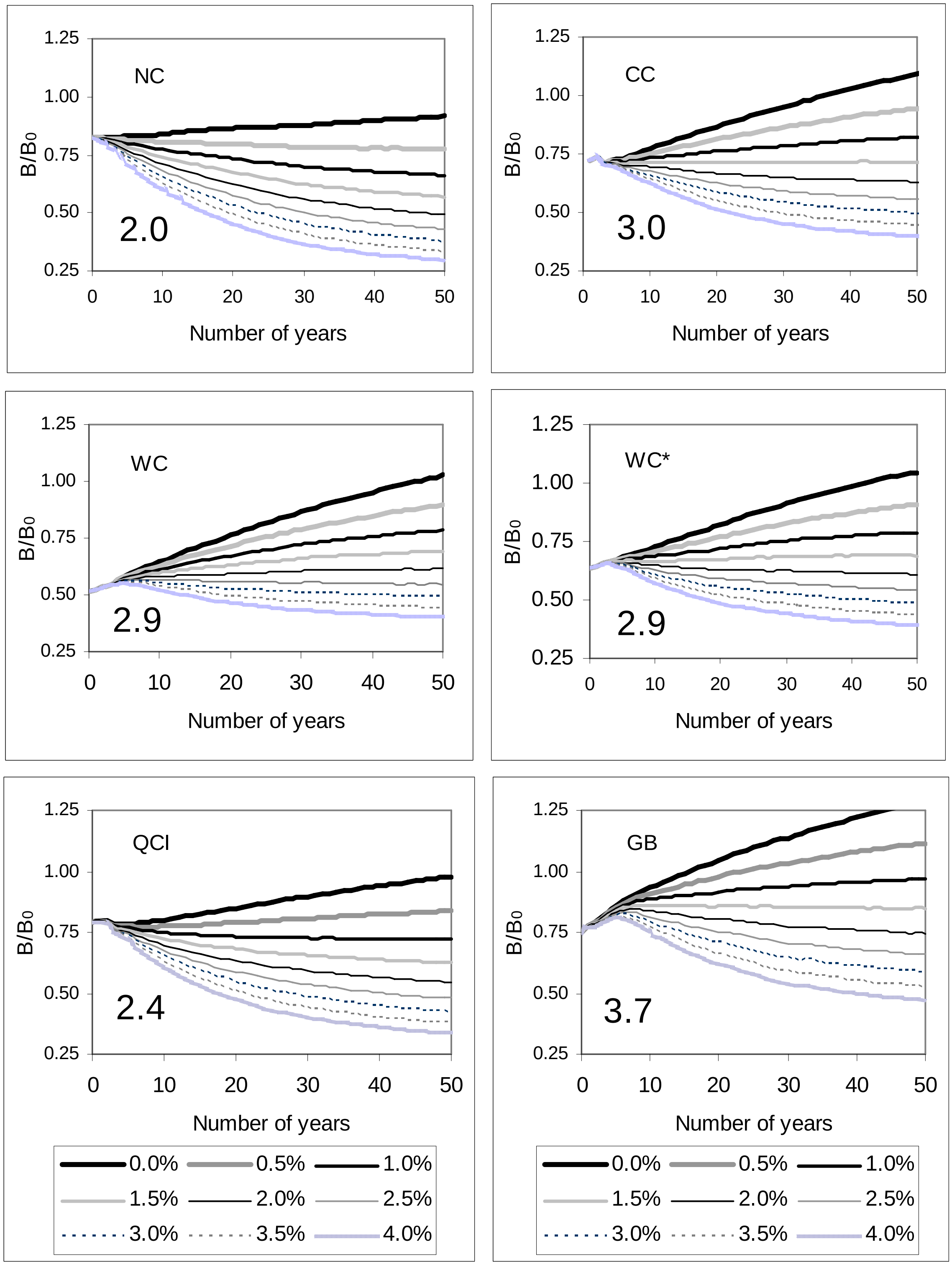

Fig. 18. Simulated changes in relative biomass at the 10th percentile with different exploitation rates. Recruitment simulation starting year is 1940 and *M* is 0.016. NC -- North Coast, CC -- Central Coast, WC -- West Coast of Vancouver Island, WC* -- West Coast of Vancouver Island without sea otter, QCI -- Queen Charlotte Island, GB - Georgia Basin.

