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Review of data collected during the annual sea cucumber (*Parastichopus californicus*) fishery in British Columbia and recommendations for a rotational harvest strategy based on simulation modelling

Examen des données recueillies au cours de la pêche annuelle du concombre de mer (*Parastichopus californicus*) en Colombie-Britannique et recommandations pour une stratégie de récolte par rotation basée sur un modèle de simulation

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Abstract

The sea cucumber (*Parastichopus californicus*) fishery in British Columbia is in Phase 1 of development, according to the nationally-adopted protocol for new or data-limited fisheries, wherein profit-based fisheries are held at conservative levels while the necessary stock assessment data are collected. Since 1997, the fishery has been restricted to 25% of the coast and management areas are harvested annually at 4.2% of estimated biomass. Commercial harvesters have expressed concern that the annual fishery is negatively impacting stocks.

A focussed review of research and fishery data was undertaken to evaluate the annual harvest regime and to identify any potential conservation concerns. The spatial distribution of harvest was examined to estimate localized harvest rates in this dive fishery. Harvest effort was found to be concentrated in approximately 12% of open areas, by shoreline distance, resulting in average local harvest rates of 30% of estimated biomass. Analysis of market sample, biological sample and survey density data failed to reveal significant impacts of annually-concentrated effort on sea cucumber populations, however sample regimes for estimating animal size distribution were found to be flawed.

A simulation model is presented, which uses estimated local harvest rates to evaluate risks and benefits of annual versus rotational harvest strategies. Model results suggest that at high local harvest rates, annual harvest leads to decline in animal size and population density while longer rotation periods result in larger animals and higher spawning densities. This paper describes a new program of experimental fishing designed to test rotational harvest and provide more informative data for management decisions in both the short-term and the long-term. Recommendations are provided for how a pilot rotational harvest could be conducted within a portion of the open fishery, including changes in data collection that would improve the ability to detect localised fishing effects.

Résumé

La pêche du concombre de mer (*Parastichopus californicus*) en Colombie-Britannique est au stade 1 de développement, selon le protocole adopté à l'échelle nationale pour les pêches nouvelles ou dont les données sont limitées, tandis que les pêches axées sur les bénéfices sont maintenues à des niveaux prudents pendant que les données nécessaires sur l'évaluation des stocks sont recueillies. Depuis 1997, la pêche est limitée à 25 % des côtes et les zones de gestion sont exploitées annuellement à raison de 4,2 % de la biomasse estimative. Les pêcheurs commerciaux ont exprimé des préoccupations, indiquant que la pêche annuelle nuisait aux stocks de cet animal.

Ce document passe en revue les données de recherche et les données de pêche afin d'évaluer le régime de pêche annuel et de déceler tout facteur de préoccupation possible. La répartition spatiale de la récolte a été examinée en vue de déterminer les taux localisés de cette exploitation en plongée. On a constaté que cette pêche a été concentrée sur 12 % des zones ouvertes, selon la distance à la côte, ce qui a donné des taux d'exploitation locaux moyens de 30 % de la biomasse estimée. L'analyse des données recueillies sur des échantillons de la pêche commerciale et des échantillons biologiques, ainsi que des données de densité obtenues dans le cadre de relevés, n'a révélé aucun impact significatif de l'effort de pêche annuel sur les populations de concombres de mer, mais on a découvert que les régimes d'échantillonnage servant à estimer la structure de tailles des populations étaient déficients.

Le document présente un modèle de simulation qui, à l'aide des taux d'exploitation localisés, mesure les risques et les avantages des différentes stratégies de pêche, annuelle ou par rotation. Les résultats du modèle de simulation semblent indiquer que le nombre et la taille des concombres sont réduits lorsqu'une pêche annuelle est pratiquée à des taux d'exploitation locaux élevés et qu'ils augmentent lorsque les périodes de rotation sont plus longues. Le document décrit un nouveau programme de pêche expérimentale visant à tester la récolte par rotation et à obtenir de meilleures données en vue de la prise de décisions de gestion, à court et à long terme. Les auteurs font des recommandations sur la pratique d'une pêche pilote par rotation dans le cadre de la pêche ouverte, préconisant notamment des changements dans la collecte de données pour accroître la capacité de déceler des effets localisés de la pêche.

1 Introduction

The sea cucumber (*Parastichopus californicus*) fishery began in British Columbia (BC) in 1980 and developed in the manner typical of new and/or data-limited fisheries; an early period of growth in capacity and landings leading to area closures, arbitrary quotas and licence limitation. In order to implement the phased approach in the development of new or data-limited fisheries (Perry et al. 1999) and to work towards conservation-based sustainable fisheries, the sea cucumber fishery underwent a review in 1997 by Fisheries and Oceans Canada (DFO). Following the review, the fishery was restricted to 25% of the BC coast, to be fished annually, while up to 25% of the coast was approved for use in conducting fishery experiments (Boutillier *et al*. 1998, Hand and Rogers 1999). Annual fisheries, versus rotational fisheries, were intended to provide the fishery-dependent data necessary to allow the estimation of stock abundance and maximum sustainable yield through biomass dynamic models. The collection of data from an annual fishery would also speed the process of evaluating fishery impacts. Since the institution of this adaptive management approach, the Pacific Sea Cucumber Harvesters Association (PSCHA) has been highly involved in collecting survey and biological sample data and in conducting experimental fisheries. The PSCHA have also supported biological personnel to manage scientific data, conduct analyses and document results.

Industry has expressed interest in returning to a rotational harvest strategy, due to concerns about decreased sea cucumber size in favoured fishing locations. Because small sea cucumbers are inefficient to process and are considered a lower quality product, decreased animal size could adversely affect the price and thus the potential economic benefit to harvesters. Harvesters have observed that areas left for several years to recover provide higher densities of larger sea cucumbers relative to those harvested every year; this implies potentially higher economic benefits, as well as higher spawning densities. The PSCHA believes that a regulated spatial rotation is an efficient way to reverse or prevent negative impacts of harvest on the sea cucumber stocks. Given the fact that PSCHA funds much of the research activities, and that policy in DFO is moving towards shared decision-making responsibilities with the commercial sector (as well as stock assessment costs), participants in the sea cucumber fishery are eager to provide their perspective and input into the management of the fishery.

A necessary precursor to considering a change to rotational fishing is a review of data collected since 1997 from the commercial fishery and experimental fishing areas (EFAs), in order to evaluate the annual harvest regime and identify any potential conservation concerns. This paper includes an exploration of whether anecdotal evidence of decline in sea cucumber size in annually fished areas is substantiated by the existing data, and examines trends in density. This paper also aims to estimate localised harvest rates from spatial fishery data, and identify any impacts of localized harvest on animal size and population density. We also explore questions relating to the experimental fishing program: has information of the expected utility been gained through the program, and have problems been identified with the sampling design that can be corrected in planning future research?

A simulation model has been developed to evaluate the risks and benefits of annual versus rotational harvest strategies for the sea cucumber fishery (Humble 2005). Modelling results predict that at high localised harvest rates, annual harvest leads to decline in animal size and population density, while longer rotation periods result in larger animals and higher spawning densities. These results are consistent with those of past studies of rotational harvest for red sea urchins, geoduck clams, and other invertebrate fisheries (discussed in Section 5.1 of this paper). Extending Humble's analysis, this paper includes a modelling component that uses harvest rates estimated from spatial data on sea cucumber fishing-distribution as input to the existing model. Thus, it provides a prospective analysis of annual versus alternative rotational harvest strategies for the sea cucumber fishery for consideration in future management decisions.

Finally, this paper includes a description of a new program of experimental fishing that is designed to test rotational harvest and provide more informative data for management decisions in both the short-term and the long-term. We also provide recommendations for how a pilot rotational harvest could be conducted within a portion of the currently-open commercial area, including changes in data collection that would improve the ability to detect localised effects of fishing.

2 Trends in Density and Average Weight

2.1 Market Sample Data Analysis

2.1.1 Rationale

According to harvesters, some locations that are traditionally harvested year after year, particularly in Pacific Fisheries Statistical Areas (Areas) 6 and 7[1], continue to retain good population densities, but are producing smaller sea cucumbers. In 2004, buyers commented that:

"The product weight recovered from small animals cannot justify the costs associated to processing. The fleet should be more aware of the size of the animal, and should move to new ground when the average size of the product becomes too small"

(D&D 2003). This comment implies that the annual fishery may be having a negative impact on sea cucumber size in some areas, and that the product price could be affected. An analysis of market sample data is justified because if the data reveal a decrease in the average size of harvested sea cucumbers, this would indicate a shift in size composition of the population, which can be a conservation concern as well as an economic one. Areas 6 and 7, where the fishery is particularly concentrated, were chosen as the focus for this analysis of change in average weight of harvested sea cucumbers.

2.1.2 Methods

Samples of harvested animals are collected as part of the dockside validation program in the commercial fishery, as described in Campagna and Hand (2004). Port monitors randomly select approximately 25 sea cucumbers per sample from harvest containers (totes or cages) and obtain the total weight (to the nearest 50 g) and exact count. The number of samples collected per vessel-landing depends on the time available to the sampler after weighing the vessel loads, and ranges from one to 15 per

[1] The BC coast is divided into Statistical Areas, for use in the management of salmon stocks. The system has no application to other species, but is convenient and therefore used extensively. Statistical Areas are further divided into Sub-Areas.

landing. From these data, the mean weight of harvested animals was calculated by Sub-Area, Area and year (1997-2003). Weight in pounds was converted to grams.

To determine whether harvest frequency has affected animal size, all geographic locations within Areas 6 and 7 where harvest events overlapped for at least three consecutive years were identified. Data from these 'overlap' locations thus represent 'annually-fished' areas, whereas harvest data from the Area as a whole, which includes the 3-year overlapping data, can be thought to represent less frequent harvest.

Mean weight of harvested animals was calculated, by year, in each of the individual 'annually-fished (overlap) locations. Data from annually-fished locations were then pooled by Area, and mean animal weight was calculated for each year. Mean weight over time was compared between these pooled annually-fished locations and the Areas overall. Finally, the change in mean weight of harvested sea cucumbers that occurred in six years of annual harvest (1997-2003) was compared to changes in the overall Area. Confidence intervals for change in mean weight were calculated using the usual *t* statistic:

$$\left(\overline{X}_1 - \overline{X}_2\right) \pm t \sqrt{S \left(\frac{1}{n_1} + \frac{1}{n_2}\right)}$$

where: $\overline{X}_1$ and $\overline{X}_2$ are the mean weights for 2003 and 1997, respectively;

S is the pooled standard deviation of mean weights for both years; and

n_1 and n_2 are the sample sizes in 2003 and 1997 (number of weight measurements).

No attempt was made to compare weight changes between locations harvested at different frequencies, because harvest frequency fluctuated greatly and was thus impractical to quantify. Thus, the objective of determining the effect of harvest frequency from commercial fishery data was addressed only to the extent of this comparison between Areas as a whole, and annually fished locations within these Areas.

2.1.3 Results and Discussion

Weight declines were apparent in some annually-fished locations, however this trend was not consistent (no graph is presented). On a Sub-Area basis, no clear trend in average sea cucumber weight was apparent in Areas 6 or 7 (Figures 1 and 2). There is considerable variability in mean sea cucumber weight on a small spatial scale and consequently impacts of harvest pressure, if they exist, are not readily detectable.

Pooled data from annually-fished locations in all of Area 6 appeared to show a slight downward trend in average weight from 1997 to 2003, as compared to a slight increase in Area 6 as a whole; the same general result holds for Area 7 (Figure 3), although the estimates are highly variable. Slopes in the un-weighted regression were not significantly different from zero in either Area (Table 1).

Potential impacts of annual fishing were found by examining the change in average weight between 1997 and 2003. There was a substantial decrease in average weight in annually fished locations in both Areas 6 and 7, as compared to a substantial increase in both Areas 6 and 7 overall (Figure 4). The confidence intervals for the change in weight do not overlap in either Area, which indicates a significant difference in the 6-year change in mean weight between annually-fished areas and the Areas as a whole. This result provides some evidence that annual fishing leads to smaller sea cucumbers than less frequent harvest.

The lack of clear declining trends in average weight of harvested sea cucumbers does not necessarily demonstrate that there is no fishery effect on sea cucumber size in local populations. Several factors can explain why market samples may not reveal declines in size:

1. *Spatial uncertainty in market samples.* More than one shoreline location is often fished in a day, however fishing crews do not separate the catch from different locations. Furthermore, when more than one sample is taken from a vessel's catch, sample weights and piece counts are summed to calculate an overall average weight, which is assumed to represent all sites covered by the vessel in that day. Consequently, there is no way to link market sample weights to specific shoreline locations. In addition, individual fishing events are usually substantially longer than the overlap among them. As an example, for a sample of four overlap sites in Area 7, the ratio of the overlap length to the average length of the fishing events that compose the overlap is 0.47:

$$\frac{length\_of\_overlap}{average\_length\_of\_fishing\_events} = 0.47$$

   Thus, it is likely that average weights calculated over time for overlapping fishing locations would include samples taken outside the locations that were fished annually.

2. *Variable size selectivity.* Even if spatial certainty in market samples were to be improved, the PSCHA believes that, due to changes in size selectivity over years, and over days within a fishing season, market samples do not represent the average size of sea cucumbers in the population. Factors affecting harvesters' size-selection behaviour are complex and interactive. Some of these factors include the number of licenses held by a vessel, spatial fishing patterns related to port access, different buyer-preferences for how soon the harvested product has to be landed, and individual diver behaviour. Also, harvesters sometimes search longer to find larger animals, when they consider it necessary to prevent buyers from lowering the price paid per pound (K. Ridgway, pers. comm.). Because harvesting is size-selective, and this selectivity is subject to spatial and temporal variability, the average size calculated from market samples is unlikely to represent the population average size, and may not reveal local changes in the sizes of animals in the population over time.

3. *Possible sampling bias*. If size-related sorting of harvested sea cucumbers occurs in the container during transport, prior to sample selection, market samples could be biased because samplers reach only to a depth of 20 cm (equal to the glove length).

These factors raise doubts about the basic assumption of the market sampling program: that the average weight of sea cucumbers from the commercial harvest is representative of, or acts as an index for, the average size in the population. The implication is that the program, in its current form, is unlikely to provide information on harvest impacts. Biological samples collected prior to fishing and from locations that are likely to be fished, would better represent the average size (and size distribution) of animals in the population. Replacing the current market sampling program with a pre-harvest biosampling program would provide data with a greater probability of detecting size changes.

2.2 Survey Data Analysis

2.2.1 Rationale

To further evaluate the potential impacts of annual harvest on population density and size distribution, transect and biological sample data from commercial fishery areas were examined for possible indications of declining trends. Three surveys have been conducted and replicated four years after the initial survey, with the aim of assessing the impact of annual harvests of 4.2% of the lower 95% confidence bound of estimated biomass (i.e. using the lower end of 90% confidence interval of estimated density to calculate biomass).

2.2.2 Methods

Transect survey methods are described in Campagna and Hand (2004). Briefly, transect locations were randomly chosen within the defined survey stratum (surveys were stratified by Sub-Area or habitat) and surveyed by SCUBA divers. The number of cucumbers within a 4-metre wide swath extending between 0 and 60 ft (18m) gauge depth was recorded, along with the depth, substrate type and algae. A later series of surveys attempted to replicate the transect coordinates from the first survey. Differences in density between the two survey times were tested for significance using a Z test.

Samples of 50 sea cucumbers were collected from each of three randomly-selected transects per survey stratum, the locations of which were retained in subsequent surveys. These animals were split (cut open longitudinally and drained of fluid) and individually weighed.

2.2.3 Results and Discussion

There was no significant difference in estimated density between any of the survey pairs, although the results from all three surveys showed a decline in density (Table 2). In comparisons of mean weights estimated from biological samples, Area 12 showed no statistical change between years, while the decrease in mean weight in Bella Bella and Gil and Gribbell Islands data between years was significant (t test, $p<0.05$) (Table 2).

