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# Stock Assessment Framework for the British Columbia Geoduck Fishery, 2002

# Cadre d'évaluation des stocks pour la pêche à la panope du Pacifique en Colombie-Britannique, 2002

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## ABSTRACT

A stock assessment framework for the provision of biomass estimates in a quota-managed geoduck fishery is presented. Presentation of this framework was driven by the need to examine the sources of uncertainty and error in the parameter estimates necessary for biomass calculation, and to prioritize data analysis and future data collection for more effective stock assessment.

Through collaboration with resource stakeholders, a large amount of fishery-dependent and fishery-independent data have accumulated, particularly in the last decade. The methods used to collect and analyze data on geoduck density, mean weight and geoduck bed area are described, and the errors, biases and assumptions discussed. Geoduck bed area is identified as the parameter that is measured with the least accuracy and is recommended as the highest priority to resolve. The current methods of extrapolating estimates of density to unsurveyed geoduck beds assume that populations that are closer together are more similar than those more distant. It is recommended that more spatially-explicit approaches be used for extrapolation which utilizes all of the available information on geo-physical properties of the geoduck bed and the associated characteristics of the populations within them.

## RÉSUMÉ

On présente un cadre d’évaluation des stocks dans le but de fournir des estimations de la biomasse des panopes du Pacifique dans un régime de pêche géré par quotas. La présentation d’un tel cadre a été motivée par la nécessité d’examiner les sources d’incertitude et les erreurs dans les estimations des paramètres utilisés pour le calcul de la biomasse, et de classer par ordre de priorité l’analyse des données et les prochaines collectes de données en vue d’arriver à une évaluation plus efficace des stocks.

Grâce à la collaboration des intervenants qui s’intéressent aux ressources, on a recueilli une grande quantité de données dépendantes et indépendantes de la pêche, particulièrement au cours des dix dernières années. On y décrit les méthodes employées pour recueillir et analyser les données sur la densité des panopes, le poids moyen et la superficie des gisements de panopes, ainsi que les erreurs et les hypothèses qui ont fait l’objet de discussions. On a déterminé que la superficie des gisements de panopes est le paramètre mesuré avec le moins d’exactitude et il est donc recommandé que ce point à régler soit traité en priorité. Les méthodes actuelles employées pour extrapoler les estimations de la densité des zones de gisements de panopes non échantillonnées présument que les populations à proximité sont davantage semblables que celles plus éloignées. Aux fins d’extrapolation, il est recommandé d’avoir recours à des approches plus explicites sur le plan spatial qui mettent à profit toute l’information disponible sur les propriétés géophysiques des gisements de panopes du Pacifique ainsi que les caractères associés aux populations présentes dans ces zones de gisements.

# 1. INTRODUCTION

The geoduck clam (*Panopea generosa* Gould 1850) is an infaunal bivalve with a geographic range from Alaska to southern California on the west coast of North America (Quayle 1970). Populations exist in almost all sedimentary substrates, but are generally only harvestable in soft sand, mud and small aggregate sediments. A commercial fishery began in British Columbia (BC) in 1976, and it has since grown to be one of the highest valued fisheries in BC at $33.7 million in 2004 (Fig. 1). The fishery developed prior to the DFO's adoption of a national policy on new and emerging fisheries, and it initially operated as an open-access, competitive fishery which was assessed with limited information. The fishery has since evolved to a limited licence, individual quota fishery that, through time and the active involvement and financial contribution by the Underwater Harvesters Association (UHA), has become one of the more data-rich fisheries in BC.

Geoduck quota options have been prepared by Science Branch and presented to the Pacific Science Advice Review Committee (PSARC) since 1995 (Hand *et al.* 1998a, 1998c, 1998d, Hand and Bureau 2000). Methods of calculating quotas have not changed since their development by Operations Branch in the early 1980's. A constant catch strategy is used, where quotas are calculated as the product of estimated virgin biomass and the recommended exploitation rate (Fig. 2). Virgin biomass ($B_0$) in each geoduck bed is estimated as the product of estimates of virgin density, individual geoduck weight and bed area. Quotas fluctuate from year to year as adjustments are made to the estimated virgin biomass from new data and information, and with varying geoduck biomass between rotational areas.

This working paper is motivated internally by the Stock Assessment Division to generate discussion and seek advice on the status and directions of science activities as they relate to providing advice to managers for a stable and sustainable commercial fishery (Appendix 1). This paper describes the sampling and statistical methods used to estimate each of the parameters required to calculate estimates of virgin biomass and its precision, and how they are applied to individual geoduck beds. Sources of uncertainty and error are discussed. Also described are the future directions in the collection and application of research data, and the obstacles to achieving those targets. Finally, recommendations are made regarding priorities in data collection and analysis.

## 1.1 EARLY HISTORY OF ASSESSMENT AND MANAGEMENT

The early geoduck fishery in BC has been described in terms of regulations, landings and quota estimation by Cox (1979), Harbo and Peacock (1983), Farlinger and Bates (1985), Farlinger and Thomas (1988), and Harbo *et al*. (1986, 1992, 1993, 1994, 1995). The fishery was initiated at a time when much of the biology of geoducks was unknown. Estimates of virgin biomass were initially determined from broad-brush surveys conducted by the Marine Resources Branch, Provincial Ministry of Environment, in 1977 and 1978. These surveys were mainly intended to establish the range of commercial geoduck concentrations; the average estimated density was low, around $0.06/m^2$, but the area over which it was applied was extensive.

Prior to 1979, there were no quotas (Fig. 1). An initial quota of 3,600 metric tonnes (t) was set in 1979 (1,600 t in the North Coast and 2,000 t in South Coast), based on initial stock estimates from the Provincial surveys, evaluations of patterns of effort, historical landings, and expectations of additional stocks not yet discovered. An arbitrary annual harvest rate of 2% to 5% was suggested (Harbo *et al.* 1992). In some areas, arbitrary exploratory quotas were set for new fishing grounds to promote development of the fishery. In 1980 a revised exploitation rate of 1.2% to 2.5% was suggested, based on early biological data from Washington State studies (Harbo *et al.* 1986). Later in 1980, this exploitation rate was again revised to 0.75%-2% of estimated virgin biomass, based on the first estimates of growth, mortality and recruitment from analyses of BC data in south coast waters (Breen 1982). A value towards the lower end was chosen because Goodwin and Shaul (1984) suggested that fishing may have an adverse effect on recruitment.

The main problem facing managers was the uncertainty in stock biomass estimates. Quotas were reduced in 1981 to 2,722 t (6,000,000 lbs) and there were discussions about reducing the quotas in a stepwise manner each year because of uncertainty in stock size. Surveys were conducted in select areas of the Strait of Georgia and southwest Vancouver Island (Breen and Shields 1983) and in the central coast of BC (R. Harbo, DFO, personal communication). These surveys sites were selected for their high density and the studies were primarily designed to obtain estimates of biological parameters.

With poor knowledge of stocks hindering expansion of the fishery, managers requested that additional resource surveys be carried out. There were concerns that certain areas were being over-exploited, while the overall stock was potentially being underexploited. The feasibility of improving the geoduck stock assessment was investigated by Sloan (1985) where he concluded that accurate resource surveys could only be carried out by divers. It was acknowledged that such surveys would be costly due to the constraints of diving, and the patchy distribution and wide occurrence of geoduck populations.

Quotas began to incorporate commercial logbook data (specifically, estimates of bed area) in 1988 (Harbo *et al.* 1992). In 1989, a pilot individual vessel quota (IVQ) program was initiated where the coastwide quota was divided equally among the 55 licence holders. In the same year, a three-year rotational fishery was set, primarily for logistical reason to reduce the number of delivery ports for validation of quotas. Also in 1989, an on-grounds monitor (OGM) became an integral part of directing and observing the fishing fleet in the north coast. Because of the IVQ fishery and the requirement to validate all landings at dockside, catch and effort data since 1989 are accurate and timely. Quotas decreased steadily between 1990 and 1997 as a result of the elimination of most exploratory fisheries, a reduction of density and bed area estimates, the introduction in 1994 of limit reference point (50% $B_0$) conservation closures in beds where the total landings were estimated to be greater than 50% of the original biomass (Harbo *et al.* 1994), and the introduction in 1995 of quota reduction (later termed ‘amortization’; see section 3.1) to compensate for high quotas and landings resulting from biomass estimation errors.