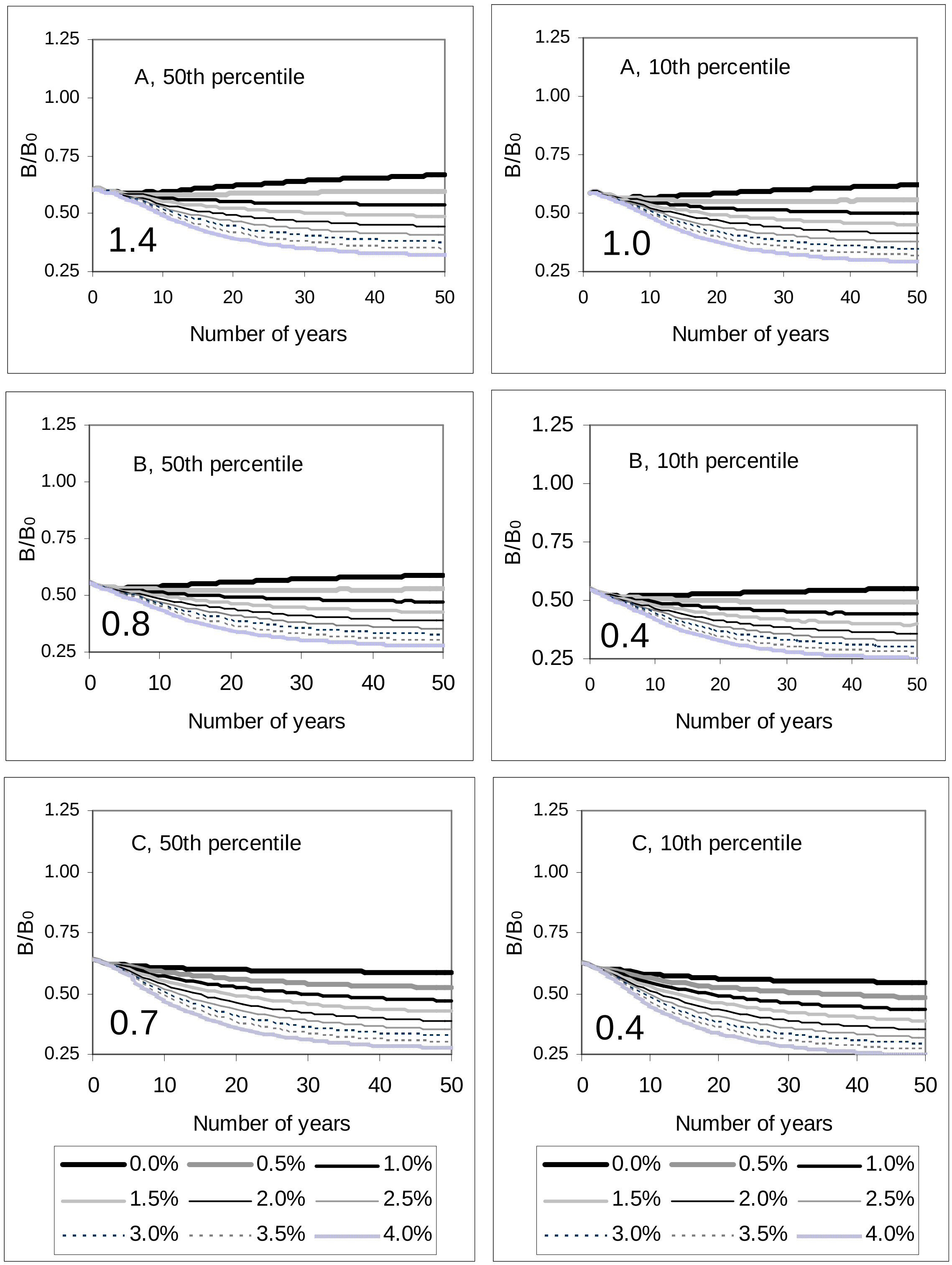

Fig. 19. Changes in relative biomass at 50th and 10th percentiles with different exploitation rates. Recruitment simulation starting year is 1960 and *M* is 0.036. A -- Low Productivity, B -- Intermediate Productivity, C -- High Productivity.