One factor that may confound the interpretation of these results is the distribution of fishing effort in relation to the randomly placed sampling locations (biosample and density transects). If most sampling locations do not coincide with fishing locations that consistently harvested, and the results are calculated by Statistical Sub-Area, which are several hundred km long, then localized declines may not be detectable.

Figure 5 shows that in the Bella Bella area, biosample transects are located some distance away from annually fished areas, where effort is concentrated near the two communities. Because sea cucumbers have limited mobility, the above biosample analysis would likely not reveal impacts of this localized effort concentration. The fact that there was a significant decrease in mean weight of animals in the Bella Bella area is hard to interpret. Density transects, however, did coincide with annually-fished areas of the commercial fishery. An exploratory analysis of change in density, using pooled data from transects close to where effort was concentrated vs. those >100m away from these locations, showed no significant change in density for either the annually-fished or the non annually-fished locations.

To improve the likelihood that data from biological samples will provide a measure of change in animal size, if occurring, a change in sampling procedures is recommended. Biosample transects should be placed in locations where fishing effort is likely to be concentrated. Maps of past fishing distribution could be used to define popular fishing areas, and biosample transect locations randomly chosen within those areas of interest. One potential research question might be: is there a significant difference in mean animal size (or the proportion of larger animals) between fished locations and those farther away from where effort is concentrated?

2.3 Experimental Fishery Data Analysis

2.3.1 Rationale

A final source of data available to examine trends in density and average weight are experimental fisheries. These experiments were established in 1998 to determine the impact of different harvest rates on sea cucumber population abundance and individual weight. In this section, mean weight of harvested animals, mean weight of biosampled animals and population density are estimated, by year, for each experimental treatment site in each of the four Experimental Fishing Areas (EFAs).

2.3.2 Methods

Experimental fishery protocols and data analysis methods are described in Hand and Rogers (1999) and Bureau and Hand (2005). Briefly, EFA's consist of five treatment sites measuring 10 km of shoreline length and randomly assigned an exploitation rate of 0% (control), 2%, 4%, 8% or 16%. Each treatment site was assigned 15 to 25 transects which were surveyed to estimate total abundance prior to fishing. Transects were randomly positioned within each site and completed as described in Section 2.2.2.The same transect positions were used every year that a site was surveyed. Experimental quotas, in number of animals, were calculated for each site from the mean estimated density (in units of number of cucumbers per metre of shoreline[2]), the shoreline length (10 km) and the assigned exploitation rate. During the harvest, the number of sea cucumbers landed, the fishing effort and auxiliary data (e.g. depth, substrate) were collected. Harvesters fished as they would normally; no attempt was made to distribute fishing effort evenly over the whole shoreline available for harvest. Two transects per experimental site were randomly chosen and 50 animals sampled from each, then split and individually weighed.

Mean weight of harvested animals was calculated for each experimental site and year by dividing the harvest weight by the sum of the piece counts of sea cucumbers harvested. Confidence intervals were calculated using a t-statistic, at an alpha level of 0.10 (90% confidence level). The sample size was the number of individual landings that were recorded per site and year. Where only one landed weight was recorded in a given site and year, the standard deviation was taken as the maximum standard deviation of average weight in any year for that site.

Mean weight of individual sea cucumbers was also calculated from biosample data collected from each experimental site and year. Data from the two biosample

[2] Shoreline length is used as a unit of area for calculating sea cucumber biomass because sea cucumbers are ubiquitous and do not exist in discrete, measurable, beds. It is assumed that the underestimation and overestimation of subtidal area that results from irregular shorelines (i.e. bays and headlines) are in balance.

transects per site were pooled. Confidence intervals were calculated using a z-statistic at an alpha level of 0.05 (95% confidence interval).

Density was calculated for all EFA's to 2003. Mean density was calculated from each experimental site and each year and tested for significance using ANOVA and paired *t* tests.

2.3.3 Results and Discussion

Estimated mean weight of harvested animals and 90% confidence intervals, by EFA, treatment (exploitation rate) and year, are illustrated in Figure 6. Decreasing trends can be seen in many of the time-series plots, including sites with relatively low harvest rates, with the Zeballos and Jervis EFAs showing more decline than others. Some sites with relatively high harvest rates showed an increase in mean weight of harvested animals. The time-series of mean weight may not reveal fishery effects on animal sizes, or may show inaccurate trends, for several reasons: 1) different locations within the site are harvested in different years, combined with animal size varying over small spatial scales; 2) animal size selectivity varies over time due to buyer size-preferences and differences in fishing behaviour among divers, 3) strong and weak incoming year classes will reduce or increase mean length, respectively. For these reasons, no regression analysis was conducted.

Mean weight of sea cucumbers from biosample data, by EFA, site and year are shown in Figure 7. The data do not show clear declining trends in the 8% or 16% sites, as expected. In some cases, lower exploitation-rate sites show greater declines in mean weight than in higher exploitation-rate sites; in other cases, increases in size are seen in high harvest rate sites (Laredo 16% site).

Mean density of sea cucumbers, by EFA and year, are shown in Figure 8. In the limited time-series of data, few consistent trends are evident; the only significantly declining trend was found in the 16% sites of Jervis Inlet and Zeballos. The 8% site in Jervis Inlet was also significantly different over time (ANOVA, $p<0.05$), but the trend was not consistently downward. Paired *t* tests from the first year to the latest year found only Jervis Inlet 16% site to be significantly different. Of interest is the density variation that occurs over time even in the 0% control and lightly fished 2% sites.

Several factors obscure the interpretation of EFA survey results (biosample and density data). First, location-differences in animal size, population density and recovery rate may confound the comparison of effects among sites of different harvest rates. For example, the 16% site in the Jervis EFA appears to have naturally higher densities of larger sea cucumbers than the other sites in this EFA, and thus recovery due to adult immigration is thought to be faster than occurs elsewhere (K. Ridgway, pers. comm.), masking the potential effect of fishing on animal size. This problem would best be addressed in future fishing experiments by harvesting larger sites; the greater the shoreline length harvested, the less prominent will be recovery by small scale horizontal immigration, and the more likely that potential effects (as might occur in a large scale fishery) will be revealed. Larger scale experimental fisheries would increase the ability to compare results among sites, and to apply the results to the commercial fishery.

Second, density and biosample transects that are periodically re-surveyed to monitor changes in animal size and population density in response to fishing are subject to spatial uncertainty. Although the vessel can return to the approximate GPS location, currents and vessel drift mean that the divers may reach the bottom tens of metres away from the location originally surveyed. Sea cucumber sizes and population densities can vary greatly over very short distances due to small-scale spatial variability of the substrate (Campagna and Hand 1999). Consequently, location effects can confound the determination of time effects on population density and aspects of size distributions. In other words, the data may not capture changes in mean weight and density over time, because the exact same locations are unlikely to be re-surveyed. A suggestion from industry is to establish permanent transects. This solution would improve the power of fishing experiments to estimate population response to harvest.

Thirdly, density and biosample transects are randomly located within a 10-km experimental fishing site and often do not coincide with the harvested locations. This problem is more pronounced in sites with low exploitation rates, where only 5 to 10 % of the shoreline is harvested to meet quotas (as discussed in the next section). Although an 'edge effect' may occur via migration on a small scale, it is possible that only the population inhabiting the areas immediately adjacent to the harvested area will be affected because of the limited mobility of sea cucumbers (da Silva et al. 1986). Consequently, the site-wide survey data may not reveal the effect of localized harvest.

3 Proportion of Shoreline Fished and Local Harvest Rate

3.1 Rationale

Recognising that effort is concentrated in the sea cucumber fishery, as it is in all dive fisheries, local harvest rates will be higher than the harvest rate applied over a designated management area. Changes in sea cucumber characteristics are more likely to be seen on local scales and be dependent on local harvest rates. The second objective of this paper involves a spatial analysis of fishery data to estimate the proportion of shoreline actually harvested and the local harvest rates that have occurred in the commercial fishery and in the EFAs. An earlier exploratory analysis of the Jervis Inlet EFA harvest data showed that the amount of shoreline harvested to achieve the quota at each 10-km site increased with the target exploitation rate (Bureau and Hand 2005). By comparing large-scale estimates of the proportion of shoreline fished and local harvest rates from the commercial fishery with small-scale estimates from EFAs, basic characteristics of effort concentration and harvest intensity for this fishery may be better understood.

3.2 Methods

Firstly, we calculated the proportion of shoreline fished in the commercial fishery as the ratio of the length of shoreline fished to the total shoreline length. Spatial data representing the shoreline fished in individual harvest events, as reported on harvest logbook charts, were overlaid in GIS, and the overlapping sections excluded to yield a 'corrected' total length fished (L_{fished}). These corrected shoreline lengths were grouped by statistical Sub-Area (which is the finest scale of shoreline length estimates available), and the proportion fished was calculated for each year between 1998 and 2003, inclusive. Proportions fished were calculated independently for Sub-Areas that have been transect-surveyed and for unsurveyed Sub-Areas, which rely on conservative extrapolated density estimates (Campagna and Hand 2004). Estimates from unsurveyed areas were further separated into 'good habitat' and 'poor habitat', following the convention of Campagna and Hand 2004, and averaged over Quota Management Areas (QMAs).

Local harvest rates in the commercial fishery were calculated for both surveyed locations on a Sub-Area basis, and for all commercial areas (whether surveyed or not) on a QMA basis. The estimated biomass for the shoreline fished (B_{est}) was calculated as:

$$B_{est} = D * W * L_{fished} \qquad (1)$$

where D is either the mean density estimate (in number of animals per metre of shoreline) for surveyed Sub-Areas or the conservative extrapolated density estimate for unsurveyed areas, and W is the average weight of an individual sea cucumber, based on market sample data. The local harvest rate (E_{loc}) was calculated for each year (i) as the ratio of the landings (C) to the estimated biomass for the shoreline fished,

$$E_{loc} = \sum_{i}^{n} \frac{C_i}{B_{est}} \qquad (2)$$

and then averaged over the number of years (n). Proportions of shoreline and local harvest rates were also calculated from a spatial analysis of EFA data. Length of shoreline fished per experimental site and year was measured as the total length covered by a series of adjacent dives that are closer together than approximately 200m, using Arcview GIS software at a scale of 1:60,000. Where only one dive was recorded, no measurement was taken. The proportion of the 10 km- long site that was fished (P) was calculated as this total length of shoreline fished (in units of m) divided by 10,000 m, the shoreline length of experimental sites.

The local harvest rate, or exploitation rate, (E_{loc}) was estimated per site and year using the following equation:

$$E_{loc} = \frac{E_{target}}{P} \qquad (3)$$

where: E_{target} is the proportional exploitation rate assigned to the experimental site (e.g. 4% of estimated biomass). The derivation of the above equation is given in Appendix 1.

3.3 Results and Discussion

Effort concentration is described by the average proportion of shoreline fished within surveyed Sub-Areas (Table 3). On average from 1998 to 2003, only 12.5% of the total shoreline was fished, in any given year, within each Sub-Area. In contrast, estimates of proportion shoreline fished within unsurveyed management areas are lower at 8.8% for ‘good’ habitat areas and 4.8% for ‘poor’ habitat areas (Table 4). The difference between surveyed and unsurveyed areas is due to lower quotas being applied in non-surveyed areas, since they are based on conservative density estimates; harvesters need to fish less shoreline in order to achieve these lower quotas.

Average harvest-rate estimates for surveyed Sub-Areas are presented in Table 3. These estimates are likely to be more accurate than those for un-surveyed areas. The overall average estimate for local harvest rates is 0.385, and the median is 0.314 (Figure 9a), the difference being due to a number of relatively large Sub-Area estimates.

Estimates over 1.0 (more than 100% harvest rate) are a result of fished locations having an actual density that is higher than the mean estimate from the survey.

Harvest rate estimates for all commercial areas, using the lower 95% confidence bounds of mean biomass (whether surveyed or extrapolated) are presented in Table 4. Non-surveyed areas have higher estimated harvest rates than surveyed areas because the extrapolated density estimates that are used to calculate biomass are conservative; therefore, the ratio of landings to biomass (Eqn. 2) is higher. For unsurveyed areas with poor habitat, the average harvest rate is higher still, in direct relation to the even lower extrapolated density estimate used for biomass calculations. This result implies that density estimates are underestimated in non-surveyed areas, at least in the locations fished.

Estimated harvest rates for surveyed commercial areas have a similar frequency distribution (Figure 9a) to that of estimated harvest rates for EFAs, with similar statistics (Figure 9b). Although the EFA harvest-rate distribution has a tail that is less skewed toward high values (due to more accurate density estimates within the 10km experimental sites), and with a lower mean value, the median value (0.32) is similar to that for the commercial areas (0.31). These best-estimates imply that the harvest rate achieved on a local scale by the sea cucumber fishery is about 30%, due to the effort concentration which naturally occurs in this dive fishery.

Estimates of local harvest rates in EFA's are subject to uncertainty in the estimates of length of shoreline fished. The measurement of the distance covered from the first dive to the last, in a group of dives, underestimates the shoreline length fished by divers because only the entry point of each dive is recorded. The number of accurately recorded dives differed among years due to logistical constraints; in some cases, scientific crew were able to record coordinates for every dive and in others, only select dives were recorded. In years where fewer dives were recorded, shoreline fished would be underestimated due to gaps between recorded dives. This would result in overestimated harvest rates for some sites in some years. However, the similarity in harvest-rate estimates from commercial fishing data and EFA data provide some confidence that the effects of this bias are not large.

Spatial analysis of EFA harvest data shows that the size of area fished is directly related to the exploitation rate on which quotas are based; the smaller the target exploitation rate, the smaller the proportion of shoreline of the experimental sites that was fished (Figure 10). Data from 4% experimental sites are comparable to the commercial fishery, which sets quotas based on a 4.2% exploitation rate; the mean estimate of the proportion of shoreline fished in these sites (12.5%) is the same as for surveyed areas of the commercial fishery (Table 3). Similar estimates of local harvest rates and proportion of shoreline fished for surveyed commercial areas and the 4% site of EFAs (Figs. 9 and 10) reveal important characteristics of how the sea cucumber fishery is executed. First, higher quotas result in a larger proportion of coastline fished (about 12% of the shoreline in areas with 4% quota and 53% when the quota is 16%). Second, in localities that are fished, the actual harvest rate is about 30% of the estimated local biomass. These results have two implications. First, conservative harvest rates required for an annual fishery will likely be exceeded on a local scale. Second, effort concentration creates temporary harvest reserves (areas that are left unfished, in a given year, once quotas are met).

The results suggest that the fishing experiments are not implementing what they were designed to test (the impact of different fixed exploitation rates), because low exploitation rates are not achieved on local scales. Given that effort concentration and high localized harvest rates are not avoidable without expensive monitoring and intervention, a change in the approach to experimental fisheries is needed. Although we have limited control on the localized harvest rate, we can control the frequency of harvest through spatial rotation. Experiments should be designed to determine the period that is required to allow animal size and population density to recover, over a range of different habitat types. The lessons learned from the harvest-rate experiments, in terms of survey and sampling designs, should be applied to new experiments in order to ensure that population changes can be detected with reasonable precision.

Given the moderately high estimates of harvest rates, a pulsed harvest using spatial rotation would be more conservative than an annual harvest. Although a purely area-based management system could work in this fishery, the industry values the quota system because it provides stable catches for individual license holders (K. Ridgway, PSCHA, pers. comm.).

4 Modelling Analysis

4.1 Rationale:

Computer simulation models are useful in prospectively evaluating the potential risks and benefits of alternative harvest strategies. Models can predict how different strategies might be expected to perform in light of the uncertainty inherent in biological systems, and rule out options with undesirable outcomes in terms of conservation and economics.

Past simulation-modelling studies predict that rotational harvests result in higher spawning biomass than annual harvest for red sea urchins (Botsford et al. 1993, Pfister and Bradbury 1996), horse clams (Zhang and Campbell 2002), and American sea scallops (Myers et al. 2000). Similarly for geoduck clams, Breen (1992) found that, when the proportional harvest rate exceeded 2%, mean biomass increased with the rotation period. Campbell and Dorocicz (1992) found not only increased mean biomass for geoduck clams, but also decreased probability of collapse under longer rotation periods. Studies that explored high harvest rates found that longer periods of rotation also resulted in increased mean annual yield (Breen 1992, Campbell and Dorocicz 1992, Lai and Bradbury 1998, Myers et al. 2000).