The consistent downward trend in quotas during that time prompted stakeholders to request more quota stability in order to reduce growing concerns in the market. Quotas remained relatively stable after 1997, however by 2003 there were increasing concerns about the impact of sea otter predation and the status of stocks on the West Coast of Vancouver Island (WCVI). The WCVI returned to an annual fishery, with an industry-funded OGM to observe the fishery and to record observations on fishing success and evidence of otter predation. These concerns led to a decrease in quota in 2005.

## 1.2 GEODUCK BIOLOGY

### Age, Growth, Longevity and Reproduction

Geoducks are among the longest-lived animals in the world, often reaching ages over 100 years, and with a maximum recorded age of 168 years (Bureau *et al*. 2002). Geoducks grow rapidly in the initial 10 to 15 years, after which time the growth in shell length ceases while total weight increases at a slow rate through a thickening of the shell and an increase in meat weight (Harbo *et al.* 1983, Goodwin and Shaul 1984, Sloan and Robinson 1984). Geoducks begin to recruit to the fishery at age 4 and are fully recruited at 12 years (Harbo *et al*. 1983).

Spawning occurs annually, mostly from June to July in association with increases in seawater temperature (Sloan and Robinson 1984). Females release from 7 to 10-million eggs which are fertilized and develop in the water column until settlement on the bottom within 40 to 50 days (Goodwin *et al.* 1979, Goodwin and Shaul 1984). The settled post-larvae are active crawlers and can travel along the bottom, aided by a byssal thread parachute, for several weeks. At a shell length of approximately 2 mm, they begin to burrow into the substrate. At settlement and for the first two years, juvenile geoducks are vulnerable to a number of predators, including snails, sea stars, crabs (*Cancer spp*), shrimp and fishes (Goodwin and Pease 1989). Fast growing clams can bury to a refuge depth of 60 cm in two years, and the end of the burrowing stage coincides with the beginning of reproductive activity. Sexual maturity is related more to size than age, and has been found to occur as early as two years on the WCVI near Tofino and three years from a sample of slower growing geoducks collected in the Strait of Georgia (Campbell and Ming 2003).

Growth rate and maximum size vary substantially between regions, between geoduck beds and between individuals within a bed, and both slow and fast growing geoducks can attain small or large maximum sizes(Bureau *et al.* 2002, 2003). Geoducks from southern BC were found to be generally smaller, younger and have faster growth than geoducks from northern BC. It was speculated that the difference was due to the fishery having harvested more of the accumulated biomass of older, slower-growing, geoducks over the longer fishing history in the south coast, as well as inherent individual characteristics.

Estimates of natural mortality rate for mature geoduck populations in BC range from 0.01 to <0.05 (Breen and Shields 1983, Harbo *et al*. 1983, Sloan and Robinson 1984, Noakes and Campbell 1992). Geoduck juveniles are scarce and studies have largely concluded that recruitment rates are low (e.g. Breen and Shields 1983, Harbo *et al.* 1983). Age-frequency distributions from populations sampled during recent surveys show prominent modes, some of which appear coastwide (Bureau *et al*. 2002, 2003). This suggests that geoduck populations may be supported by widespread recruitment pulses.

### Population Distribution, Structure and Dynamics

Geoducks are found from the low intertidal to at least 110 m (Jamison *et al.* 1984). They occupy a wide range of un-consolidated substrate, from fine silt to pea gravel, and a range of habitats from low-exposure bays with little tidal flow to surf-swept outer coasts or tidal channels.

Geoducks have a patchy distribution, likely in response to small-scale variations in substrate, exposure and tidal current. Within the patches, distribution is uniform (Breen and Shields 1983). The level of connectivity in geoduck metapopulations and the extent to which individual beds are self-sustaining is unknown. Commercial fishermen and on-ground observers report that some beds are slow to recover from harvest while others consistently show good recruitment. These observations suggest complex dynamics of larval flow and recruitment success. Generally, the beds that experience regular annual recruitment are located in areas of moderate to high water movement (e.g. beds in the Tofino area). Similar observations have been made in Washington State geoduck populations (Orensanz *et al.* 2000).

# 2. ESTIMATION OF GEODUCK BIOMASS

Geoduck biomass is estimated, on a bed-by-bed basis, as the product of mean density, mean individual geoduck weight, and bed area. The error in each parameter estimate is incorporated into biomass calculations to produce 95% confidence bounds on mean biomass.

## 2.1 DENSITY ESTIMATES

### Background

The first estimates of geoduck density came from large-scale transect diving surveys in 1977 in Queen Charlotte, Johnstone and Georgia Straits on the East coast of Vancouver Island (Cox and Charman 1980) and in 1978 on the WCVI and the north coast by the Provincial Marine Resources Branch.  These surveys are discussed and results tabulated in Harbo *et al*. (1992) and Sloan (1985). Sites were arbitrarily chosen from viewing nautical charts and determining areas with suitable unconsolidated material within diving depths. Transect locations were determined beforehand. No information was provided in the literature on how transect locations were determined, although from archived charts, they appeared to be randomly positioned within arbitrary areas. Transects (2 m wide by 50 m long) were laid perpendicular to the shoreline and counts were made of the number of visible geoduck siphons and probable shows (siphon tip that could be felt beneath the sand). No correction was used to compensate for geoducks not showing.  Estimated densities were very low (0.06 geoducks/m$^2$ in Pacific Fisheries Management (PFM) Areas 12 to 18) over large expanses of area (32,600 ha). These survey data were not intended for stock assessment and were considered of little use to estimate quota options.

In the early 1980's, transect surveys were conducted over very small areas, chosen for study because of their high densities of geoducks (Breen and Shields 1983; R. Harbo, DFO, personal communication). The main objective of these studies was to obtain estimates of mortality, recruitment and growth rate, rather than density. Some of these surveys included a measure of 'show factor' to estimate the percentage of geoduck siphons visible to divers. Survey locations were based on commercial fishing experience and suggestions from industry. Density estimates in these beds (some virgin and some harvested) ranged from 15/m$^2$ to 0.16/m$^2$ over areas of 60 to 120 m$^2$. Other surveys were conducted by DFO staff in areas of interest over small areas (100 to 250 m$^2$) and produced density estimates ranging from 0.9/m$^2$ to 12.3/m$^2$. These surveys are summarized in Table 13 of Harbo *et al*. (1992).

### Modern Surveys

Sloan (1985) recommended a program of shallow-water dive transect surveys to increase the reliability of stock estimates. It was not until 1992 that surveys of geoduck beds were conducted to specifically estimate density for biomass calculation purposes. Marina Island was surveyed (Campbell *et al.* 1996b) with the objective of determining stock status in the closed bed, and also to evaluate their survey technique by estimating the optimal sample numbers for efficiency and statistical power. Transects were placed systematically over the estimated location of harvested area at 100 m intervals. Results suggested that maximum transect spacing should be between 200 and 300 m.

Surveys were conducted annually thereafter (Table 1), initially by DFO staff and commercial geoduck divers and then with the additional help from First Nations fisheries programs. Industry stake-holders took on a serious and active role in conducting surveys in 1995, when they contracted a biologist who, working closely with DFO, designed survey protocols and supervised and participated in the collection of survey data by Industry and First Nations divers. High standards of experience were set for the participation of industry divers. Since 1992 and to date, 32% of the total estimated bed area on the BC coast has been surveyed, from which 41% of total geoduck harvest has originated.

Criteria for selecting areas to be surveyed have evolved over time. Initially, surveys were conducted to provide benchmark density estimates over a wide range of bed types and geographic locations. In any given year, priority was given to areas where little or no data existed and to beds that have supported significant fisheries. Initially, beds were specifically chosen, based on recommendations from fishermen or on-grounds observer and reviews of catch history. Later, bed-groupings within a chosen region were selected at random. As more of the geographic data gaps were filled, priority shifted to re-surveying select beds, in order to answer specific questions. These questions include monitoring the recovery in closed (e.g. Marina Island) or heavily harvested (e.g. Comox Bar) beds, verifying initial survey results where there was a conflict between the perception of commercial fishers and survey data (e.g. Houston Stewart Channel, QCI), and lately, to examine the impact of sea otter predation on geoduck populations (e.g. Winter Harbour).