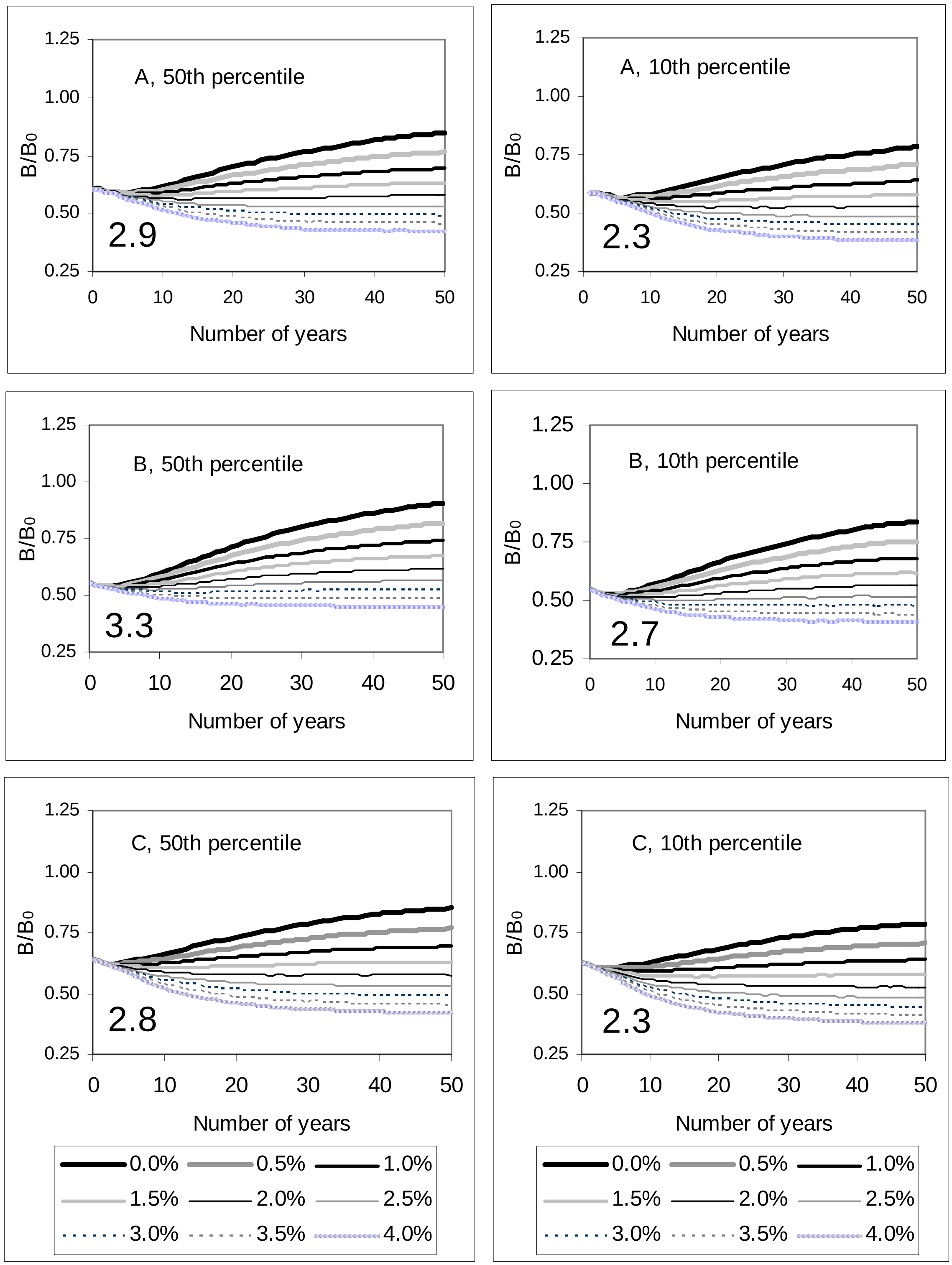

Fig. 20. Changes in relative biomass at 50th and 10th percentiles with different exploitation rates. Recruitment simulation starting year is 1940 and *M* is 0.036. A -- Low Productivity, B -- Intermediate Productivity, C -- High Productivity.