Humble (2006) developed a model for the sea cucumber fishery and found that, while longer rotation periods always increased spawning biomass, the period that maximises long-term catch depends on the harvest rate and population dynamics; characteristics which may vary over time and space. An adaptive rotational harvest was explored, where animal size and population density were used as biotic feedback indicators in harvest control rules that determine the appropriate period between harvest events. Under an adaptive strategy, more productive areas can be harvested more often than less productive areas, thus maximizing yield while ensuring conservation of the population. Two alternative strategies for adaptive rotational harvest were described. In the first “harvest when ready” strategy, recovery in size and density are measured each year, and re-harvest is allowed as soon as recovery targets are met. In the second strategy, “harvest then adjust”, the rotation period is initially set to 4 years and is adjusted after harvest if necessary. Recovery measurements are taken after the first four-year interval prior to harvest, and harvest is carried out as planned; if recovery targets have not been met, the rotation cycle is increased by one year, and if recovery targets are exceeded by a certain magnitude, the rotation cycle is decreased by one year. The latter strategy presents a more logistically feasible option since it allows the costs of travel and surveying to be recovered.

The objective of the modelling analysis for this paper was to compare the long-term performance of annual harvest, rotational harvest under fixed periods of 3, 4, and 5 years, and an adaptive rotational harvest strategy. Performance criteria include mean body mass of sea cucumbers, total spawning biomass, and mean annual catch. Proportional harvest rates of either 25% or 50% were assumed, which approximately spans the range of estimates of true harvest rate for the commercial fishery (Section 3).

4.2 Methods

The simulation model used to forecast stock trajectories is a stochastic age-structured model, adapted from the generalized model described by Constable and de la Mare (1996). Following the approach of de la Mare (1996), the basic model was modified to simulate a range of scenarios covering the range of uncertainty in our understanding of sea cucumber population productivity and resilience. Stochastic variation in annual recruitment was added using a Beverton and Holt stock-recruitment relationship, and assuming it to be a function of the mature population within the site. In each year of the stochastic simulations, the calculated number of recruits is multiplied by a random number from a lognormal distribution with a mean of 1 and a coefficient of variation of 0.5, drawn from the range observed for the red sea urchin (Smith et al. 1998). A lognormal distribution has a tail that is spread to the right, thus characterising the rare but large recruitment events that occur in broadcast spawning invertebrates (Morgan et al. 2000).

The model was parameterized using published estimates of the lifespan, natural mortality rate, maximum size, ages at maturity and recruitment to the fishery (Table 5a), as well as length and mass measurements, size distributions from survey data, and the weights of sea cucumbers sampled from the commercial fishery. Since sea cucumbers cannot be aged, these estimates contain a fair degree of uncertainty.

The model simulates the repeated harvest of a single population inhabiting an arbitrary 1-km length of shoreline, with an unfished density of 50 cucumbers per meter shoreline. This density is considered by harvesters to be “commercially worthwhile” (Campagna and Hand 1999). A high-density population was modelled in order to represent those areas likely to be targeted by commercial harvesters; areas that are also likely to be important larval sources.

The model assumes a closed population, with no emigration or immigration of adults and no settlement of larvae from outside the local population or dispersal of larvae from within the population. These assumptions are largely conservative, in that a less isolated stock would be less vulnerable to localized overfishing. Given that the extent of migration and larval dispersal are unknown and may be spatially constricted, it is important to assess how different harvest strategies might perform if local aggregations were isolated. Departures from these assumptions would be expected to improve the predicted performance of each harvest strategy. Retention of larvae represents an optimistic assumption, however, in that recruitment might be lower than predicted if larvae produced by the spawning stock in the simulated population were to disperse beyond the small area considered. The consideration of different scenarios of numerical recovery (resilience) may compensate for the overestimation.

Because population dynamics of the sea cucumber are poorly understood and are likely to vary spatially, a range of plausible scenarios were modelled to account for uncertainty. In this way, it was possible to evaluate how well each harvest strategy would perform under different hypotheses, or conditions that might occur in nature. This analysis included the following scenarios of population dynamics:

1. Base-case (best estimates of parameters),
2. Low and high productivity (defined by varying the growth and mortality rates),
3. Low and high numerical recovery (defined by varying the shape of the stock recruitment relationship). Numerical recovery is the level of recruitment at low spawning stock abundance.

Parameter values used in productivity and resilience scenarios are shown in Table 5b.

The three harvest strategies evaluated here include annual harvest (either 25% or 50%) implemented without error, rotational harvest under fixed periods of 3, 4, and 5 years, and adaptive rotational harvest ("harvest then adjust"). Recovery targets for average individual weight and population density, which determine whether the rotation period should be lengthened or shortened in the adaptive strategy, were defined as the approximate size at maturity and the lower range of density considered by harvesters to be commercially viable, respectively (Table 5c). Measurements of mass and density were subject to observation error. Because the average body weight and population density that occur naturally will depend on site conditions, these thresholds could, in practice, be determined specifically for each site based on survey estimates prior to fishing.

The model assumes that size selectivity varies in response to population density, because divers are generally more selective when density is high (K. Ridgway, pers. comm.). When density is over 40 cpms, harvesters will select only those individuals larger than 300 g, the size preferred by the market. As density decreases, harvesters will progressively become less selective until density falls below the threshold density (about 25 cpms, assuming the base-case growth rate) when all individuals present are taken. These thresholds are arbitrary, based on harvester accounts of fishing behaviour and on survey estimates of density in 'worthwhile' and 'possibly worthwhile' areas.

In each year of harvest, the model assumes harvest rates of 25% and 50% as a proportion of the vulnerable population. Lower harvest rates were not modelled because they are not achieved in practice on a local scale, as shown in Section 3. The model assumes the same proportional harvest rate for annual and rotational harvest: this reflects the nature of dive fisheries, in that effort is always concentrated. If quotas are ultimately scaled according to the rotation period, harvesters will tend to change the extent of the areas they fish, not the harvest intensity within these areas.

Population Model:

The number of animals in each age class in each year ($N_{a,t}$) is calculated based on the numbers that survived from the previous age class and year ($N_{a-1,t-1}$):

$$N_{a,t} = (N_{a-1,t-1} - c_{a-1,t-1}) * S \qquad (4)$$

where: $c_{a-1,t-1}$ is the number of animals harvested, from the previous age class and year;
S is the survival rate (e^{-M});

M is the mortality rate.

The number of recruits (animals of age 1; $N_{1,t+1}$) is calculated from the B/H stock-recruitment equation, R_t :

$$N_{1,t+1} = R_t \qquad (5)$$

$$R_t = \frac{\alpha * N_t}{\beta + N_t} * \varepsilon(cv)_t \qquad (6)$$

where: N_t is the total number of mature individuals in a given year

$\alpha = m * recK$

K is the carrying capacity, here defined as the number of mature (reproductive) animals in the unfished population (determined from the initial stock structure and the age at maturity function),

m is the ratio of the number of recruits at infinite population size to the number of recruits at carrying capacity (K). The most resilient population occurs when m=1 (constant recruitment),

$recK$ is the number of recruits at carrying capacity (this number is calculated based on an assumed unfished density of 50 cpms, for a 1 km length of coastline),

$\beta = K * \left(\frac{\alpha}{recK} - 1 \right)$,

$\varepsilon(cv)_t$ is the lognormally distributed error term.

For each harvest strategy and scenario of population dynamics, we ran 1000 stochastic Monte-Carlo simulations ("trials"), each consisting of a 100-year stochastic population trajectory. For each trial, performance measures, including average annual catch, average mass of individual animals, and proportion of spawning biomass to the unfished level, were averaged over the final rotation cycle, when the system can be considered to be near equilibrium. By taking the average result over the final cycle, with each year being at different levels of recovery, the results represent a network of harvest areas, each at different stages of recovery. Results were then averaged over the 1000 trials.

4.3 Results and Discussion

The full results produced by the model are shown in Table 6; notable aspects of the results are discussed below.

Average sea cucumber size was affected most noticeably by annual harvest when productivity was assumed to be low. Although the mean weight of sea cucumbers differed little among the different harvest strategies under the base-case scenario (Figure 11a), under a scenario of low productivity (slow-growing sea cucumbers), annual harvest resulted in substantially lower mean body mass than a 3-year fixed rotation period (Figure 11b). Rotation periods of 4 and 5 years performed similarly to the 3-year rotation. Depending on the harvest rate, “Harvest then adjust” changed the rotation period to allow the average mass to reach the recovery target, reaching average rotation periods of 4 and 2.4 years at 50% and 25% harvest rates, respectively. In the more optimistic scenarios of high productivity and numerical recovery, differences among harvest strategies were less pronounced, in terms of average mass.

Annual harvest resulted in low spawning biomass in the base-case, low productivity, and low numerical productivity scenarios (Figures 12 a, b, and c), particularly at the higher harvest rate of 50%. Rotational harvest of 3, 4, and 5-years performed relatively well in terms of spawning biomass, even at a 50% harvest rate, unless numerical recovery was low (Figure 12c); in this case, a 50% harvest rate resulted in very low spawning biomass for all strategies except the adaptive rotation. This result implies that for isolated populations where recruitment at low stock abundance is limited, a rotation period as long as 5 years is not sufficient for recovery of the harvested population. For these populations, “harvest then adjust” reached average periods of 10 and 6.2 years for 50% and 25% harvest rates, respectively.

Under scenarios of high productivity and numerical recovery (Figures 13a. and b.), annual harvest at 50% still resulted in unacceptably low spawning biomass, whereas each of the fixed and adaptive rotational harvest strategies allowed for relatively high spawning biomass, relative to the unfished state. The “harvest then adjust” strategy reached rotation periods of less than 2 years under the high-productivity scenario, due to control rules that allow a reduction in period if the density and mean mass exceed moderate target levels (thus allowing for higher catch). Thus spawning biomass is maintained above 30% of initial levels, but not higher. If the maximization of catch were not a management objective, a minimum rotation period could be added to the harvest-strategy control rules as a constraint.

In terms of average annual harvest, the relative performance of fixed-rotation-period strategies depends on the harvest rate and scenario of population dynamics, while the adaptive strategy consistently maximizes yield, subject to recovery constraints (Figure 14). In the base-case scenario (Figure 14a), if the harvest rate is 25%, yield is maximized by annual harvest, whereas at a 50% harvest rate, yield is maximized at a 3-year rotation period. “Harvest then adjust” results in similar yield for both harvest rates by changing the rotation period in response to the rate of recovery, which differs between harvest rates.

In the low productivity scenario (Figure 14b), yield is maximized at a 3-year rotation period for both harvest rates, but the adaptive strategy reaches a 4-year and a 2.4 year (average) cycle, with similarly high catch levels, for the 50% and 25% harvest strategies, respectively. The 4-year cycle is required in order to meet recovery targets for animal size and population density. Representing a trade-off against yield, the conservation advantage of the adaptive strategy is shown by higher spawning biomass than the 3-year fixed rotation at a 50% harvest rate (Figure 12b).

In the low numerical recovery scenario (Figure 14c), yield is maximized at longer fixed rotation periods: 4 years for a 25% harvest rate, and at least 5 years for a 50% harvest rate. Similarly to the low productivity scenario, “harvest then adjust” reaches longer rotation periods on average (6 and 10 years for the 25% and 50% harvest rates, respectively) than the “optimal” periods, due to the recovery rule for density, which is the controlling factor in this scenario. Accordingly, spawning biomass is highest at a 50% harvest rate in the adaptive strategy (Figure 12c), although at a 25% harvest rate and an average cycle of 6 years, the spawning biomass is lower than in the 5-year strategy due to the variable cycle length of the adaptive strategy (standard deviation = 2.2 years) which can allow more frequent harvest.

Under favourable conditions of high productivity and numerical recovery (Figure 15a and b), the adaptive strategy provides less catch than annual harvest, which is consistent with higher spawning biomass levels (Figure 13a and b). In the high numerical recovery scenario (Figure 15 b), yield (catch) is maximized by annual harvest for both harvest rates. However, “harvest then adjust” reaches a longer cycle on average (2.6 and 1.7 years, for 50% and 25% harvest rates), because it requires the average animal weight to reach a recovery target. In contrast, annual harvest results in lower average mass (233 g) than “harvest then adjust” (266 g) at a 50% harvest rate, under this scenario (Table 7). Again, the adaptive strategy represents a trade-off between catch and conservation.

General conclusions of this analysis are as follows:

1. Given the high local harvest rates estimated for the commercial sea cucumber fishery, rotational harvest at a fixed rotation period of three or more years results in higher average animal mass and higher spawning biomass than does an annual harvest strategy.

2. If populations are isolated (numerical recovery is slow) and the harvest rate is high, a rotation period of 5 years may be insufficient to prevent depletion of spawning biomass to below 25% of unfished levels.

3. The adaptive rotational harvest strategy consistently maintains spawning biomass above 25% of initial levels, while adjusting the rotation period in order to meet recovery targets at different harvest rates. Simply by monitoring recovery in average animal weight and population density, this strategy finds the rotation period that maximizes catch within conservation constraints.

The adaptive strategy is robust to uncertainty in population dynamics and in the harvest rate. This is highly advantageous, considering that there is a high degree of uncertainty in the parameter estimates used in the model, since no method has been found to age sea cucumbers.

An adaptive rotational harvest strategy would require small-scale area management in order for the population to share the same population dynamics, and thus recover homogeneously. The costs of spatially intensive management may be offset by the ability to meet management objectives under uncertainty, so that large-scale surveys are not required to accurately calculate the total allowable catch based on a target harvest rate. Instead, smaller scale surveys are used to determine when areas are to “re-open” for harvest. The challenge in using this strategy, however, is to address the sampling issues discussed in Section 2, in order to minimize the uncertainties in interpretation of survey and sampling results. The sampling protocols for monitoring recovery criteria, required to provide the information necessary for reliable feedback to the management process, is an important consideration. Suggestions for improvements over the existing protocols, which were found to contain too much uncertainty, are provided in the following section.

Pessimistic assumptions of no immigration and low numerical recovery contributed to low predicted performance for the annual and fixed rotational harvest strategies. The model did not account for the self-regulating behaviour of harvesters: in general, they will not continue to harvest an area if the density is not commercially viable. In addition, catch limits based on a conservative harvest rate create temporary harvest reserves (due to effort concentration), and substantial densities are found below fishing depths; thus, due to immigration and larval dispersal, recovery is likely to be faster than predicted here. Given these safety factors, an adaptive rotational strategy may not be required in order to conserve the population. However, given that annual harvest resulted in poor conservation performance even under optimistic scenarios of high productivity and numerical recovery, a fixed rotation cycle of at least 3 years would be a scientifically defensible, precautionary management strategy. In any case, a fixed rotation strategy is not inconsistent with an adaptive strategy; if recovery is not evident after three years, we would always consider whether the next cycle should be longer.

5 Rotational Harvest Experiments

Having identified problems in implementing the experimental design for the current experimental fishing program (Section 2.3) and outlined the basic characteristics of effort concentration and high local harvest rate revealed through spatial analysis of fishery and experimental data (Section 3), the information gained can be used to design improved fishing experiments. In this section, recommendations are provided for the methodology of an experiment designed to test rotational harvest.

5.1 Changes from current EFA's

1. **Use larger-scale experimental harvest sites** to reduce the potential for edge effects and immigration which might result in a faster recovery than would be achieved in the larger areas that are fished commercially.

2. **Harvest the entire length of the shoreline within an experimental site** (or at least those parts that are logistically feasible and that harvesters consider to have economically-worthwhile densities), instead of setting quotas based on a given harvest rate. In other words, the harvesters fish the site to the extent they would in the commercial fishery. The rationale is twofold:

a) This will represent areas targeted by the commercial fishery where harvesters concentrate effort (e.g. areas with good quality habitat that are close to port).

b) This will help to ensure that harvesting coincides with density and biosample transects, and thus survey data will be more likely to show the effects of harvest on animal size and population density.