## Survey Methods

To date, a total of 53 surveys have been completed in 49 different areas of the BC coast (Table 1); some of which have been published (Campbell *et al.* 1996a, 1996b; Farlinger and Thomas 1991; Hand *et al*. 1998b; Hand and Dovey 1999, 2000). Surveys completed before 1996 were systematic in design. After 1996, a two-stage design of randomly-placed transects with subsampling of quadrats along each transect, was recommended (Campbell *et al*. 1998b). Optimal sampling intensity, in terms of the number of quadrats sampled within each transect, depends on the characteristics of the geoduck bed; wide bank-type beds could be surveyed with fewer quadrats per transect, allowing more transects to be completed. The current convention is to sample every fourth quadrat on transects measuring over 400 m, every third quadrat for transects lengths between 200 m and 400 m, every second quadrat for transects between 50 m and 200 m and every quadrat for transects 50 m or less. Survey areas are stratified by geoduck bed, and transects are randomly selected within each stratum (geoduck bed). Over time, survey effort has increasingly been focussed on known geoduck habitat as fishery-dependent (logbooks, OGM reports) and fishery-independent (acoustic substrate surveys) information on bed location has accumulated and improved.

Once a survey area is chosen, the number of individual geoduck beds that can be surveyed at a target transect-spacing of 1 transect per 300 m of shoreline distance (Campbell *et al*. 1996a), in a 10-day period, is determined. A ten-day survey is considered to be a good balance between logistics (availability of personnel, cost effectiveness of travel) and sample size. A reference line approximately parallel to the shoreline is drawn on the nautical chart in each geoduck bed (stratum) to be surveyed, and transect positions are located randomly along this line. Lead-core transects, marked at 5-m intervals, are laid perpendicular to depth contours, extending from 3 m to 18 m (10 to 60 feet) chart-datum depth. Two SCUBA divers work together, one on either side of the transect, and count visible geoduck shows or dimples[1] within 1 m (using a metre stick) of each side of the transect. At the end of each 2m by 5m quadrat to be sampled, the divers stop to record the total number of geoducks and horseclams counted, the depth, the dominant algae species present and the three most dominant substrate types.

## Show Factors

Individual geoduck siphons are sometimes withdrawn below the substrate surface due to physical and/or biological effects, and are not readily visible to divers (Goodwin 1977, Turner and Cox 1981). The proportion of the total abundance of geoduck siphons that are visible to divers during a single observation is called the ‘show factor’. Show factors are estimated by monitoring 10m x 2m plots, the location of which are chosen to contain relatively high geoduck abundance and be representative of the substrate, depth and exposure encountered during the survey. On every day of the survey, the plot is visited, the geoduck shows counted and the position of every newly-emergent geoduck is marked with a flag. The show factor for any given day is determined by dividing the number of shows observed on that day by the total number of geoducks flagged during the survey. The estimate of total population size in the plots assumes that all geoducks in the plot are flagged during the period of the survey, that no mortality occurs during the survey, and that the plot boundaries do not change (from water current or other disturbance) or the geoduck neck positions do not change relative to the boundary of the plot.

## Analysis of Survey Data

Since the survey strata are defined by an imperfect knowledge of bed location, transects can be placed on bedrock or other unsuitable habitat. As well, some beds that are included in the survey are so small that they are assigned only a couple of transects. The result is high between-transect variability. In an attempt to reduce this variability, procedures include combining of bed polygons, or strata, to increase the sample size and omitting transects that are located outside geoduck beds, as determined by independent mapping of the geoduck bed from acoustic surveys and from the OGM. Beds are grouped by visual similarity of exposure and slope or by qualitative descriptions by the OGM. Data can also be post-stratified on the basis of the substrate type recorded during the survey. Regardless of whether the entire transect was placed over suitable substrate, no individual quadrat counts were omitted within a transect.

Analyses follow the procedures described in Campbell *et al*. (1998b) and Hand and Bureau (2000). The mean survey density ($d_s$) for a given bed is calculated as the ratio of sums for the number of geoducks counted ($g$) and the transect area ($a$) over all transects $i$, as

$$d_s = \frac{\sum_i g_i}{\sum_i a_i} \qquad (1)$$

Non-parametric bootstrapping methods are used to calculate 95% confidence bounds on the mean density estimate, as described in Hand and Dovey (2000).

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[1] Shows are visible siphons. Dimples are visible indentations in the substrate left by a retracted siphon. Dimples were counted as shows if the siphon retracted in response to probing.

## Calculation of Virgin Density

The yield model upon which the 1% harvest rate was based was formulated in terms of virgin biomass (Breen 1982). To calculate estimates of virgin density, geoducks harvested prior to the survey, expressed in average numbers harvested per square metre of bed fished, were added to the estimated density from surveys. It is assumed that natural mortality and recruitment are in balance and no accounting was taken of those parameters.

Reported landings prior to the date of the survey for each surveyed bed are obtained from the logbook database and converted to number of animals, using estimates of mean geoduck weight, also from the logbook database. Density removed is calculated by dividing the number of geoducks harvested by the area that was included in the survey protocol. The area surveyed is estimated as a product of the average length of transects and the protocol reference line (shoreline distance of strata). Reconstructed virgin density estimates are influenced by the estimate of area over which the geoducks were harvested and by the estimate of mean individual weight, since the harvest must be converted from landed weight to number of animals.

## Extrapolation of Density Data to Unsurveyed Beds

Unsurveyed geoduck beds are assigned estimates of density that are extrapolated from surveyed beds stepwise from the same Geoduck Management Area (GMA), PFM Subarea, PFM Area and Region, as the data permit. For example, if only some beds within a GMA have been surveyed, all remaining (unsurveyed) beds within that GMA are assigned the mean density estimate from the surveyed beds. Similarly, unsurveyed beds for which a GMA density estimate isn't available are assigned the average density estimate from within the same PFM Subarea, PFM Area or Region, as available. This approach assumes that proximal beds more similar to each other than beds that are more distant.

## Sources of Uncertainty in Density Estimates

*1) Recruitment and natural mortality not equal.*
In the reconstruction of virgin density from the sum of survey density and removals by the fishery, the assumption that recruitment balances natural mortality in any given bed is likely incorrect. While it may be true for virgin populations in the long-term, the effect of fishing on recruitment is not known. Limited early studies suggested that recruitment was directly related to adult density (Goodwin and Shaul 1984), however more recent results from biological sampling has shown that recruitment can be strong in beds that have supported long-term fisheries (Bureau *et al*. 2002). Research is currently being conducted to investigate population recovery after harvest.

*2) Wide confidence bounds from poor knowledge of geoduck distribution prior to surveying.*
The location of geoduck beds is often poorly determined and, as a result, some transects are located on seabed that is not suitable for geoducks (e.g. bedrock). This leads to lower estimates of mean geoduck density and wide confidence bounds. The extrapolation of these density estimates to nearby unsurveyed beds is expected to be appropriately conservative, given that unsurveyed areas would likely also include unsuitable habitat. However, the wide 95% confidence bounds in the density estimates resulting from zero counts leads to wide confidence bounds on quota recommendations for managers. To produce more usable quota

recommendations, density can be estimated with more precision by first mapping the bed (using acoustics; see Section 2.2) so that only the bed is surveyed and not unsuitable substrate. These higher, more precise, density estimates should not, however, be extrapolated over large unsurveyed areas because to do so would probably lead to inflated biomass estimates. Extrapolations must be done with caution.

*3) Accuracy of visual counts.*

Another factor that may have an influence on density estimates is the accuracy of the visual counts. This can be affected by the detection abilities of the survey divers and their ability to distinguish between geoducks and other similar species like horseclams, piddocks or false geoducks *(Panomya spp.)*. This source of error is considered to be minimal because the participants are all experienced commercial divers who furthermore have to satisfy criteria set by the industry regarding their fishing experience in the region being surveyed.