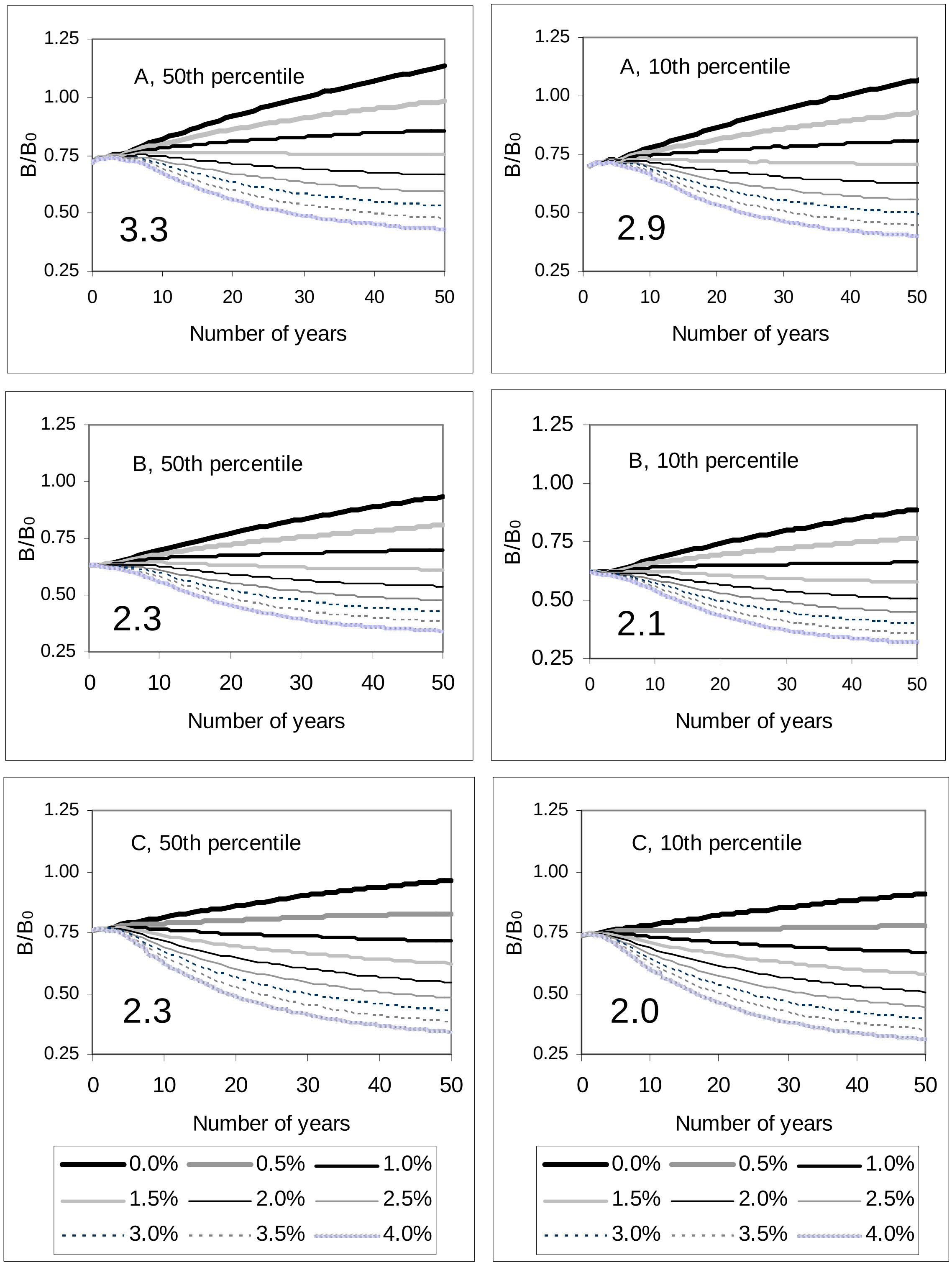

Fig. 21. Changes in relative biomass at 50th and 10th percentiles with different exploitation rates. Recruitment simulation starting year is 1960 and *M* is 0.016. A -- Low Productivity, B -- Intermediate Productivity, C -- High Productivity.