3. **Establish permanent transects** for density and biological samples to avoid small-scale location differences confounding the comparison of density and animal size between years. Also, samples may be taken from different depths in different years, confounding the comparison in size between years, because animal size can vary with depth in some locations (K. Ridgway, pers. comm.). In the current procedure, transects to be sampled are selected at random and the diver swims along the line toward shallower water and collects the first 50 animals encountered. If too few animals are found along the transect, the diver swims a wider distance to meet the sample size requirement. A method of biosampling that would more consistently represent the size distribution in a given area would be to set up two permanent lines 4-m apart and harvest all animals found between the two lines within a given depth range. In this way, the same area is always sampled. It is expected that such a small-scale depletion will not have a lasting effect on future density estimates in the area. These samples can be used to estimate not only the size distribution of animals in that area, but also the population density. Some consideration is required as to whether these samples can be used in place of the current density-transect surveys. In any case, increasing the

number of biosampling locations (from 2, in a 10-km-long experimental site) would increase the likelihood of detecting changes in the size distribution of sea cucumbers within an experimental fishing site. While the total sample size from these two biosamples may be enough to produce narrow confidence bounds on estimates of average size, uncertainty remains as to whether this would capture the effects of harvest, whereas increasing the number of biosample sites will increase statistical power.

4. **Establish survey transects in "fishable" locations** (feasible to harvest, with sufficient commercial density), so that sampling will coincide with harvest, increasing the likelihood of detecting the effects of harvest on animal size and population density.

5.2 Objectives

1. To determine the range of periods required for population recovery in different areas along the coast, and to determine whether habitat type or local oceanographic conditions affects recovery period.
2. To measure the performance of fixed rotation periods (annual, 3 and 4 years) and an adaptive rotation period, in terms of the recovery of animal size and population density, over repeated harvest pulses (several rotation periods).

5.3 Experimental Treatments

Each of the treatment options listed below would require a number of replicate sites, representing each of two or three habitat categories. Harvesters have observed that areas of low current, such as protected bays or inlets, generally have larger sea cucumbers and take longer to recover, in terms of population density and average size, after harvest. Suitable categories for habitat could be based on criteria that harvesters consider to indicate higher vs. lower-productivity habitat, or faster vs. slower-recovering sea cucumber populations. Comparison of recovery rates between habitat types would allow the data analysis to separate the effect of habitat, which is likely to explain part of the variability among recovery rates along the coast.

1. **Controls.** A number of control sites should be assigned, and not harvested, but surveyed on the same schedule as the harvest treatment sites. These sites would indicate the level of variability in animal size and population density that occurs over time in the absence of harvest. The controls should be matched as closely as possible to the habitat types in the areas harvested in the treatment areas. Ideally these should not be located immediately adjacent to harvested shoreline so as to be buffered against edge-effects.
2. **Depletion/Recovery.** A treatment to monitor recovery from intensive harvest and determine recovery period is warranted for several reasons. First, a critical source of uncertainty in the modelling analysis was resilience or numerical recovery after harvest. Specifically, if numerical recovery was very low after an area was intensively harvested, then a longer rotation period (up to 12 years) was required to maintain spawning biomass and sea cucumber size. An appropriate research question is, to what extent do size and density recover each year relative to initial conditions and how many years until recovery to, say, 80% of initial levels?

   A secondary objective of a depletion/recovery study would be to determine whether the dominant mechanism for recovery after harvest is immigration or larval settlement / juvenile recruitment. Addressing this question would be useful because, if immigration is dominant, then a lag-time in detecting depletion would be likely. If lagged depletion does occur, an adaptive strategy which adjusts the rotation period to ensure recovery to a target level might be warranted. Towards this objective, size-frequency data could be collected over time. To interpret this data: immigration dominates if, one year after harvest, the majority of sea cucumbers in the site are large (for example, no significant decline in the proportion of sampled cucumbers over 300g). Recruitment dominates (through either larval settlement or local immigration of juveniles from kelp habitat), if the majority of sea cucumbers sampled one year after harvest are small. Harvesters have observed mostly the latter, with some exceptions, however scientific sampling would reduce the uncertainty

A final rationale for this treatment is that results will provide, within a few years, preliminary data on sustainable fixed rotation periods for the commercial fishery. In addition, the variability in recovery time among locations would provide the range of rotation periods that could be expected to occur.

The 16% sites from EFA's have been intensively harvested for several years, and may provide ideal sites to measure recovery, since we have baseline data from these sites (although biosample data are limited). Comparison of recovery after harvest in these sites with recovery at previously unfished sites may reveal whether previously unfished sites recover faster than repeatedly fished sites.

3. **Adaptive Rotation Period**. Given that recovery time may vary over time and among locations on the coast, managers might consider an adaptive rotational harvest strategy. In the "harvest then adjust" strategy to be tested, survey estimates of size and density taken immediately prior to harvest would determine whether the rotation period needs to be lengthened or shortened for the next cycle. The adaptive strategy could begin with a 3-year rotation period which would be lengthened or shortened on the basis of pre-harvest surveying.

   Comparing the results of this adaptive strategy versus a fixed rotation period would determine whether an adaptive strategy is required. For example, if recovery targets are consistently met within 3 years in all experimental harvest sites then a fixed rotation period would be the best management option for the commercial fishery and monitoring of recovery and adjusting the rotation period would not be required.

   For the adaptive rotational harvest treatment, criteria for size and density recovery could be developed on a site-specific basis. For example, experimental site A may have naturally smaller sea cucumbers than site B, so the threshold for average mass, which determines whether the site has recovered, would be lower.

4. **Fixed Rotation Periods**. Experimental harvesting on fixed rotation periods would capture any potential longer-term impacts of repetitive harvest, such as a lag in depletion of density due to immigration. Monitoring of rotational harvest experiments will provide better data than might be possible in a commercial pilot rotation fishery, through the use of permanent transects that are sampled annually to assess the state of recovery. Initial surveys would provide data for estimation of baseline density and animal size distributions; annual surveys and pre-harvest surveys would allow estimation of the level of recovery of density and size. If results differ between habitat types, comparison of results within habitat types should improve the ability to detect differences among rotation period treatments.

5.4 Criteria for experimental harvest sites

In order to obtain reliable pre-harvest baseline data, sites should be selected that have not been recently fished. A 10-year limit for no-harvest seems reasonable because modelling results predict that weight and density recover to commercially desirable targets within 9 years unless resilience is very low. Harvesters have observed full recovery within three years (K. Ridgway, pers. comm.), indicating that resilience in popular areas is likely good, but it should be recognized that some recovery may be due to immigration from adjacent, less-favourable, habitat.

The number of sites in each treatment should be sufficient to represent the range of recovery times that might be observed in different habitat types. An analysis of previous sampling data should be conducted to determine the number of replicates required. Nine sites per treatment would allow three sites per habitat type. Each site should encompass as much area of high sea cucumber density as possible, and be considered commercially feasible to fish. These sites should represent commercially vulnerable localities on the coast (low density areas are unlikely to be targeted by harvesters, thus testing harvest effects in these areas is not a priority). Survey data, as well as harvesters' knowledge of productive fishing localities, can be employed in choosing suitable experimental sites.

Sites should be large enough to offset the possibility that the scale of harvest is not applicable to a larger commercial fishery. The larger the areas harvested in an experiment, the more confident we can be that we will not underestimate the potential effects of large-scale harvest.

5.5 Data collection and interpretation:

1. Conduct initial surveys to characterize baseline conditions of average size, size distribution, and population density, and to determine a suitable sampling regime that will provide the desired ability to detect change in abundance or mean weight.
2. Conduct annual surveys to monitor recovery in animal size and population density.
3. Conduct surveys prior to harvest in the year each site is scheduled for harvest, to assess the extent of recovery that has occurred before re-harvest.
4. Variables of interest:
   - average weight of sea cucumbers
   - proportion of sampled cucumbers over 300g (or a size that occurs with high frequency in the size distribution data from initial surveys)
   - density of sea cucumbers over 300g

5.6 Potential for Additional Research

In a subset of the intensive harvest sites, ROVs (Remotely Operated Vehicles) could be used at depths greater than 20 m to study post-harvest vertical migration of sea cucumbers. ROVs could be used to survey density to perhaps 80 m (or some depth at which densities are expected to drop). Both ROV surveys at depth and SCUBA surveys above 20m would be conducted in the site before harvest to estimate initial density. A comparison of pre- and post-harvest estimates of density for deep and shallow portions of the survey would enable a quantitative estimate of the extent of migration. Before resurveying, some time should be allowed for the immediate effect of downward migration by cucumbers (thought to be a predator avoidance response triggered when guts drain into the water from onboard processing) to be reversed, and for animals at depth to migrate up. An appropriate re-survey time might be 15 days, as a minimum, which is long enough for a sea cucumber to move 60 m net into shallows at an average daily movement distance of 3.9 m per day (Da Silva et al. 1986). Studies using ROVs should be conducted in areas not fished in recent years, to avoid the possibility that deeper segments of a population may have been depleted to some degree.

6 Pilot Rotation in Commercial Areas

As well as PSCHA's interest in sustaining sea cucumber populations for a long-term fishery, they are interested in a rotational fishery for economic reasons. From their experience with *ad-hoc* rotational fishing, harvesters have observed that populations have larger sea cucumbers and a more varied size structure than areas fished every year (K. Ridgway, pers. comm.). Fishing efficiency is improved and the price obtained for the product will be higher.

A pilot rotation would provide an opportunity for Industry, Science and Management to gain practice in implementing a rotational strategy. Accompanied by improved data collection (discussed below), the pilot can also provide data on conservation of animal size and population density as compared to annual harvest. New data collection procedures can be implemented, potential problems related to management and feasibility can be discovered, and solutions devised. This learning will be particularly useful if and when rotational fishing is implemented on a larger scale.

Implementing a pilot rotation within only surveyed areas of the current commercial fishery would be feasible because local density estimates could be used to delineate areas of similar abundance for spatial rotation. In addition, harvesters would not be limited to fishing in the designated rotational harvest areas, but could fish in the rest of the (unsurveyed) commercial areas, so that they are not "bumping shoulders". To assess the performance of pilot rotation areas, permanent transects (as described in Section 5.1) should be established in locations where fishery data or transect data show relatively high densities.

7 General Discussion

The sea cucumber fishery was changed from a rotational to an annual fishery in 1997 in order to provide an uninterrupted time-series of fishery data for use in biomass dynamic models and to speed the process of evaluating population responses to harvest. Given the lack of biological information about sea cucumbers, fishery data were assumed to be the most feasible tool available to evaluate stock status (Boutillier et al. 1998). These authors, however, pointed out some problems associated with fishery logbook data that had prevented their use of it for estimating biomass and quotas. These problems included pre-season scouting, leading to underreporting of fishing effort, and hyperstability of catch-per-unit-effort (CPUE) resulting from the movement of harvesters from spot to spot to maintain acceptably high catch rates. CPUE will not initially decline even if the population as a whole is declining through serial depletion. For these reasons, CPUE is not considered a reliable index of abundance for fitting biomass dynamic models. Furthermore, to successfully employ the results of biomass dynamic models in setting catch levels for an annual harvest, a theoretically sustainable harvest rate must be achieved. The results of spatial analysis of commercial fishing data in this paper show, however, that conservative harvest rates are not achieved on the spatial scale of localized harvesting activities due to effort concentration. Effort concentration and high harvest rates naturally occur in dive fisheries, where most animals encountered in the target area are taken. As a result, the local harvest rate is much higher than the conservative harvest rate used to set catch limits.

Regulations aimed at reducing or spreading out effort would be required in order to maintain an annual harvest system. As demonstrated in the experimental fisheries, lower TACs would result in less shoreline fished. Similarly, defining smaller-scale quota management areas in an attempt to spread out fishing effort would merely result in more small areas of effort concentration, while increasing management costs as well as travel costs for harvesters and buyers.

In addition to the argument that annual fishing is not providing the intended time-series data for stock assessment, model predictions as well as harvesters' reports raise concerns about annual harvest with regards to conservation and economic benefits. The sea cucumber harvest model predicted that annual harvest (at harvest rates estimated for this fishery) could lead to decline in animal size and spawning biomass, as well as lower catches in the long term, as compared to rotational harvest. These predictions are supported by industry experience: harvesters have found that annually fished areas often have smaller sea cucumbers, whereas a two or three year recovery period allows for both recovery of animal size and easier fishing. Both of these factors may allow greater economic benefits through keeping the product price high and sustaining a more efficient industry.

The sea cucumber fishing industry is requesting a return to spatial harvest rotation, in combination with a conservative harvest rate, for the next phase of the commercial fishery: specifically, a 4% quota every 3 years (as opposed to a 12% quota every 3 years) (DFO 2003). Under this strategy, expanding the fishery to include the 50% of the coast currently closed to fishing would not increase the TAC; it would mean that an area three- times larger than the current commercial areas would be harvested with the same TAC at one-third the frequency. Each area under rotation would thus be harvested at 4% (which, according to our results, would result in a 30% localized harvest rate in portions of the management area), every 3 years. Survey data show no significant evidence of an impact in the commercial fishery, which is currently based on a 4% quota every year; thus, the same quota every 3 years is more conservative than the current annual strategy. If a rotational harvest strategy were implemented only within the current commercial areas, the same TAC would be concentrated in one-third the area, which harvesters are concerned would put unnecessary pressure on the stocks as well as lead to competition for space that would have to occur in order to meet quotas within restricted areas (K. Ridgway, pers. comm.). However, a small-scale pilot rotation within surveyed areas of the commercial fishery might be beneficial in providing improved data on population response to harvest, and could begin to work out potential implementation problems for a larger scale rotational harvest.

A plausible and precautionary management option might be to implement the above conservative regime in an expanded area of the coast, while scientific research is conducted on the effect of rotational harvest at higher quota levels. This data could be used eventually to determine a sustainable period of rotation (or an adaptive rotation) for a future time when the exploitation rate used to set quotas is to be multiplied by the rotation period (as is generally done in rotation fisheries). This management option would allow industry to access more coastline on a rotational basis, while keeping exploitation at a very precautionary level until results from rotational harvest experiments provide the information required to determine a scientifically defensible increase in TACs.

8 Recommendations

1. Redesign protocols for the collection of market sample data. The current program fails to provide information of acceptable sensitivity to evaluate fishery effects. Samples of harvested animals must be uniquely identified and linkable to specific harvest events that are accurately mapped.
2. Implement a modified biological sampling regime where permanently marked swath-transects are established in select localities and from which all sea cucumbers are collected and sampled immediately prior to harvest. Sample sites should include areas that are regularly fished to detect potential changes in cucumber size and unfished locations to take into account natural variability.
3. Begin a pilot 3-year rotational harvest regime in surveyed commercial-fishery areas in Areas 6, 7 and 8 to identify and resolve administrative difficulties related to the management and enforcement of area closures. This provides an opportunity to engage the fishing industry in a consultative process to implement rotational fishing.
4. A change in the approach to experimental fisheries is needed. Design and implement experiments in select localities in the 25% of the coast open to scientific experiments to determine the range of periods that are required to allow animal size and population density to recover from typical harvest intensities, and to determine the sampling regime necessary to detect population changes at the desired level of significance. The scale of these experiments should be large enough to represent commercial harvest activity.
5. Begin the consultative process with the fishing industry to define sections of the closed portion of the coast to be opened on a rotational basis, and identify currently-open areas in need of recovery. Experienced harvesters can advise on considerations of logistical constraints related to travel costs, as well as communicate their knowledge of sea cucumber distributions.

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Table 1. Number of market samples collected and regression statistics for the relationship between average weight of harvested sea cucumbers and year.

	Number of Samples									
	1997	1998	1999	2000	2001	2002	2003	Slope (g/year)	p-value	R^2
Area 6 overlaps	19	20	41	14	31	37	47	-3.57	0.54	0.08
Area 6 all	70	54	122	115	195	176	207	2.81	0.46	0.11
Area 7 overlaps	25	20	49	75	105	27	83	-9.78	0.54	0.08
Area 7 all	55	175	172	166	158	67	197	9.06	0.06	0.54

Table 2. Comparison of density estimates and biosample statistics from transect surveys conducted in commercial fishery areas Bella Bella - Area 7 (BB), Gil and Gribbell Islands - Area 6 (GG) and Area 12 inlets (A12). Only transects surveyed in both years were included in the analysis.