*4) Proportion showing.*

Accuracy of geoduck counts are also affected by the variable proportion of the population visible at any one time. Typically, show factors are in the order of 90-95%, and thus corrections applied to the observed data are not large. Establishing and monitoring show factor plots takes an estimated 25% of total field time, plus the additional effort required to process the data.

Factors that affect the proportion of geoducks showing operate at both seasonal and diurnal time-scales, but these factors have not been specifically researched. Fishermen report that proportions showing can change drastically over a matter of hours with changing tides. Disturbance from storms also has an effect on siphon visibility, which usually lasts for days. It is not known whether portions of geoduck populations may be dormant for long periods of time.

Of the show factor assumptions listed on page 6, the assumption that all geoducks in the plot are flagged during the survey has the largest impact on data accuracy. A typical survey is completed in 10 days, however usable show data are only available for 9 days because the plot takes about a day to recover from the disturbance of being set up. A 10-day period is likely insufficient to obtain a census of all animals in the plot, and therefore show factors are probably conservative. In ‘research plot show factors’, which are monitored over a longer time period, field teams were able to find more geoducks after a month of repeated flagging (Alan Campbell, DFO, personal communication). Mortality experiments conducted in Washington have found that geoducks can remain retracted for at least 5 days (Bob Sizemore, Washington Department of Fish and Wildlife, pers. comm). Breen and Shields (1983) first surveyed, and then intensively harvested, five study plots in the Strait of Georgia and WCVI. The ratio of the initial estimate (counts on the first day) to final estimate of density (total number of geoducks collected in plots over the course of sampling) was consistently around 0.53 (range 0.48 to 0.56). However, these studies took place in October and November, which is approaching winter storm activity, and the proportion showing may have been low compared to that of peak show period in the summer months. Researchers in Washington State have found an average show factor over 12 sites established throughout Puget Sound from 1984 to 1993 of 0.62. (Bradbury *et al*. 1999). Since 1994, they have used a standard show factor of 0.75 for all surveys between the months of March and October, which they consider to be conservative.

As part of survey activities in 2001 in the Strait of Georgia, show plots were established at Boastwain Bank, East Valdez Island and Round Island. These plots were not dismantled after the survey, as usual, so that they could be intensively harvested at future opportunities by commercial fishers. Results are preliminary, but suggest that more animals were harvested than were counted in the 10-day monitoring period (Grant Dovey, UHA contract biologist, pers. comm.).

Analysis of existing data should be conducted to learn more of the factors that influence neck retraction and the duration of effects. Fixed conversion factors should be established instead of relying on costly show factor plots, leaving more time to complete transects. Alternatively, density data from surveys could go uncorrected, which would yield more conservative density estimates.

5) *Density Removed by Fishery*
There are known errors in the location of landings from the early years of the fishery when geo-referencing of harvest events was poor. To compile landing statistics by year, the under-reporting of landings prior to the IQ program and dockside validation was corrected by the ratio of harvest logs to sales slip data, on a Statistical Area basis. For the purposes of calculating the density removed by the fishery, harvest log data are not corrected for under-reporting. This is more conservative, since no assumptions are made about the origin of un-reported catch in early years.

Landings (in number of animals) are averaged over the spatial area of the survey, as opposed to the digitized area of the bed polygon so that expressions of survey density and harvested density are compatible. The calculation of survey area is not precise, being the product of mean transect length and shoreline distance, for each survey stratum. Improvements can probably be made to this method, which will improve the accuracy of the estimated density removed.

## 2.2 BED AREA ESTIMATES

Beginning in 1997, when it was acknowledged that bed areas are estimated with some degree of imprecision, area estimates were assumed to be accurate within an arbitrary error of 10% of the mean estimate.

### Background

Since the inception of the geoduck fishery, commercial licence holders have been required, as a condition of licence, to submit harvest logs accompanied by a map showing the location of harvest. Geoduck beds have been spatially defined from these records, where dive locations are transcribed onto hydrographic charts and used to construct harvest bed polygons, which are then digitized to calculate bed areas. The GIS software utilized for this purpose has evolved from GAP1, which provided only an estimate of area via planometric measurement, to Compugrid in which bed polygons were first digitized and displayed as computer-generated bed maps overlaid onto a coastal basemap, to the next generation GIS program, ArcView, where bed polygons can contain many attributes, including biological, environmental or harvest information.

Bed boundaries were defined by following the convention of upper and lower depth limits of 2 fathoms to 10 fathoms, respectively (later changed to 3 m and 20 m with the introduction of metric charts). Geoducks are found below these diveable depths but deep water populations are not included in biomass estimates. As new harvest logs were submitted, fishing events were either coded to an existing bed polygon, or to new bed code if fishing occurred on new ground. Geoduck beds, which are identified by unique bedcodes, are often comprised of aggregations of neighbouring polygons. There are about 1,500 separate bedcodes in BC, which include about

3,300 separate polygons. Unfortunately, many of these polygons are inappropriately lumped (for instance they may be on opposite sides of a channel or island), resulting in a loss in precision of harvest information.

Most of the existing bed polygons in the South Coast and many polygons in the north coast are based on harvest charts submitted in the early days of the fishery. These harvest maps were very inaccurate, often taking the form of hand-drawn sketches or photocopies of large-scale maps with an ‘x marking the spot’. In addition, conventions have become more conservative as more was learned over time about the spatial distribution and patchiness of beds. Since more of the recently mapped beds are in the north coast, the spatial area estimates are considered more accurate and more conservative than in the South Coast.

Observer-fishing, designed to verify the location and extent of geoduck beds and address inconsistencies between the estimated biomass and feedback from industry, was conducted in a number of locations in the South Coast. A grid was placed over the assumed location of the bed in question, and the fishery conducted with an on-board observer who recorded catch and effort information and diver’s observations of substrate, density, product quality and ‘digability’ in each 180 m by 180 m grid square (1/10th of a nautical mile grid). A total of 25 observer fisheries were conducted between 1996 and 1999. Bed polygons on the reference charts were redrawn from the results of these fisheries and, generally, the areas decreased. Observer fisheries have been suspended for the time being because the level of geo-referencing and spatial detail was inferior to new remote-sensing technology now in use. These types of data-collection fisheries have the merit of providing information on geoduck quality, sub-bottom substrate characteristics (related to ‘digability’), presence of juveniles, etc., and could still be considered, with some improvements in protocol, for some fishery areas in conjunction with remote substrate mapping.

In 1997, all of the bed polygons were transferred onto new paper charts because of the tattered state of many of them and also because new metric editions were available. At the same time, a revision of the bed polygons was undertaken by deleting areas of bed that were drawn over rocks and reefs, by downsizing ‘outlier’ beds where the density removed was extremely low (the ratio of geoducks harvested over area would be low if the area was overestimated) and using information from observer grid-fishing, on-grounds monitor and surveys. Accordingly, the area estimate for every bed changed, even if no modifications were made other than merely transcribing the same polygon shape to a fresh chart. Some increase in area estimates occurred as a result of conversion from imperial to metric charts. This illustrates the sensitivity of area estimates to the accuracy of hydrographic charts.

In 2000, an intensive review of the bed maps in the Prince Rupert rotation was completed, using detailed information from the north coast on-grounds monitor (OGM) from the 1999 fishery, survey results and a limited examination of archival harvest charts. Objectives of this review were to recode landings to a smaller spatial scale and thereby increase the precision of their geo-referencing, and to revise the spatial extents of bed polygons using the best available information. The exercise was repeated the following year for beds in the Haida Gwaii rotation, using observer information from the 1997 and 2000 fisheries. The remaining rotation, the Central Coast, is scheduled to be reviewed in the near future with OGM reports from the 1998 and 2001 fisheries. Although an on-grounds monitor has been present on the fishing grounds for every fishery since 1989, it was not until 1997 that Global Positioning Systems (GPS) tools were readily available to enable the compilation of the year’s fishing events in a convenient format for accurately mapping bed boundaries. Approximately one third of the beds in the North Coast were discovered in 1997 or later, and hence it is possible to map the location and extent of these beds with fair accuracy by referring to the maps provided by the OGM. The review of beds fished before 1997 but not since involves a more time-consuming effort of retrieving original harvest charts from the logbook archives.