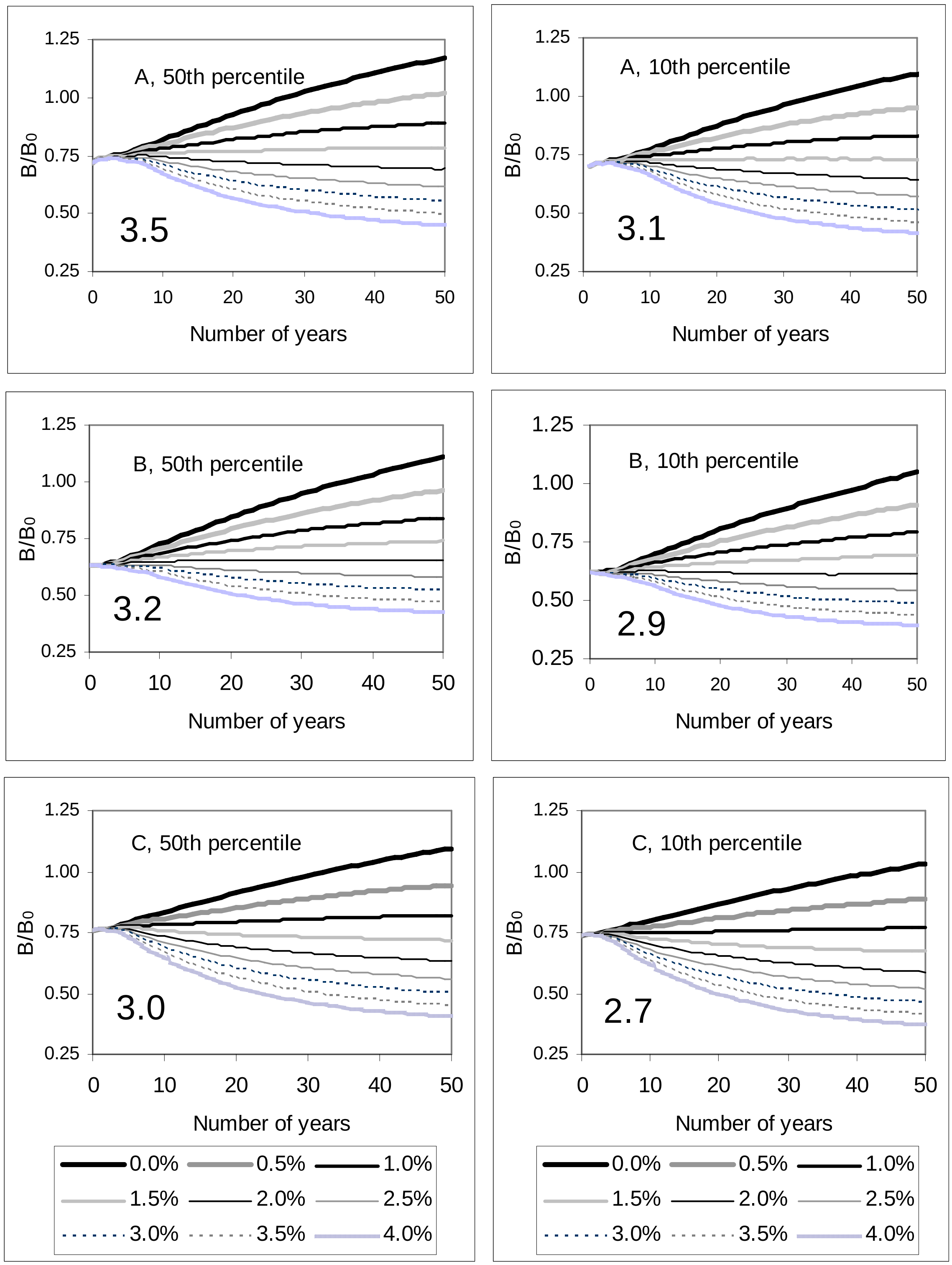

Fig. 22. Changes in relative biomass at 50th and 10th percentiles with different exploitation rates. Recruitment simulation starting year is 1940 and *M* is 0.016. A -- Low Productivity, B -- Intermediate Productivity, C -- High Productivity.