	Density Transects						Biological Samples			
Survey Title	Year of Survey	# of Transects	Mean Density (c/m-sh)	P-value	Lower 95% Confidence Bounds	P-value	# of Animals	Mean Individual Spit Weight (gm)	SE	P-value
BB	1998	190	13.87		12.09		391	343	**6.0**	
	2002	190	12.86	0.49	11.49	0.48	415	293	**7.2**	**<0.05**
GG	1999	235	19.79		18.05		325	248	**7.5**	
	2003	235	17.38	0.11	15.86	0.10	462	217	**4.8**	**<0.05**
A12	2000	129	9.35		8.03		285	301	**4.0**	
	2004	129	7.44	0.09	6.34	0.08	272	298	**3.7**	**0.78**

Table 3. Proportion of shoreline fished and annual local harvest rate by Statistical Sub-Area, based on estimated mean biomass in surveyed Sub-Areas and averaged over the years 1998 to 2003.

QMA	StatArea	Sub-Area	Mean Density (c/m-sh)	Mean Individual Weight (gm)	Shoreline Length (m)	Avg. Shoreline Fished (m)	Proportion Shoreline Fished	Local Harvest Rate	SE Harvest Rate
12B	12	40	8.09	405	124,807	8,356	0.067	0.405	0.179
12B	12	41	7.12	314	229,085	8,293	0.036	0.794	0.134
24A	24	4	7.12	377	38,788	6,495	0.167	0.480	0.202
24A	24	5	7.12	489	54,143	8,278	0.153	0.154	0.030
24A	24	6	7.12	313	29,707	3,798	0.128	0.458	0.187
24A	24	14	7.12	373	29,215	2,737	0.094	0.226	0.006
24B	24	7	7.12	346	74,176	11,098	0.150	0.374	0.079
24B	24	10	7.12	419	52,655	4,378	0.083	0.107	0.007
6A	6	5	19.82	244	203,683	30,438	0.149	0.207	0.032
6A	6	27	19.82	258	6,871	2,014	0.293	0.251	0.087
6A	6	28	19.82	218	22,411	5,953	0.266	0.298	0.076
6B	6	3	19.82	255	141,540	17,740	0.125	0.314	0.090
6B	6	6	19.82	225	86,906	14,660	0.169	0.341	0.049
6B	6	7	19.82	234	28,829	6,030	0.209	0.311	0.084
6C	6	9	7.15	319	367,366	16,159	0.044	0.494	0.075
7A	7	15	12.86	355	134,531	11,157	0.083	0.161	0.029
7C	7	17	12.86	310	205,719	31,385	0.153	0.337	0.048
7C	7	30	12.86	313	37,330	2,746	0.074	0.522	0.200
7C	8	5	15.27	258	43,176	4,975	0.115	1.387	-
7C	8	6	38.21	252	21,958	1,120	0.051	0.163	0.048
8A	8	3	16.51	236	12,860	994	0.077	0.509	-
8A	8	4	16.51	285	216,207	17,210	0.080	0.310	0.065
8A	8	16	13.59	340	70,442	7,549	0.107	0.244	0.067
Average							0.125	0.385	

Table 4. Average proportion of shoreline fished and local harvest rate, based on the lower 95% confidence bound of mean estimated biomass, in all Quota Management Areas over the years 1998 to 2003. Estimates are presented separately for surveyed areas and for unsurveyed areas where density estimates are extrapolated.

QMA	Lower 95% Density Estimate (c/m-sh)	Proportion of Shoreline Fished	Local Harvest Rate Average	Local Harvest Rate Range	
Surveyed Areas					
12B	5.60	0.046	0.790	0.099	1.986
24A	5.45	0.149	0.440	0.061	1.887
24B	5.45	0.158	0.345	0.131	0.850
6A	17.85	0.244	0.245	0.034	0.549
6B	17.85	0.166	0.352	0.108	0.756
6C	5.76	0.036	0.628	0.373	0.962
7A	8.84	0.085	0.213	0.118	0.367
7C	13.05	0.145	0.523	0.104	1.723
8A	12.77	0.103	0.344	0.120	0.646
Average		0.126	0.431	0.128	1.081
Extrapolated, good habitat					
12A	5.08	0.050	0.754	0.176	2.967
12B	5.08	0.144	0.590	0.058	2.061
5A	5.08	0.071	0.897	0.197	5.234
5B	5.08	0.066	0.995	0.197	2.868
6A	5.08	0.180	0.574	0.263	1.186
6B	5.08	0.065	3.175	0.368	12.143
6C	5.08	0.066	0.515	0.089	1.492
7A	5.08	0.111	0.799	0.179	4.196
7B	5.08	0.090	1.218	0.215	7.422
8A	5.08	0.036	2.095	0.337	13.223
Average		0.088	1.161	0.208	5.279
Extrapolated, poor habitat					
13A	2.50	0.061	1.627	0.489	2.889
13B	2.50	0.058	2.843	0.550	13.737
5A	2.50	0.049	3.167	0.433	14.360
7B	2.50	0.013	2.717	0.400	7.374
8A	2.50	0.060	1.598	0.641	4.342
Average		0.048	2.391	0.503	8.540
Overall Average		0094	1.143	0.239	4.384

Table 5a. Population parameters used in the operating model.

Parameter	Value	Source
Lifespan (t_{max})	12 years	Speculative estimate of maximum age by P. Fankboner (Phillips and Boutillier, 1998)
Natural Mortality (M)	0.37*	Boutillier et al. (1998) estimate M using the Hoenig (1983) model: $\ln(M) = 1.44 - 0.982 \ln(t_{max})$
Length at maximum age (L_∞)	500mm	Maximum length is estimated at 500mm (Fisheries and Oceans website); I assume this is close to length at max. age.
Age at 50% maturity	5.5 years	Mature animals are >4.6 years (Cameron and Fankboner 1989); Individuals reach sexual maturity at 5-6 years (Fisheries and Oceans website)
Age at 95% maturity	7 years	
Age at 50% selectivity	5 years	Speculative estimates of the age at recruitment to the fishery range from 4 to 8 years (Boutillier et. al., 1989).
Age at 95% selectivity	7 years	
Von Bertalanffy growth rate	0.20*	Found iteratively to meet assumption of the initial average mass of animals selected equal to 310 g (based on data from the commercial fishery) given selectivity at age. Some areas have higher average mass, so this growth rate may be an underestimate.
Interannual variability in Recruitment (coefficient of variation)	0.5*	Recruitment variability observed for red sea urchins: 0.5 to 1.0 (Smith et al., 1998)

* these values are varied to represent the different scenarios of population dynamics.

Table 5b. Parameter values used in the model to characterise different scenarios of productivity, numerical recovery and interannual variability in recruitment. Beside each scenario, the critical parameters are shown in bold font.

Scenario		Von Bertalanffy growth rate	Natural Mortality rate	Recruitment "m" parameter	Coefficient of variation in recruitment
Base case		0.20	0.37	1.3	0.5
Productivity	low	**0.16**	**0.20**	1.3	0.5
	high	**0.26**	**0.73**	1.3	0.5
Numerical recovery	low	0.20	0.37	**3.0**	0.5
	high	0.20	0.37	**1.05**	0.5

Table 5c. Thresholds for average individual weight and density used to define recovery in the adaptive rotational scenario.

	Threshold	Source
Body Weight	260 g	Age of maturity is 4.6 yrs (Cameron and Fankboner 1989), which equates to 257 g (using base-case growth parameter estimates). 260 g is also considered a desirable size for the market (Paulo Tai, Evergreen International Foodstuffs Ltd., pers. comm.).
	280 g	Through an iterative process, the estimate that resulted in an equilibrium rotation period that maximized the long-term yield at low, medium and high levels of productivity, given a 50% harvest rate.
Density	15 cpms	Estimate close to the lower 95% confidence limit for survey estimates in a ‘medium density’ site that was considered ‘possibly worth harvesting’ by divers (Campagna and Hand 1999)
	30 cpms	Estimate close to the upper 95% confidence limit for survey estimates from the same medium density site. Also represents 60% of the unfished density (50 cpms) assumed for the stock.

Table 6. Full results of the simulation model

Harvest Rate	Scenario	Measure (at equilibrium)	HARVEST STRATEGY				
			Harvest then adjust	***Annual***	**3-year**	**4-year**	**5-year**
50%	**Base-case**	Mean annual harvest (kg)	1275	359	1267	1083	939
		Mean rotation period	3.2	1.0	3.0	4.0	5.0
		Mean body mass (g)	272	233	274	283	288
		Spawning biomass (scaled)	0.42	0.03	0.45	0.57	0.64
	Low Productivity	Mean annual harvest (kg)	809	2	869	807	731
		Mean rotation period	4.0	1.0	3.0	4.0	5.0
		Mean body mass (g)	266	197	258	270	277
		Spawning biomass (scaled)	0.48	0.00	0.40	0.52	0.58
	High Productivity	Mean annual harvest (kg)	2621	2682	1811	1459	1200
		Mean rotation period	1.8	1.0	3.0	4.0	5.0
		Mean body mass (g)	282	273	295	298	301
		Spawning biomass (scaled)	0.37	0.21	0.60	0.68	0.73
	Low Numerical Recovery	Mean annual harvest (kg)	263	0	63	191	312
		Mean rotation period	10.3	1.0	3.0	4.0	5.0
		Mean body mass (g)	295	249	276	281	285
		Spawning biomass (scaled)	0.27	0.00	0.02	0.07	0.15
	High Numerical Recovery	Mean annual harvest (kg)	1683	2348	1448	1191	1007
		Mean rotation period	2.6	1.0	3.0	4.0	5.0
		Mean body mass (g)	266	233	277	284	289
		Spawning biomass (scaled)	0.48	0.18	0.59	0.67	0.72
25%	**Base-case**	Mean annual harvest (kg)	1214	1355	778	621	516
		Mean rotation period	1.9	1.0	3.0	4.0	5.0
		Mean body mass (g)	279	263	294	298	300
		Spawning biomass (scaled)	0.50	0.28	0.71	0.77	0.81
	Low Productivity	Mean annual harvest (kg)	755	588	628	527	451
		Mean rotation period	2.4	1.0	3.0	4.0	5.0
		Mean body mass (g)	273	232	285	290	294
		Spawning biomass (scaled)	0.54	0.12	0.65	0.71	0.75
	High Productivity	Mean annual harvest (kg)	2135	2303	990	768	623
		Mean rotation period	1.2	1.0	3.0	4.0	5.0
		Mean body mass (g)	292	291	304	305	306
		Spawning biomass (scaled)	0.54	0.50	0.79	0.83	0.86
	Low Numerical Recovery	Mean annual harvest (kg)	327	10	407	428	397
		Mean rotation period	6.2	1.0	3.0	4.0	5.0
		Mean body mass (g)	298	271	292	297	300
		Spawning biomass (scaled)	0.40	0.00	0.29	0.44	0.54
	High Numerical Recovery	Mean annual harvest (kg)	1418	1795	821	650	535
		Mean rotation period	1.7	1.0	3.0	4.0	5.0
		Mean body mass (g)	276	267	294	298	301
		Spawning biomass (scaled)	0.57	0.46	0.77	0.82	0.85

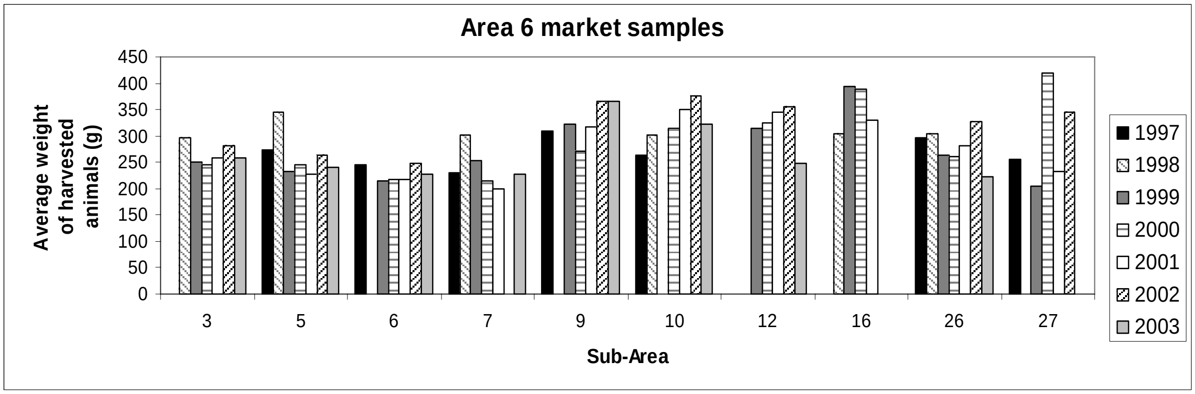

Figure 1: Mean weight, by year, of individual sea cucumbers harvested in Sub-Areas of Statistical Area 6, from market sample data.

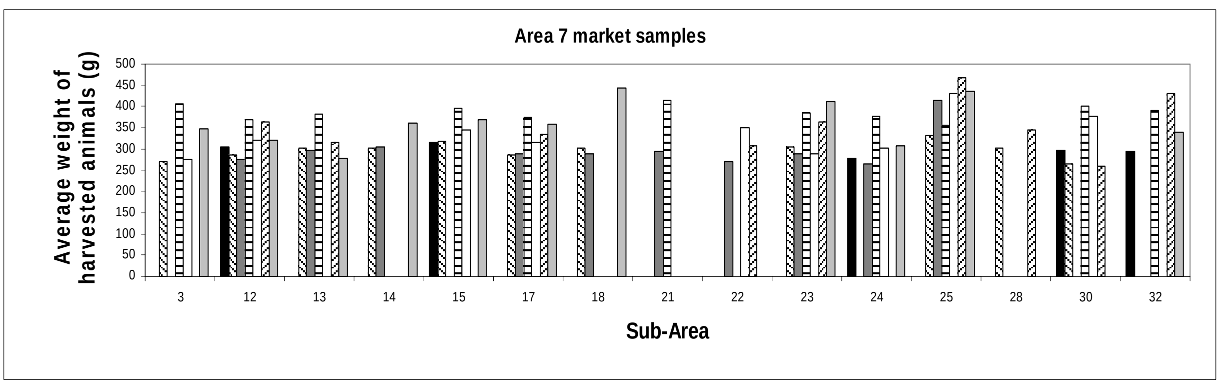

Figure 2: Mean weight, by year, of individual sea cucumbers harvested in Sub-Areas of Statistical Area 7, from market sample data.

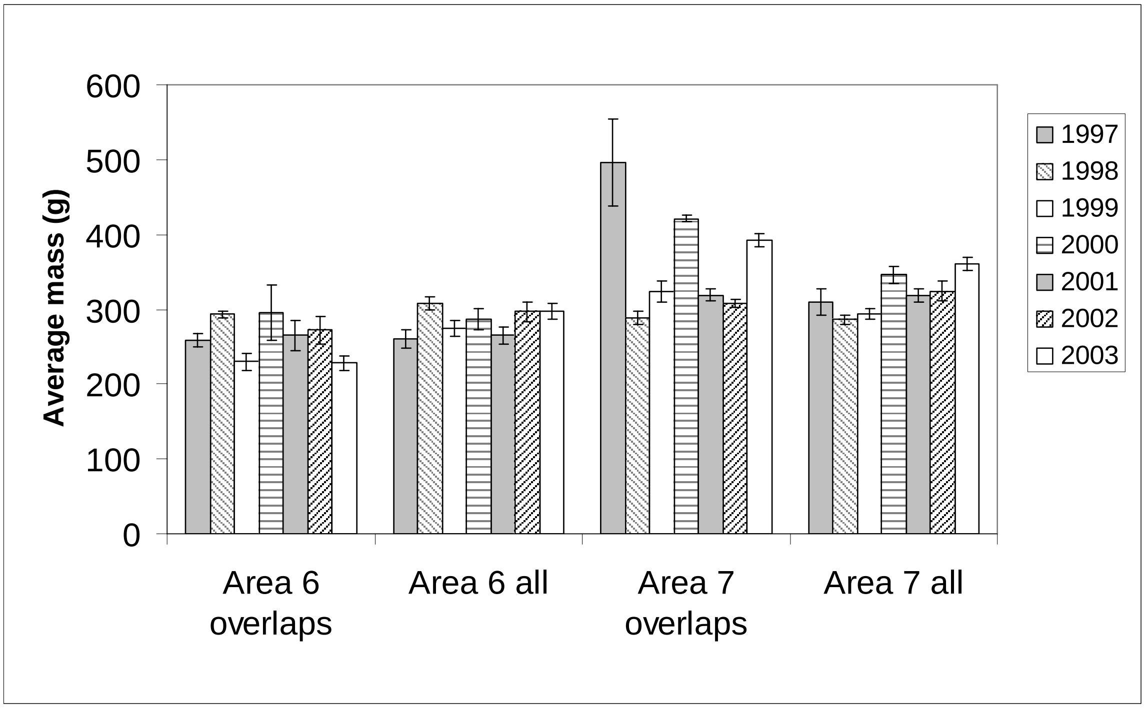

Figure 3. Mean weight of harvested sea cucumbers in Areas 6 and 7 for locations fished more than 3 years consecutively ('overlaps'), and for each Area overall, by year.