Through the review in the Rupert and Haida Gwaii rotations, some polygons were moved, some deleted altogether, some increased and some decreased (Table 2). Overall, in the Rupert rotation the area decreased by 562 ha (from 2,725 ha to 2,163 ha), however a single bed was responsible for 107 ha of that reduction. The decrease in area in the QCI rotation was less, at 227 ha. Between 10% and 20% of the beds were unchanged because of the lack of ready information; it is assumed that many of these are overestimated and efforts should be made to verify them. This review also produced useful information for calculating new error estimates around mean area, from which to derive confidence intervals around quota options. Preliminary analyses indicate that the average decrease in bed area, for the subset of beds that were revised only (i.e. no new ground added or bed aggregates split) was 13.8% and 5.2% for the Rupert and QCI rotations, respectively, with a combined average of 8.8%. The arbitrary 10% error imposed on the area estimate since 1997 is not unreasonable, at least in the negative direction. Although approximately 10% and 16% of redrawn beds in the Haida Gwaii and Rupert rotations, respectively, actually increased, the overall change in bed area was negative, so it would be incautious to continue to include an upper confidence bound for this estimate in quota calculations.

Beds on the WCVI should also be reviewed with the new OGM reports, however this information is only an accumulation of one year of fishing events and is therefore limited. There is no OGM information from the inside waters of Vancouver Island.

## Remote Sensing

New remote-sensing technology (QTCView) that uses single-beam acoustical back-scatter analysis and classification is now being applied to determine the sediment composition of the top layer of seabed (Murfitt and Hand 2004). This substrate surveying has quickly become an invaluable tool for determining the spatial extent of geoduck beds and also as a tool for planning and design of transect surveys. Since 2001, acoustical surveys of 15 beds have been completed (Table 3). Except for the noted exceptions, the new area estimate from the substrate map is les than the previous bed area that was based on fisher's charts. The beds in the Tofino area (Area 24) and Thormanby (Area 16) were selected because they were suspected of being in gross error, and therefore are not representative of the overall population of beds. The remaining beds that were mapped with QTCView, while not randomly selected, were not necessarily suspected of being grossly overestimated. The average reduction in area of these beds was about 35%.

An example of the modifications made to one bed polygon is shown in Figure 3, where the logbook-based polygon was redrawn with fishermen's input and again after substrate mapping. The final map includes an area of soft substrate that was later found to be an undiscovered geoduck bed. The example illustrates how poorly-defined some beds can be, highlights the value of interviewing experienced fishermen and establishes the accuracy of acoustical data and its potential for finding as-yet undiscovered geoduck populations.

The potential application of interpolated substrate maps from acoustic surveys and the spatial analysis of data from transect surveys and fishery catch and effort is illustrated in Figure 4. By overlaying these various data sources, one can visualize associations and trends between fishery dynamics and abundance distributions.

In 2001 and 2002, some of the beds scheduled to be surveyed were first mapped with QTCView to assist in the definition of survey strata. These include Boatswain Bank, Marina Island, Round Island, Kulleet Bay, Virago Sound and Barkley Sound. Beds at Valdez Island, Gabriola Island and Comox Bar were mapped as part of on-going efforts to systematically map all beds using acoustic technology.

### Sources of Uncertainty in Area Estimates

The accuracy of the spatial representation of geoduck beds is a function of the accuracy of the harvesters' geographic referencing and their initiative, the accuracy of transposition and interpretation of fisher's information, and the accuracy of the charts themselves. The changes to area estimates that resulted from the use of new GIS software or from the conversion from imperial to metric charts illustrates the sensitivity of this estimate.

In the Strait of Georgia and WCVI, most bed polygons are drawn from information based on harvesters' charts. In early days of the fishery, logbook charts were quite inaccurate, and liberal conventions prevailed when this information was transcribed onto the DFO reference charts. South Coast beds, the target of early fishing effort, are therefore likely overestimated. North Coast beds, on the other hand, may actually be underestimated, since the fishery developed later in North Coast, by which time a more conservative approach had been adopted in drawing new bed polygons. In addition, many of the new beds have likely not been fully explored.

The bed reviews in the North Coast are not comprehensive because many of the beds are not visited during each rotation and therefore they lack the additional information provided by the OGM. Those beds remain unverified and likely poorly defined.

The 10% arbitrary error around estimates of area should be reviewed in light of the results of bed review and verification. Through all the methods used, to date, to verify spatial area, the outcome has predominantly been a decrease in area. It would be prudent to at least discontinue the application of a positive error on area estimates.

Beds should continue to be systematically mapped using the QTCView system. Consideration should be given to combining substrate mapping and transect surveys.

## 2.3 MEAN GEODUCK WEIGHT

### Background

Quota calculations prior to and including 1995 utilized a mean geoduck weight of 1.065 kg (2.348 lb) coastwide, based on limited market sampling of geoducks collected from four sites on the WCVI, one site on the North Coast and one site from Inside Waters in 1981 and 1982 (Harbo *et al.* 1983). For 1996 quotas, mean weight estimates were calculated from a more extensive market-sample data set (Burger *et al*. 1995) and applied separately by Region (North Coast, WCVI, St. of Georgia, Johnstone Strait). Estimates varied by Region from 2.2 lb to 2.8 lb (Hand *et al*. 1998c). Mean weights for the 1997 and 1998 fisheries were calculated and applied on a finer geographic scale using additional market-sample data; estimates varied between 1.7 lb and 2.9 lb by PFM Area (Hand *et al*. 1998d). For the 1999 and 2000 fisheries, yet more market-sample data were available and estimates were applied at finer spatial resolution to a geoduck bed, a PFM Subarea or a PFM Area, as available. The range in estimates by PFM Area was similar to previous estimates at 1.7 to 2.8 lb (Hand *et al.* 1998a).

For 2001 quota calculations, market sampling was abandoned as a source of data for calculating mean geoduck weight in favour of piece count information supplied by fishermen on harvest logs. Piece-count information has been recorded on harvest logs since 1997, is available on a finer spatial scale than market sample data and is now reasonably accurate. Landed weight and the number of geoducks landed, by bed and validated landing, were extracted from the geoduck logbook database in cases where true counts of the number of geoducks harvested were made (as noted on harvest logs). Data were checked for errors, and means with upper and lower 95% confidence intervals were calculated on a by-bed, by-GMA, by-PFM Subarea and by-PFM Area basis. Mean geoduck weights by PFM Area as calculated for the 2002 fishery quotas, are shown in Table 4. The overall average is 2.397 lb, with a range of 1.5 lb to 4.6 lb.

Mean weights from piece counts are not available for every geoduck bed. For those missing this information, the average weight over the GMA, PFM Subarea or PFM Area was used, as available. Of the 1,500 beds coastwide, 55% have bed-specific mean weight estimates, 37% were assigned the mean weight value over GMA, and the remaining 8% of beds were assigned an average over PFM Subarea or PFM Area.

## Sources of Uncertainty in Geoduck Weight Estimates

The standard error of mean weight from piece-counts are calculated for each mean estimate (bed, GMA, etc.). The standard error to mean ratio is high for cases (beds, GMAs, etc.) with few landings. Therefore, only cases where the number of landings is greater than 10 are used to provide mean weight estimates for the purpose of biomass calculations. Mean geoduck weights from piece-count data are estimated with a 2.4% precision at the $\alpha$=0.05 confidence level. Of all the parameters used to calculate geoduck biomass, mean weight is the most precise.

Mean weights could be biased high if there is size selectivity occurring in the fishery. Size selectivity can occur through the spatial allocation of effort, by fishers, to avoid areas of undesirable size (by the market) or by the ability of divers to select from a mixture of size classes and avoid small clams. Population biomass and quota estimates could be inflated if density data from dive surveys include counts of animals that are ultimately avoided in the fishery due to small size. Evidence of size selection has been demonstrated in depletion experiments conducted at Ritchie Bay on the west coast of Vancouver Island (Campbell *et al.* 1998a). Mean weights remained relatively constant in the catch until divers were forced to fish beyond the usual density threshold for commercial fishing, when mean weight of geoducks declined.