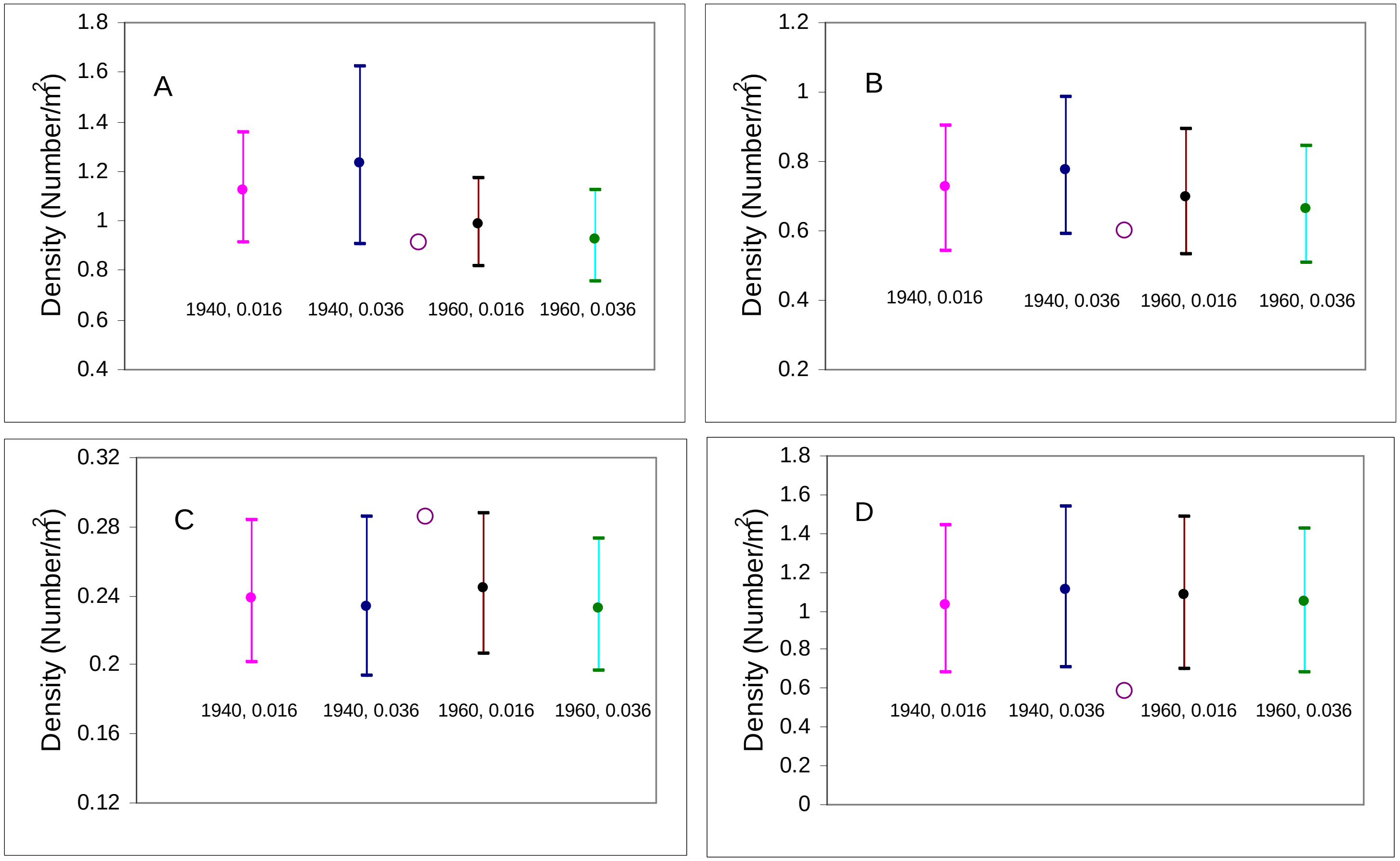

Fig. 23. Comparison of projected and survey-derived geoduck densities. The solid dots represent the predicted median densities and the two bars represent 10th and 90th percentiles. The hollow circles denote the mean densities derived from the 2nd survey. Each set of two numbers indicates the starting recruitment simulation year and natural mortality rate used in the modelling.
A - Goletas Channel; B - Winter Harbour; C - D - Comox; Mission Group.