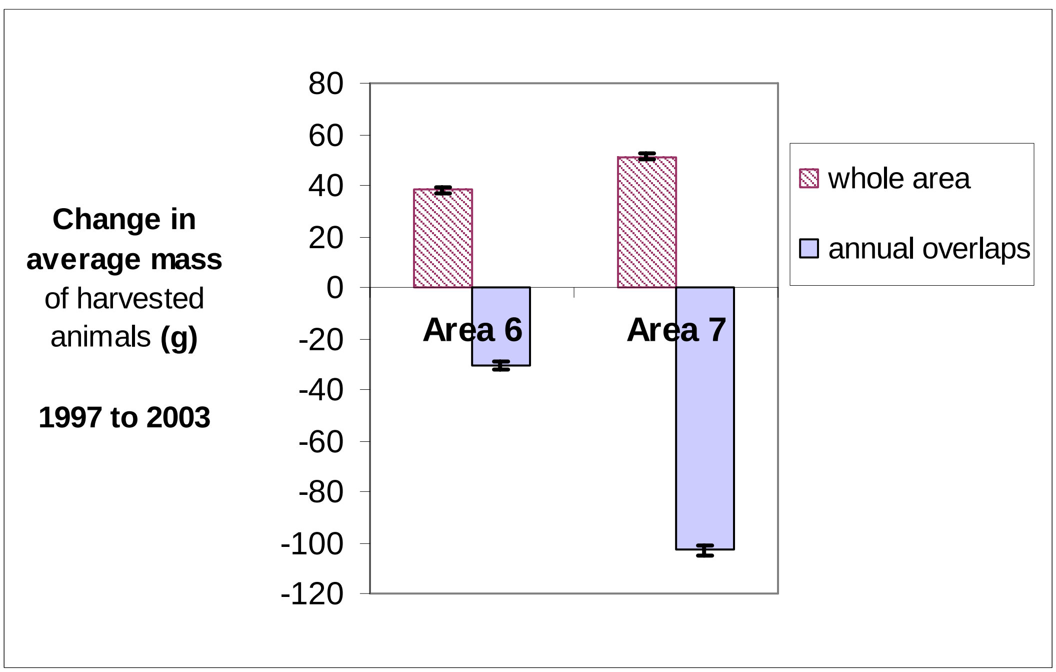

Figure 4. Change in mean weight of harvested sea cucumbers in Areas 6 and 7 for locations fished more than 3 years consecutively ('annual overlaps') and for each Area overall.

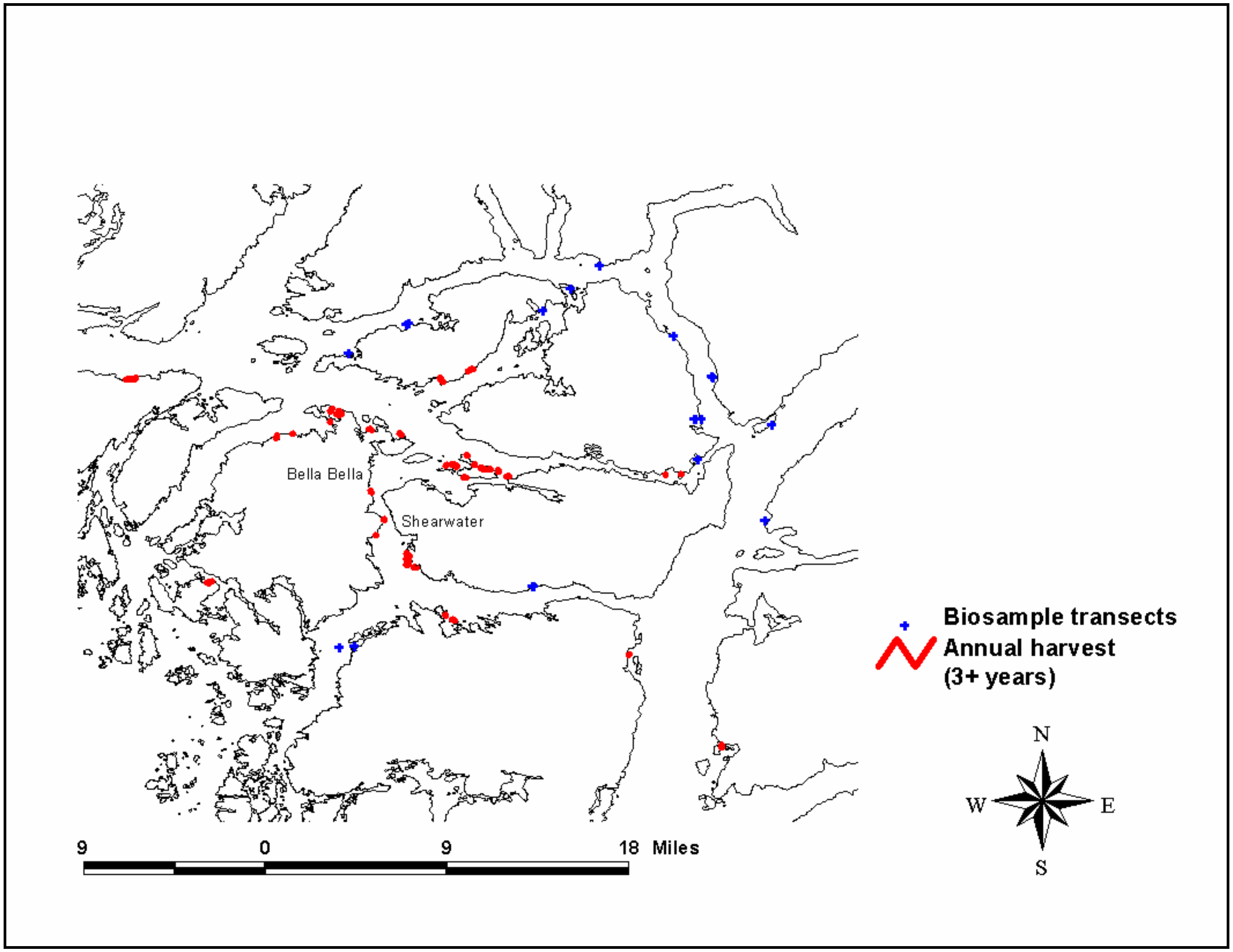

Figure 5. Locations of annual harvest (fished for 3 or more consecutive years) in relation to survey biosample locations used to monitor change in animal size.

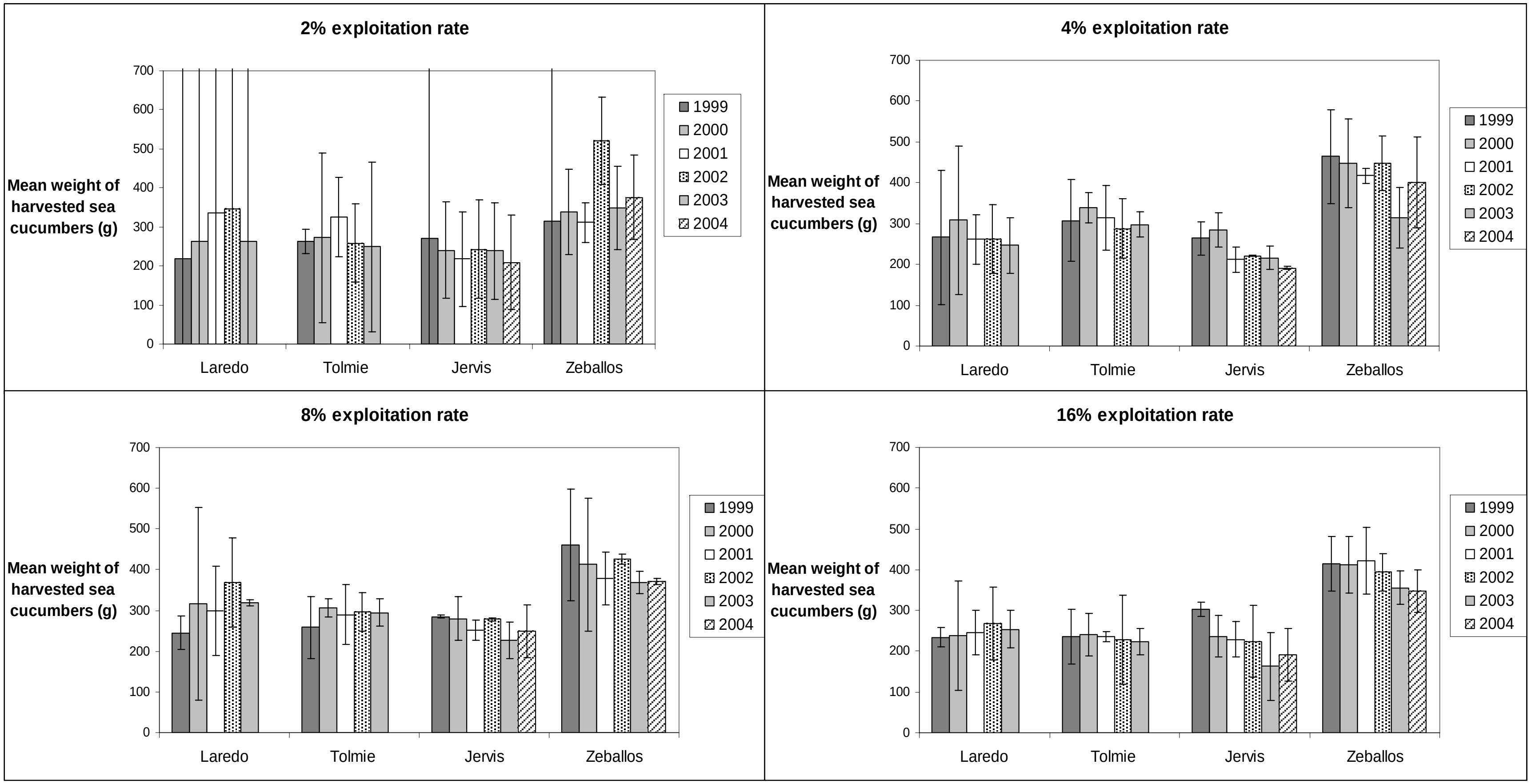

Figure 6. Mean weight and 90% confidence bounds of harvested sea cucumbers from four experimental fisheries, each with exploitation rates of 2%, 4%, 8%, and 16%. Confidence intervals that are extremely wide (e.g. 2% Site at Laredo) are a result of low sample size (low number of individual landings).

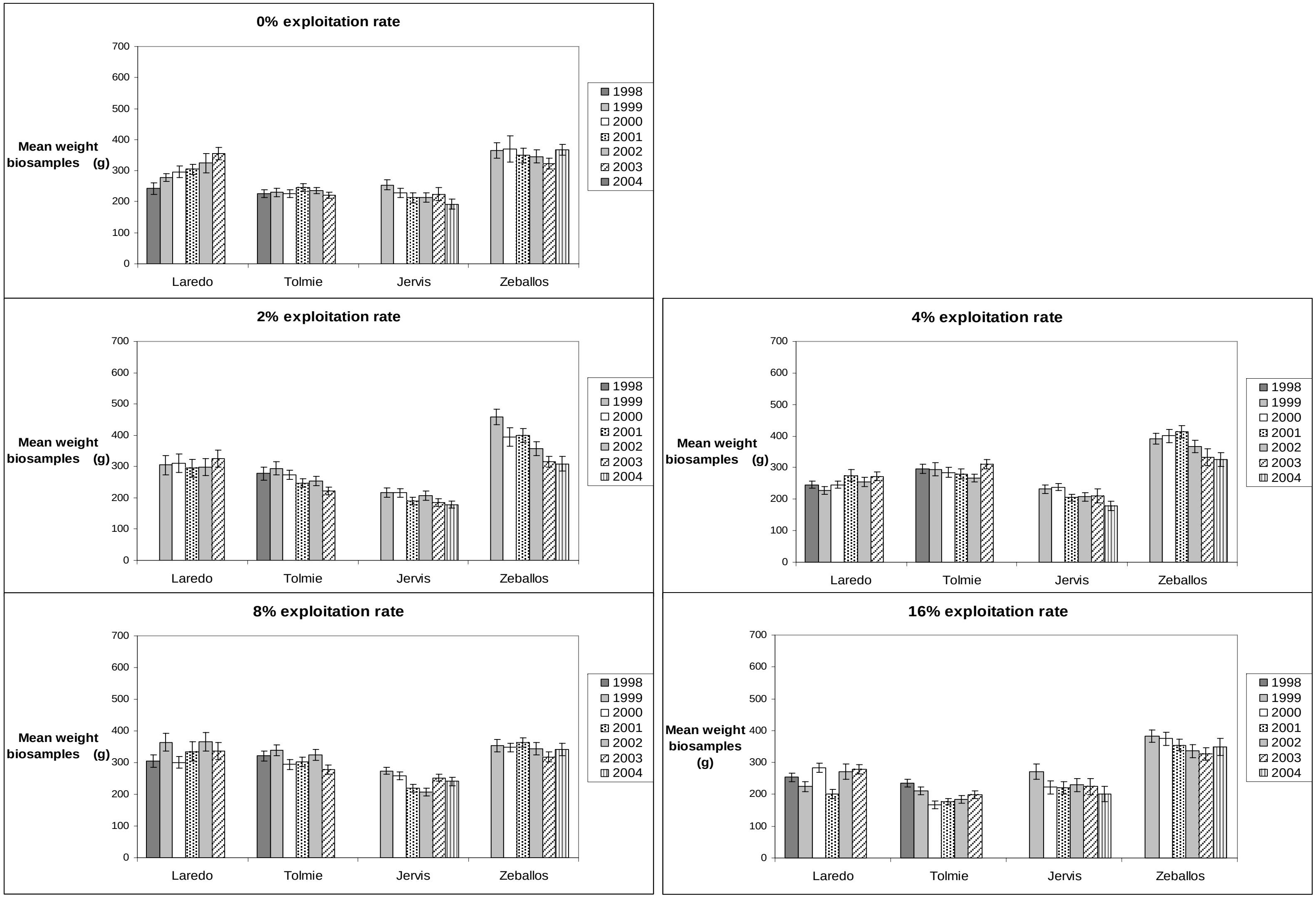

Figure 7. Mean weight and 95% confidence bounds of sea cucumbers from biological samples, from four experimental fisheries with exploitation rates of 0%, 2%, 4%, 8%, and 16%.