A comparison of mean weights, as estimated from logbook piece-count data, and from biological sampling from survey areas is shown in Table 5. The biological sample mean weight is almost always lower than the estimate from landed catch. A couple of explainations are possible: Biological samples take longer to arrive at processing plants where they are weighed than the time elapsed between harvest and dockside catch validation for piece-count data. This would result in higher water loss in the biosamples and lower weight. The proportion of the biological sample that is comprised of smaller animals than the size-threshold for harvest has not been examined. Further work on this issue should be conducted.

## 2.4 ESTIMATION OF CONFIDENCE BOUNDS ON MEAN GEODUCK BIOMASS ESTIMATES

Precision of biomass estimates are calculated in two ways. The first follows methods in Taylor (1982) for products, where the uncertainty of each parameter estimate is independent and random. The coefficient of variation (ratio of the 95% confidence interval of the estimate to the estimate itself) of $B_0$ ($V_B$) is calculated by

$$V_B = \sqrt{V_A^2 + V_D^2 + V_w^2} \tag{2}$$

where $V_A$, $V_D$ and $V_w$ are the coefficients of variation for estimates of bed area, virgin density and mean weight, respectively. Upper and lower 95% confidence bounds on the mean biomass estimate, for each bed, are obtained by adding and subtracting the product of $V_B$ and $B_0$ .

Non-parametric bootstrap techniques are also used to calculate confidence intervals around mean biomass where survey data are available, following the procedures in Campbell *et al.* (1998a). The procedure randomly samples from within the distribution of transect density data, geoduck weight and survey area, and computes 95% confidence bounds using the percentile method from 1000 estimates of mean biomass. To date, however, these estimates have not been incorporated into quota calculations. Ideally, estimates of survey area rather than digitized bed area should be used to calculate an unbiased estimate of biomass. However, an efficient method to estimate survey area is not available, as it requires accurate bathymetric charts of nearshore waters. A rough calculation of surveyed area in use is the product of shoreline length and average transect length, by stratum.

Biomass estimates for surveyed geoduck beds scheduled to be fished in 2003 have 95% confidence bounds averaging about 58% of the mean.

## 2.5 MARKET QUALITY

Geoducks vary widely in their colour, size and appearance, from dark to white flesh, short to long necks and smooth to leathery skin texture. The most desirable appearance for the market is a white and unblemished neck and a medium body size. Every geoduck harvested and landed is paid the same price, regardless of the quality of the product. However, buyers have a limit of the amount of inferior quality product that can be absorbed by the market and are usually quick to instruct vessels to fish elsewhere when loads of poor quality geoducks arrive at processing plants. All geoducks are considered equal in the eyes of stock assessment and density estimates are provided regardless of what proportion may be unmarketable. Some studies have been conducted that examined quality in relation to substrate and age (G. Jamieson, DFO, personal communication). Market samples have been collected in selected beds to gather information on mean geoduck weight and market quality for each geoduck. The data were not extensive or spatially-detailed enough to warrant their collection for quality alone after the sampling program was discontinued in 2000 for mean weight data. The extent to which bed quotas include clams that are avoided by fishermen is therefore not known. Some information on product quality for most beds in the North Coast exists via descriptions by the OGM, but this has not been utilized to date. Although it would be laborious to extract, code and geo-reference these data from the OGM reports, this work could be undertaken if resource managers wanted the information.

## 3. EXPLOITATION RATE

The first exploitation rates were arbitrarily set in 1979 at 2 to 5% of virgin biomass estimates (Harbo *et al.* 1992). In 1980, a revised exploitation rate of 1.2% to 2.5% was suggested, based on early biological data from WA studies. Later in 1980, this was again revised to 0.75%-2% of estimated virgin biomass, based on analyses and modelling of the first estimates of growth, mortality and recruitment from BC (Breen 1982). The possible negative effects of fishing on recruitment noted by Goodwin and Shaul (1984) suggested using the lower end of the estimate. Results from a study in BC in 1989 (Noakes and Campbell 1992) confirmed the low productivity and also suggested that the range was reasonable. In 1992, two PSARC working papers were reviewed which simulated population dynamics using age-structured models to examine sustainable fishing patterns in BC. Breen (1992) suggested that the current 1% level was conservative while Campbell and Dorociez (1992) suggested that exploitation rates near 0.5% were more appropriate except where recruitment was shown to be higher, in which case 2% of the original biomass could be considered. Since both authors used the same estimates of natural mortality (M=0.02), the difference in their conclusions could be attributed to differences in assumptions of recruitment.

The original yield model upon which current quotas are based (Breen 1982) estimated that quotas should be kept within 0.75 to 2.0% of the virgin biomass, depending on the stock-recruitment relationship, to achieve an equilibrium population of 50 % $B_0$. The revised model (Breen 1992) predicted that a fishing pattern of 1% exploitation rate and a 3-year rotation would result in an expected mean biomass of 70% of virgin levels after 50 years of fishing.

**<u>Sources of Uncertainty in Exploitation Rate</u>**

Predictions of equilibrium yield produced by models to date were based on the limited information available at the time. Better and more geographically explicit knowledge of recruitment, growth and mortality rates from research conducted since that time could be utilized in new yield models to explore whether spatially-explicit exploitation rates or harvest strategies are appropriate. Use of a single coastwide exploitation rate assumes that all geoduck populations have the same productivity. Recruitment mechanisms are poorly understood, however spatial variability in recruitment is suggested by commercial fishery reports. Little is known of spatial trends in natural mortality. Temporal trends in recruitment are evident from age-frequency distributions, and the possibility of coherent declines in recruitment over large spatial scales has been suggested (Orensanz *et al.* 2000). The effect of harvest on population dynamics is being investigated in several experiments in the south coast which are currently being analyzed.

### 3.1 LIMIT REFERENCE POINT AND QUOTA COMPENSATION

A 50-year time horizon was adopted by resource managers in 1995, whereby quotas are reduced to evenly distribute the remainder of estimated $0.5B_0$ over the remainder of the 50-year fishery, in any given bed. An ‘amortization factor (AF) is calculated for each bed as the ratio of years of quota left to the number of actual years left in the 50-year period.

$$AF = \frac{50 - (Landings / AnnualQuota)}{50 - (\#YearsElapsed)}$$

Landings are corrected for under-reporting and the annual quota is as calculated with the most recent estimate of biomass. Quota adjustments are applied to beds that have been harvested at higher rates because of previous biomass estimation errors, essentially as compensation. As biomass estimates decrease (usually), with the availability of new area, density or mean weight estimates, the ‘amortization factor’ increases to the point where beds are closed. Thus, a limit reference point is in place which prevents a population from falling below 50% of estimated virgin levels. Managers currently require a survey and evaluation before closed beds can be re-opened.

The application of amortization factors amplifies the imprecision in biomass and quota estimates. Quota estimates for the 146 surveyed geoduck beds to be fished in 2003 have 95% confidence bounds averaging about 122% of the mean, in contrast to the precision of biomass estimates of 58%.

## 4. CATCH ESTIMATES

There has been a logbook program in place since the beginning of the geoduck fishery in BC. Underreporting of landings has been corrected with sales slip data. High-grading (dumping of undesirable product) and poaching are not accounted for in landing estimates. The degree to which this happens is unknown, but anecdotal comments confirm that a certain level of underwater selection occurs. Generally, the practice is frowned upon by fishermen and the UHA, and a certain amount of self-policing takes place which probably eliminates gross instances. A low level of highgrading is taken for granted but not included in catch estimates.