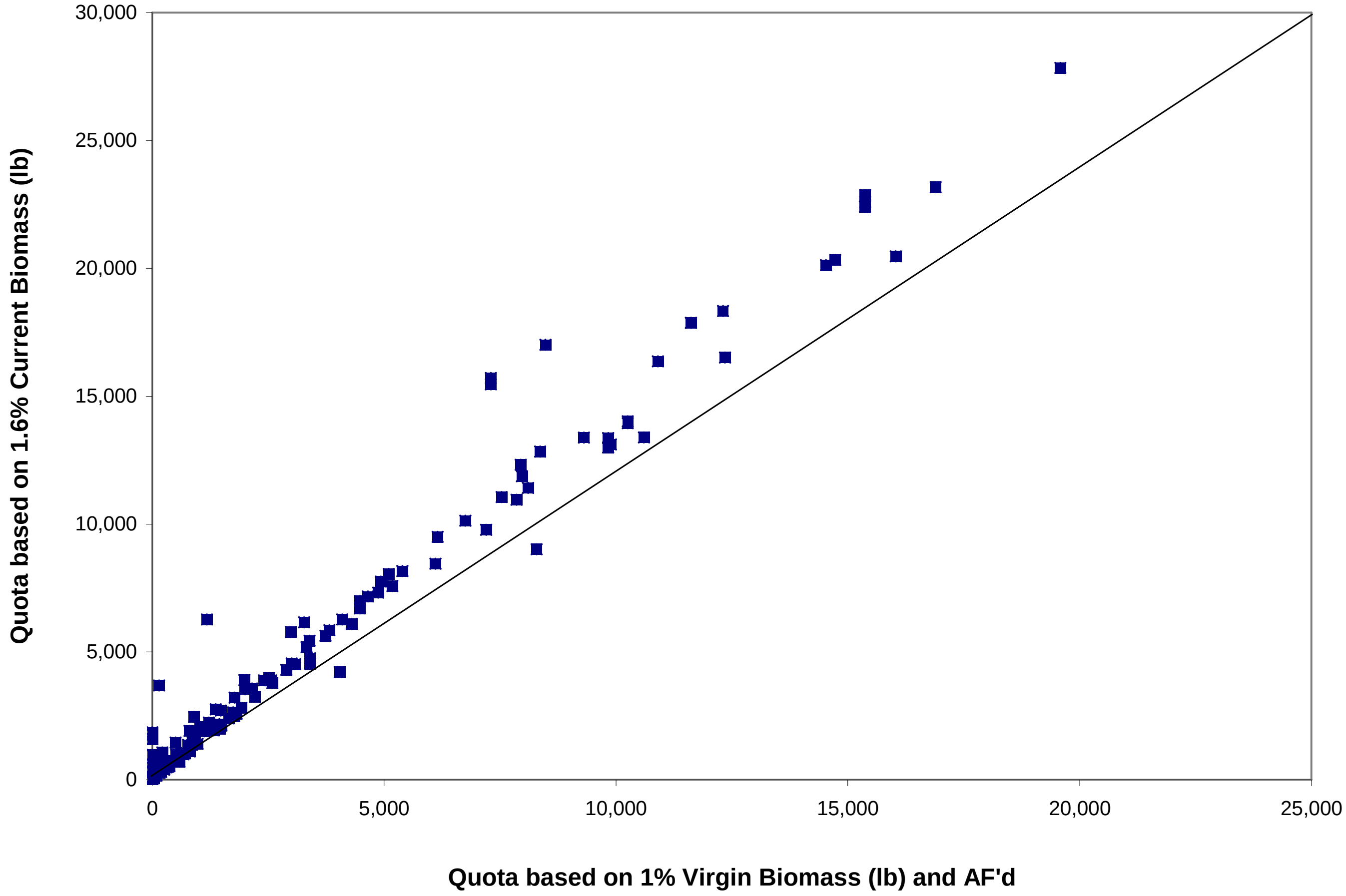

Fig. 24. Comparison of quota options for surveyed beds in the Queen Charlotte Islands using a harvest rate of 1% on virgin biomass and using 1.6% on current biomass. Quotas are presently also reduced by an 'amortization factor' (AF) which distributes the remainder of harvest in a geoduck bed over the number of years remaining in a 50-year time period since fishing began in that bed.