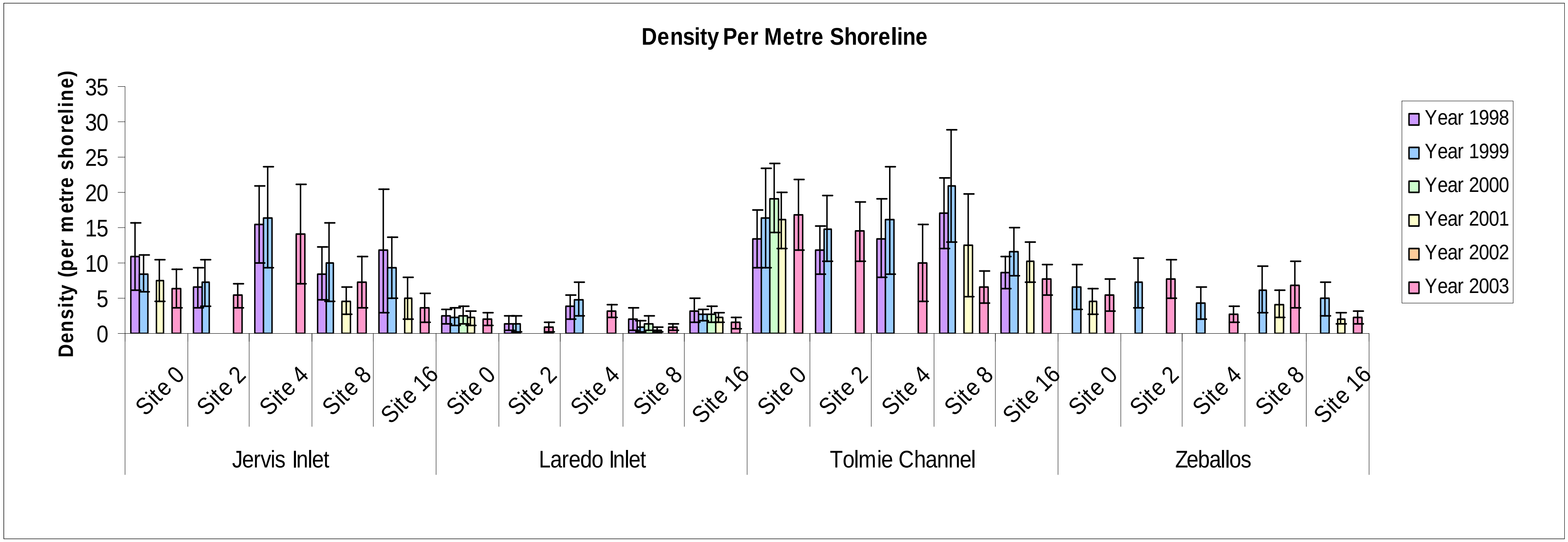

Figure 8. Estimated sea cucumber density (sea cucumbers per metre of shoreline) by year and Experimental Fishery Area (EFA), for treatment sites with exploitation rates of 0%, 2%, 4%, 8%, and 16%.

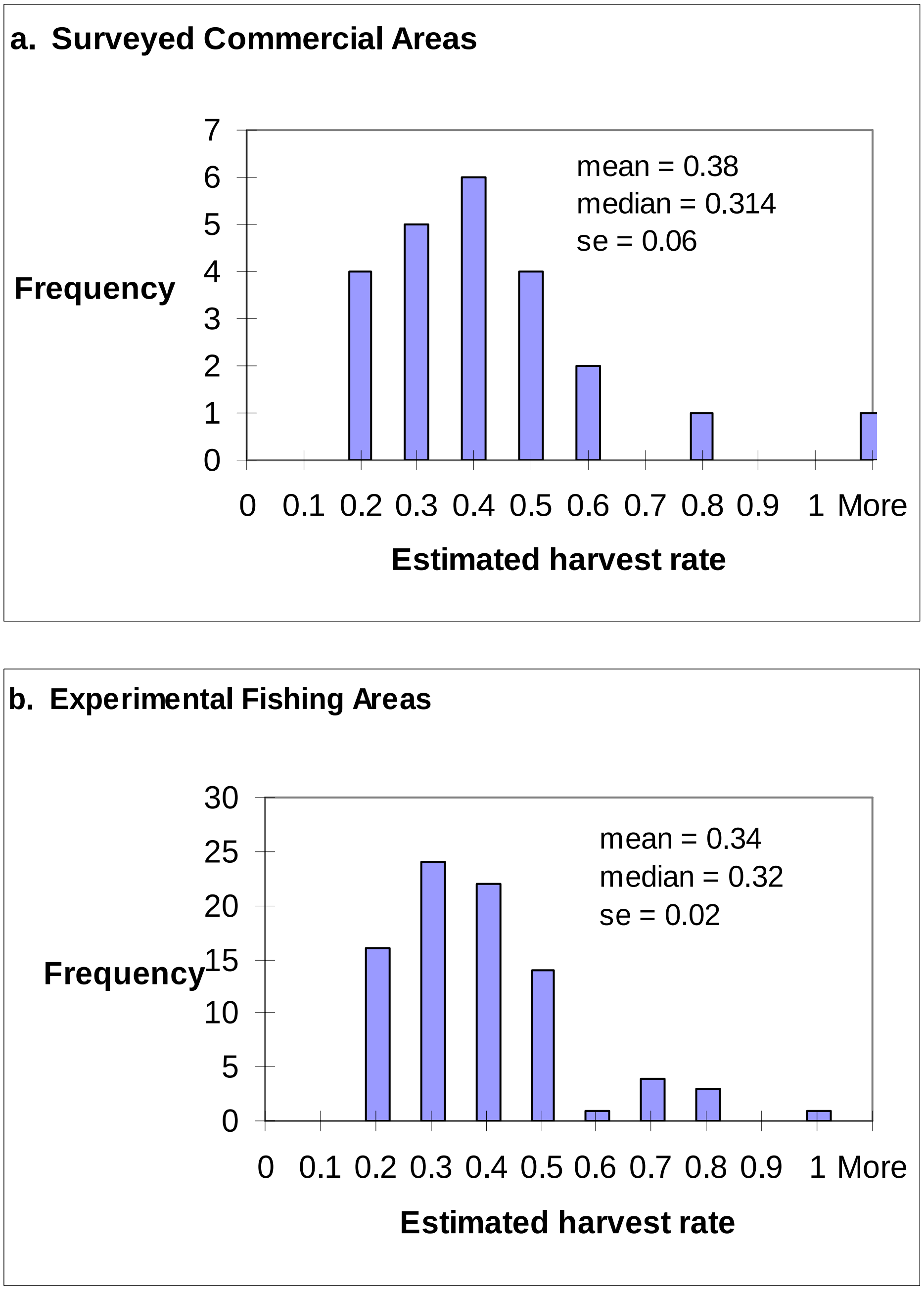

Figure 9. Frequency distribution of estimated harvest rates from a. surveyed areas in the commercial fishery, and b. Experimental Fishing Areas.

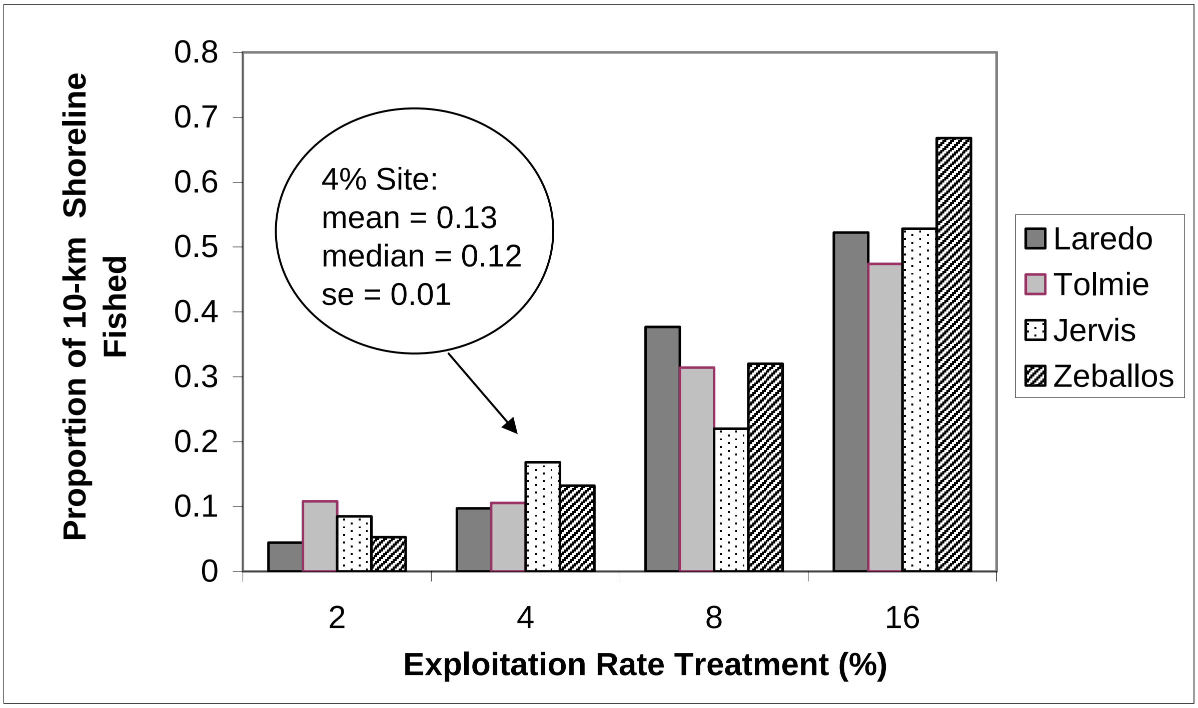

Figure 10. Relationship between target exploitation rate assigned to experimental fishing sites, and proportion of the shoreline fished within those sites.

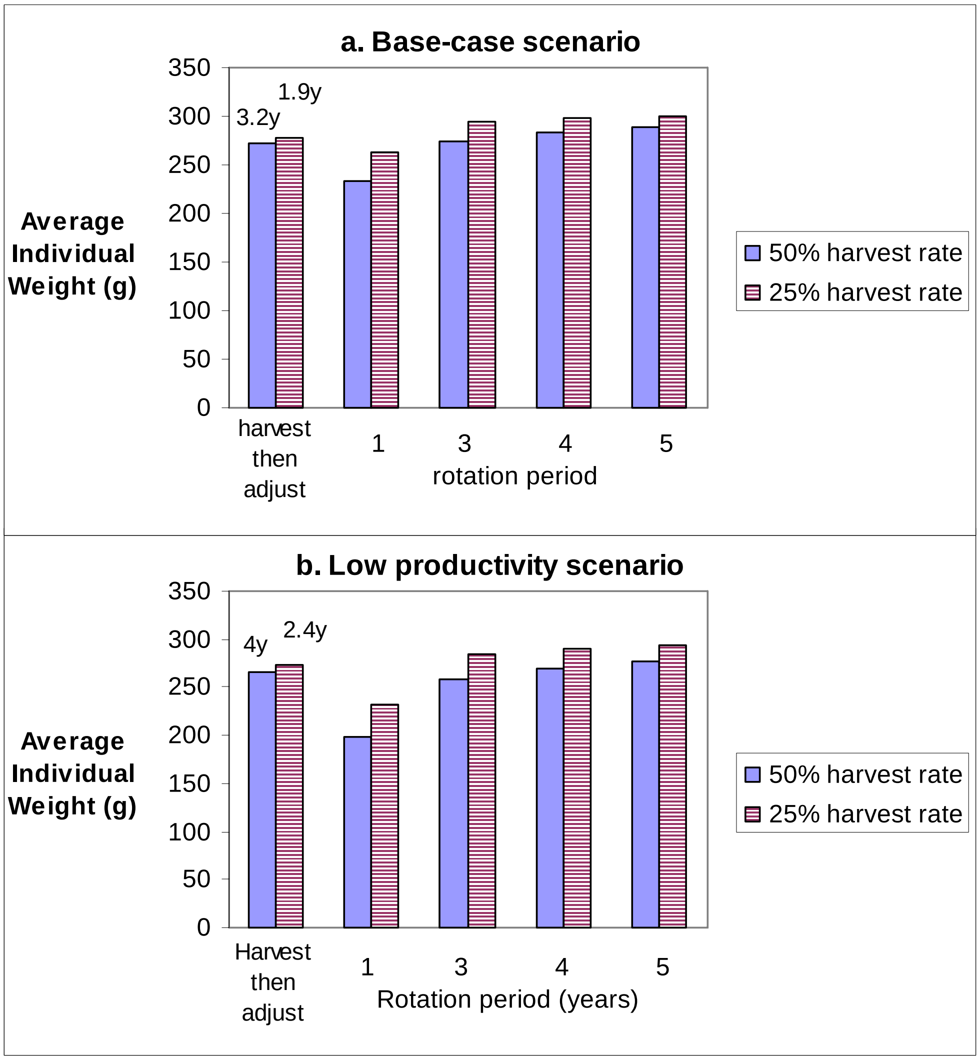

Figure 11. Average individual weight reached at equilibrium (100-year projection), for fixed and adaptive rotation periods with 25% and 50% proportional harvest rates, under scenarios of a. base-case and b. low productivity.

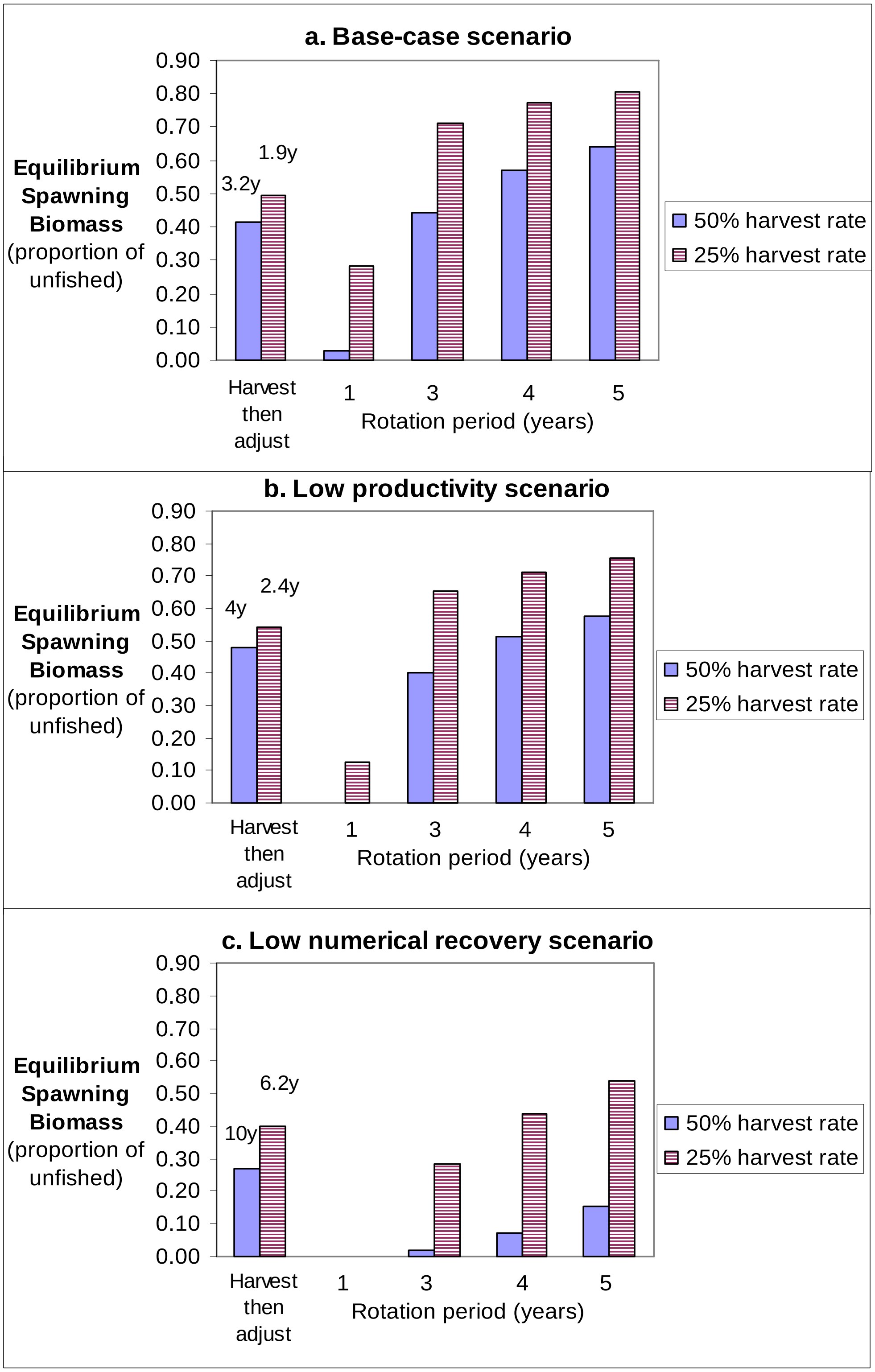

Figure 12. Spawning Biomass at equilibrium (100-year projection), as a proportion of the unfished level, for alternative harvest strategies, under scenarios of a. base-case, b. low productivity, and c. low numerical recovery.