## 5. DISCUSSION

The assessment of geoduck stocks in BC, although challenged with the issues of small-scale, spatially-structured, sedentary stocks, benefits from the co-operation and close working relationships with the industry stakeholders who have a strong incentive to maintain a sustainable fishery. This enables an effective structure for localized monitoring and detailed and timely collection of catch and effort statistics. Furthermore, the contributions by the fishing association towards annual abundance surveys, research studies, substrate mapping and biological data collection is significant; it produces both a lot of data and it creates trust in the system. Data are being collected faster than they can be analysed, and a bottleneck exists because of a lack of resources to make full use of the data and to look at the dynamics of the system as a whole. Data are now available to begin to examine fine-scale geoduck distribution patterns, spatial variation in productivity and fleet dynamics. The problem, therefore, is to prioritize the potential areas of investigation to yield the most needed information within reasonable cost constraints.

Of the parameters used to estimate biomass, geoduck bed area is the least accurately estimated and, worse, the errors generally lead to overestimation of biomass. The bed review in the north coast revealed that few beds areas are underestimated, and results suggest that an error of 10% is not unreasonable, overall, but that no upper error range should be included. Estimation errors for South Coast beds are likely much higher and every effort should be made to address these uncertainties. Ratios of landings to estimated area can be used to prioritize this evaluation. Another rich source of information is harvester’s experience.

Density estimates are highly dependent on prior knowledge of the location of geoduck beds, since survey protocols are based on their location as drawn on the reference bed charts. Spatial inaccuracies result in more variability in survey data as a result of transects being placed on non-geoduck habitat. Some degree of post-stratification has been undertaken, and more is possible. The acoustic bed-mapping program can produce pre-survey substrate maps which would improve survey designs and, ultimately, increase precision. The problem arises with extrapolating these more precise, and higher, density estimates to unsurveyed beds that are poorly estimated and likely overdrawn. The result would be overestimates of the biomass. More work will be conducted to evaluate survey data collected from pre-survey mapped beds; the first such dataset was collected in 2001.

Survey results and biological sampling has shown that the assumption of proximal similarity in geoduck density is often invalid. A much smarter way of extrapolating density data to unsurveyed beds is to classify all beds by productivity and extrapolate densities on the basis of qualitative characteristics that relate to bed productivity. Survey results should be related with local-scale habitat characteristics, using geo-spatial software and statistics, to examine relationships. Features such as substrate, exposure and slope, indices based on catch per unit effort data or historical performance, and qualitative descriptions from the OGM and fishermen can all be used to indicate, in a categorical way, how productive a bed is. This information, facilitated with the use of GIS software, should be used to assign density estimates to unsurveyed beds.

Even if individual bed density estimates are highly variable, the overall Regional averages have somewhat stabilized (Figure 5) and additional surveys are unlikely to have a large influence on overall estimates. Considering the need to improve area estimates, resolving bed mapping problems is a priority. This does not preclude conducting density surveys for special purposes, and there are many reasons to do so, including monitoring recovery in closed beds, re-surveying beds to examine pre- and post-fishery effects, and experimental fisheries. The need to identify priority field projects also highlights the fact that monitoring show factor plots may not be cost-effective, considering that 25% of field time is invested into the collection of these data. A decision should be made to abandon show plots in favour of either no correction (the most conservative) or the use of a standard correction, similar to Washington. The latter would require analysis of existing data or possibly the collection of new data.

In geoducks, the unit stock concept is only valid if stocks are defined on a very small spatial scale. The very nature of these sedentary clams guarantees that the distribution of fishing effort will be uneven. Stock dynamics and the fishing process need to be analyzed in a spatially explicit context. We have moved progressively from large-scale estimates to a more spatially–explicit context where stock biomass and dynamics are estimated on a smaller scale. A re-examination of the single coastwide exploitation rate is due. It is highly likely that beds vary in productivity regimes and that different exploitation rates are appropriate. Amid all the work directed at refining biomass estimates, time should also be allocated to take a retrospective look at the impact of past harvests on geoduck stocks in order to assess the 1% exploitation rate. Available time-series data should be compiled (e.g. catch and effort, density, mean geoduck weight, fleet dynamics) to rigorously ground-truth the area-based methodology and assumptions about productivity.

The management strategy in use for the geoduck resource relies on estimates of biomass and productivity, both of which are estimated with a high degree of uncertainty. Until these estimates can be improved by means of the work suggested, resource managers should maintain a precautionary approach to exploitation of geoduck stocks. A certain measure of precaution is afforded by the harvest refugia that naturally exists for populations in closed areas (e.g. parks, contaminated waters), unharvestable substrate and below diveable depths. Quota fisheries can be combined with other means of controlling effort to ensure that a safety net exists in the face of such uncertainty. This could include the implementation of widely-distributed harvest refugia to act as larval sources to rehabilitate depleted beds, or facilitate rehabilitation through enhancement. Given the uncertainty of stock-recruitment mechanisms, the adoption of minimum spawning stock density as a limit reference point could also be considered.

## 6. RECOMMENDATIONS

1. **Put a high priority on resolving inaccuracies in bed area estimates.** All data and information available should be utilized, and new data collected, to build a coastwide bed map with area estimates that are based on reliable data. Unresolved beds that can't be drawn with certainty should be targeted for verification during fishery openings.

2. **Discontinue the use of a positive error on bed area estimates until further review**.

3. **Discontinue the use of show factor plots to correct survey density estimates**. Conduct analyses on existing data and continue projects designed to measure 'showability' to calculate a standard factor. Alternatively, survey density may remain uncorrected..

4. **Investigate the issue of size selectivity in the fishery as it relates to bias in mean individual geoduck weight estimates.** This would involve analysis of existing data, and/or the collection of additional data, to determine the proportion of the population that is readily visible to divers during transect surveys, yet are avoided in the fishery.

5. **Re-examine exploitation rates.** Utilize new information on growth, recruitment and natural mortality as inputs for age-structured yield models to potentially be applied on smaller spatial scales.

6. **Continue to work towards spatially-explicit approaches for cataloguing information on geoduck beds.** Utilize bed classifications to extrapolate density estimates to unsurveyed beds.

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*Table 1. Transect surveys conducted to 2002, by location, with the survey design (Sys=systematic transect placement, Rand=random), survey density, density removed, back-calculated pre-fishery (virgin) density and average density estimates by Region.*