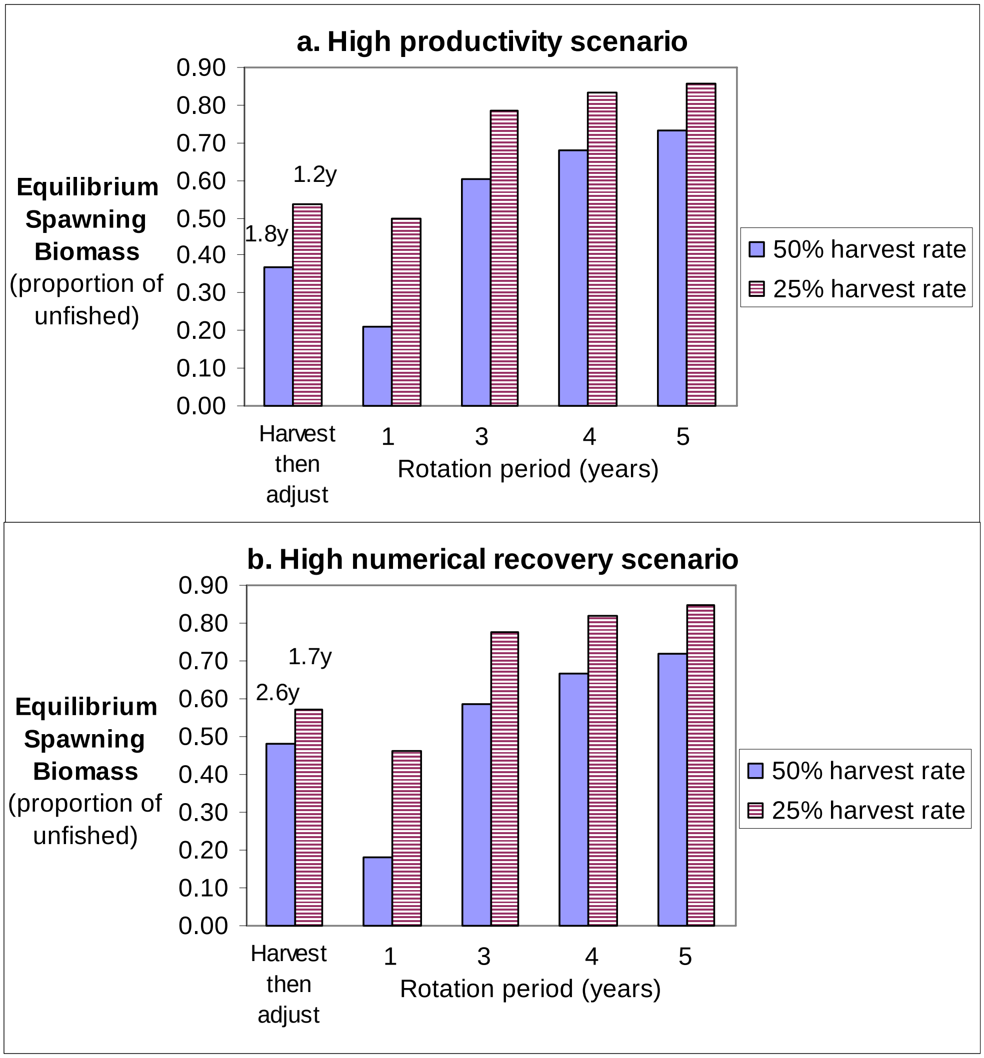

Figure 13. Spawning Biomass at equilibrium (100-year projection), as a proportion of the unfished level, for alternative harvest strategies, under scenarios of a. high productivity and b. high numerical recovery.

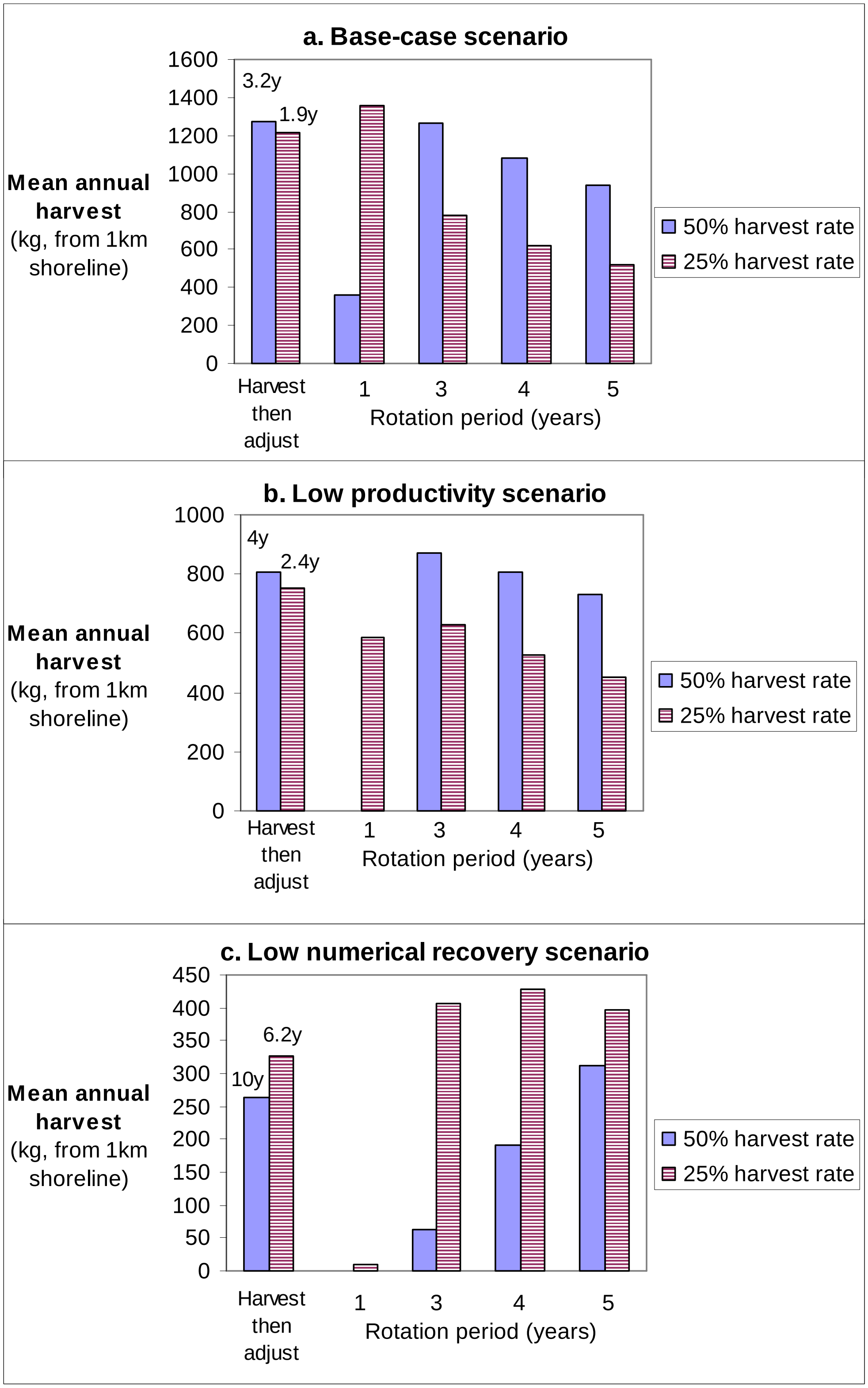

Figure 14. Mean annual harvest (catch) for alternative harvest strategies, under scenarios of a. base-case, b. low productivity, and c. low numerical recovery.

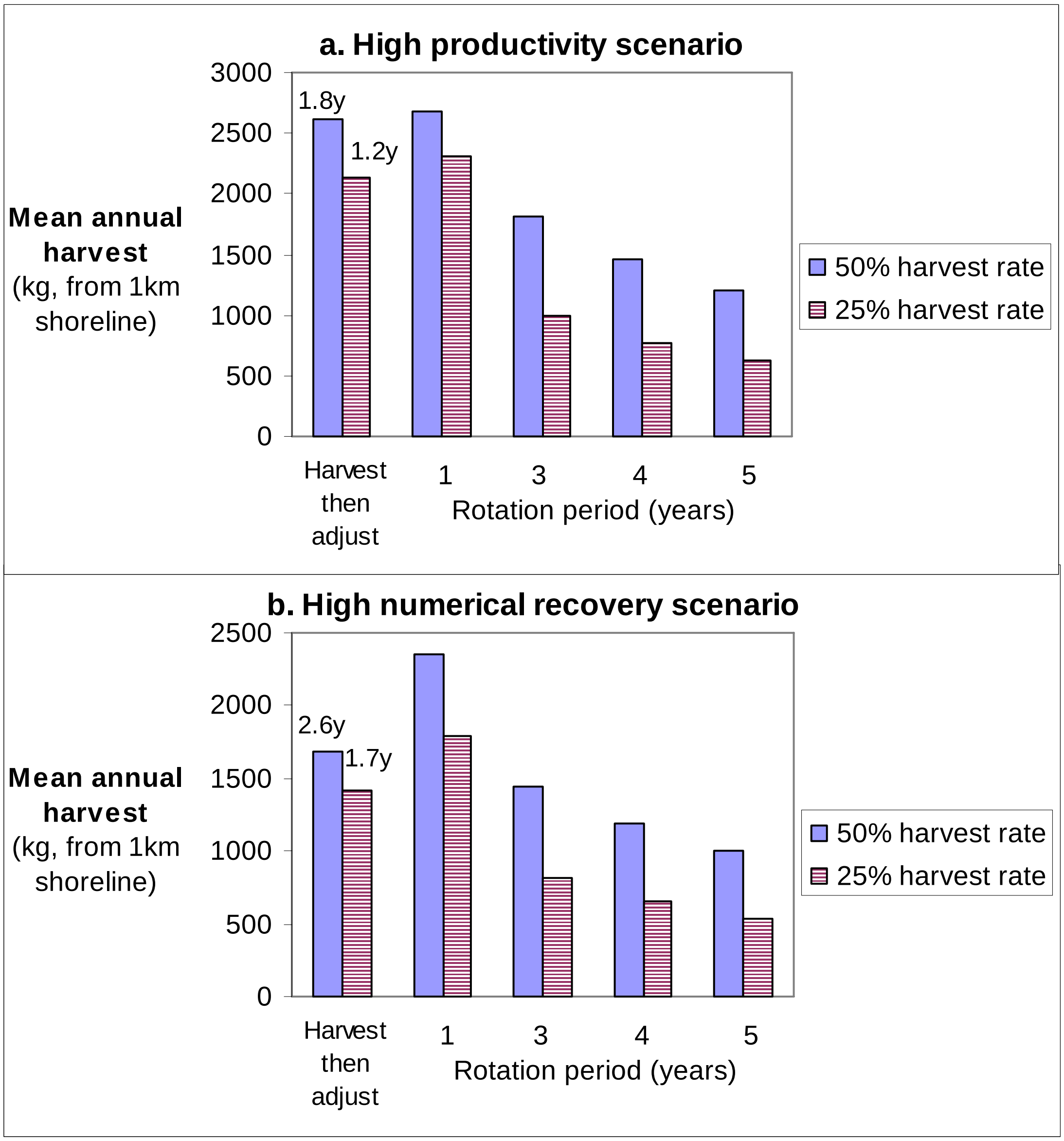

Figure 15: Mean annual harvest (catch) for alternative harvest strategies, under scenarios of a. high productivity and b. high numerical recovery.

Appendix 1

1 $$E_{loc} = \frac{C}{B_{est}}$$

where: C is the estimated split weight of the catch, and B_{est} is the estimated biomass for the shoreline fished.

2 $$B_{est} = B_{site} * P$$

i.e., the estimated biomass for the shoreline fished is the total biomass estimate for the 10 km site, multiplied by the proportion of the site fished, assuming that the animals are distributed over the entire length of shoreline. However, the equation could overestimate the local exploitation rate if high concentrations exist and are exploited preferentially.

1. Given that quotas (catch in mass) are calculated using: $C = E_{t\arg et} * B_{site}$
2. Substituting Eqn. 2 into Eqn. 1 gives $E_{loc} = \dfrac{C}{B_{site} * P}$
3. Substituting Eqn. 3 into Eqn. 4 gives $E_{loc} = \dfrac{E_{t\arg et}}{P}$

Appendix 2.

PSARC Request for Working Paper

Date Submitted: March 02, 2005

Individual or group requesting advice:
Juanita Rogers, Guy Parker, DFO Shellfish Management Biologists

Proposed PSARC Presentation Date:
April 2005

Subject of Paper (title if developed):
Review of the current annual sea cucumber fishery and recommendations for a pilot rotational harvest strategy

Stock Assessment Lead Author:
Sylvia Humble, Claudia Hand, Shellfish Stock Assessment Division

Fisheries Management Author/ Reviewer:
Juanita Rogers; Guy Parker

Rationale for request:
In 1997, the sea cucumber fishery was moved from a 2- and 3-year rotation to an annual basis, for the purpose of collecting annual fishery data for use in biomass dynamic models, to estimate population abundance. A precautionary harvest rate of 4.2% has been implemented for the open fishery; however, there is anecdotal evidence of a decrease in sizes of sea cucumbers, causing conservation concerns. The effort concentration that naturally occurs in dive fisheries causes harvest rates to be high on a local scale (we know that only a small portion of the quota area is fished). Fishing the same areas year after year may be causing this decline. Modelling results predict that at high localised harvest rates, annual harvest leads to decline in sea cucumber size and population density, while longer rotation periods result in larger animals and higher spawning densities. A review of fishery data collected since 1997 is needed in order to assess population response to the fishery, and determine how a rotational harvest system might be tested.

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

1. Is there any evidence of decline in the average size and/or density in open areas? Is there greater decline in annually fished areas than in areas harvested less frequently? Are changes in market sampling or other data collection needed to better assess impacts?
2. Recognising that effort is concentrated, what is the range of localised harvest rates in the open fishery? Can we determine the impacts of different harvest rates on sea cucumber populations from the experimental fishing data (designed to examine different harvest rates)? Can the experimental fishing data be used to examine the impact of annual vs. rotational fishing?

3. Using the existing population model and the range of localised harvest rates experienced in the fishery, how do rotational and annual harvest strategies compare in terms of conservation?
4. What is an adequate design for experiments (in research areas of the coast) to determine the performance of different rotation periods, and the range of recovery times required for different areas?
5. If a pilot rotational harvest were to be initiated in the current open areas (i.e. change to rotational harvest), what procedure could be used to determine the locations of fishing units (areas with similar densities/ fishable biomass) to provide stable yield from year to year? Would data collection change and if so, how?

Objective of Working Paper:

- To determine whether available data show significant decline in sea cucumber size or population density in open areas and, if so, assess whether this decline is related to harvest frequency. Identify any changes needed for fishery sampling protocols.
- To estimate localised harvest rates in the open and experimental fisheries, and from experimental fishing data, determine the effect of harvest rate, and of rotation versus annual fishing.
- To assess the potential impacts of rotational versus annual harvest, using the existing population model.
- To provide a protocol for experiments testing rotational fishing/ recovery time in research areas
- To provide suggestions for a possible pilot program of rotational harvest within open areas, and how to delineate fishing units for rotation.

Stakeholders Affected:

Sea cucumber licence holders, buyers, harvesters and crews, sport and FN users

How Advice may Impact the Development of a Fishing Plan: required

Timing Issues Related to When Advice is Necessary:

Required in time to write the 2005 fishing plan.