| | Location | Statistical Area | Year | Survey Design | Bio. Sample | No. of Transects | Mean Density (#/m$^2$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Survey | Removed | Pre-fishery |
| **Haida Gwaii** | | | | | | | | | |
| | Burnaby Island | 2-12,-13 | 1994 | Sys | Yes | 39 | 1.28 | 0.22 | 1.50 |
| | Hotspring Island | 2-11,-12 | 1995 | Sys | Yes | 42 | 1.45 | 0.13 | 1.59 |
| | Houston Stewart Ch. | 2-18,-19,-31 | 1996 | Rand | Yes | 59 | 1.22 | 0.14 | 1.36 |
| | Houston Stewart Ch. | 2-18,-31 | 1999 | Rand | No | 26 | 2.44 | 0.37 | 2.81 |
| | Cumshewa Inlet | 2-3 | 1997 | Rand | Yes | 84 | 0.51 | 0.14 | 0.65 |
| | Selwyn, Dana & Logan Inlets | 2-6,-8 | 1998 | Rand | Yes | 88 | 1.14 | 0.12 | 1.27 |
| | Hippa Island | 2-87,88 | 1999 | Rand | Yes | 55 | 2.88 | 0.32 | 3.20 |
| | Port Chanal | 2-89,-90 | 1999 | Rand | No | 28 | 0.60 | 0.19 | 0.80 |
| | West Skidegate Channel | 2-64,-65,-66 | 1999 | Rand | No | 31 | 0.81 | 0.14 | 0.95 |
| | Buck Channel | 2-63 | 1999 | Rand | No | 6 | 4.39 | 0.14 | 4.53 |
| | Englefield Bay | 2-49,-50,-53,-55 | 1999 | Rand | No | 45 | 1.31 | 0.18 | 1.49 |
| | Gowgaia Bay | 2-38,-39,-40,-41 | 1999 | Rand | Yes | 30 | 0.76 | 0.08 | 0.84 |
| | Kano Inlet | 2-70,-71 | 2001 | Rand | Yes | 40 | 1.55 | 0.10 | 1.64 |
| | Tasu Sound | 2-42,-43,-45,-47 | 2001 | Rand | Yes | 41 | 0.85 | 0.00 | 0.85 |
| | Langara Is., Virago Sound | 1-2, 1-3 | 2002 | Rand | Yes | - | - | - | - |
| | | | | | | **ave. QCI** | **1.51** | **0.16** | **1.68** |
| **North Coast** | | | | | | | | | |
| | Griffith Harbour | 5-20 | 1995 | Sys | No | 33 | 2.20 | 0.45 | 2.65 |
| | Weeteeam B/W Aristazabal | 6-13,-17,106-2 | 1995 | Sys | No | 29 | 1.51 | 0.40 | 1.91 |
| | S. Banks Island/Otter Pass | 6-9 | 1996 | Rand | Yes | 39 | 1.65 | 0.19 | 1.84 |
| | W. Aristazabal, Clifford Bay | 13-Jun | 1996 | Rand | Yes | 58 | 1.46 | 0.29 | 1.75 |
| | Principe Channel | 5-13 | 1997 | Rand | Yes | 60 | 2.16 | 0.02 | 2.18 |
| | Dundas Island | 3-1 | 1998 | Rand | Yes | 64 | 1.93 | 0.38 | 2.31 |
| | | | | | | **ave. Rup** | **1.82** | **0.29** | **2.11** |
| | Moore Islands | 106-2 | 1998 | Rand | Yes | 41 | 4.23 | 0.07 | 4.30 |
| **Central Coast** | | | | | | | | | |
| | W Price Island | 6-17,7-2,-31 | 1993 | Sys | Yes | 22 | 1.55 | 0.31 | 1.86 |
| | W Higgins Pass / Kitasu Bay | 6-16,-17,-18 | 1994 | Sys | Yes | 62 | 1.55 | 0.31 | 1.86 |
| | McMullin Group | 7-18 | 1994 | Sys | No | 25 | 1.27 | 0.42 | 1.69 |
| | Goose/Wurtele/Seaforth | 7-8,-9,-12,-25,-32,18-1 | 1995 | Sys | Yes | 63 | 1.56 | 0.47 | 2.03 |
| | S Bardswell/Prince Group | 7-18,-19,-20,-21,-23,-24,-25,-32 | 1996 | Rand | Yes | 83 | 2.02 | 0.38 | 2.40 |
| | Anderson Is./Laredo Ch. | 6-1,-13,-14 | 1997 | Rand | Yes | 98 | 1.88 | 0.15 | 2.03 |
| | Hakai Passage | 8-1,-2,-4,7-27 | 1998 | Rand | Yes | 104 | 1.65 | 0.40 | 2.05 |
| | | | | | | **ave. CC** | **1.64** | **0.35** | **1.99** |

| Location | Statistical | Year | Survey | Bio. | No. of | Mean Density (#/m$^2$) | | |
|---|---|---|---|---|---|---|---|---|
| | Area | | Design | Sample | Transects | Survey | Removed | Pre-fishery |
| **West Coast of Vancouver Island** | | | | | | | | |
| Elbow Bank | 24-6 | 1994 | Sys | Yes | 5 | 0.51 | 1.06 | 1.57 |
| Elbow/Yellow Bank | 24-6,-7 | 1995 | Rand | No | 44 | 1.82 | 0.54 | 2.36 |
| Winter Harbour | 27-2,-3,-7 | 1996 | Rand | Yes | 88 | 0.57 | 0.37 | 0.94 |
| Millar Ch./Yellow Bank | 24-4,-6 | 1997 | Rand | Yes | 28 | 1.72 | 0.24 | 1.96 |
| | 24-7 | 1997 | Rand | Yes | 4 | 1.38 | 0.64 | 2.02 |
| Mission Grp., Kyuquot Sd. | 26-1,-6,-7 | 1998 | Rand | Yes | 29 | 0.95 | 1.04 | 1.99 |
| Lemmens Inlet | 24-9 | 2000 | Rand | No | 12 | 0.36 | | |
| Nootka Sound | 25-6,-15 | 2000 | Rand | Yes | 54 | 0.55 | 0.99 | 1.54 |
| Maggie R./Toquart Bay | 23-10 | 2000 | Rand | Yes | 43 | 0.61 | 0.34 | 0.95 |
| Rolling Roadstead | 25-13 | 2001 | Rand | Yes | 16 | 0.30 | 2.27 | 2.57 |
| Alma Russel/Vernon Bay | 23 | 2002 | Rand | Yes | - | - | - | - |
| Winter Harbour | 27 | 2002 | Rand | Yes | - | - | - | - |
| | | | | | **ave. WCVI** | **0.88** | **0.83** | **1.77** |
| **Inside Waters** | | | | | | | | |
| S Goletas Channel | 12-16 | 1994 | sys | Yes | 77 | 1.28 | 0.40 | 1.68 |
| Duncan Island | 12-11,-16 | 1995 | sys | Yes | 103 | 0.98 | 0.35 | 1.33 |
| | | | | | **ave. north** | **1.13** | **0.38** | **1.51** |
| Marina Island | 13-15 | 1992 | sys | Yes | 73 | 0.27 | 0.46 | 0.73 |
| Marina Island | 13-15 | 2002 | Rand | Yes | | | | |
| Comox Bar/Sandy Isl. | 14-9 | 1993 | sys | Yes | 15 | 0.31 | 0.13 | 0.44 |
| Comox Bar/Sandy Isl. | 14-10,-11 | 1998 | Rand | Yes | 17 | 0.31 | 0.14 | 0.45 |
| Inside Comox Bar | 14-11 | 2000 | Rand | No | 18 | 0.52 | 0.05 | 0.57 |
| Oyster Bay-Little R. | 14-13 | 1995/96 | Rand | Yes | 55 | 0.17 | 0.04 | 0.21 |
| Thormanby Island | 16-1,-2 | 1999 | Rand | Yes | 35 | 0.52 | 0.04 | 0.56 |
| Round Island | 17-16 | 2000 | Rand | Yes | 9 | 0.38 | 0.61 | 0.99 |
| E Valdes Island | 29-5 | 2000 | Rand | No | 6 | 0.79 | 0.38 | 1.17 |
| Kulleet Bay | 17-5 | 2001 | Rand | No | 8 | 0.56 | 0.27 | 0.83 |
| Boatswain Bank | 18-7 | 2001 | Rand | Yes | 7 | 1.187 | 0.14 | 1.33 |
| Boatswain Pipeline Landfall | 18-7 | 2001 | Rand | No | 3 | 0.56 | 0.00 | 0.56 |
| | | | | | **ave. south** | **0.50** | **0.23** | **0.73** |

*Table 2. Results of bed review in the Prince Rupert and Haida Gwaii rotations.*

| | Prince Rupert | | Haida Gwaii | |
|---|---|---|---|---|
| | # beds | Area (ha) | # beds | Area (ha) |
| Pre-review total | 173 | 2,725 | 378 | 2,560 |
| Post-review total | 221 | 2,163 | 513 | 2,409 |
| Number of new beds | 9 | 29 | 95 | 190 |
| Beds that had portions split off | 16 | | 26 | |
| Beds that were split off existing beds | 38 | | 40 | |
| Beds that did not change | 39 | | 59 | |
| Redrawn beds | 111 | -384 | 127 | -227 |
| Beds that got smaller | 74 | -451 | 78 | -306 |
| Beds that got larger | 36 | 66 | 49 | 79 |
| Overall area change (ha) | | -562 | | -151 |

*Table 3. Comparison of new estimates of bed area (ha) resulting from QTC substrate mapping to previous estimates.*

| | | | Area (ha) | | | |
|---|---|---|---|---|---|---|
| **Location** | **Bed code** | **Gis code** | **Old** | **New** | **Diff.** | **% chg** |
| N of Wickaninnish Island | 24-8-1 | 532 | 116.5 | 32.0 | -84.5 | -72.5 |
| Tonquin Island | 24-8-5 | 534 | 91.5 | 13.7 | -77.8 | -85.0 |
| Calmus Pass - Vargas Isl.[1] | 24-6-23 | 510 | 42.25 | 23.9 | -18.4 | -43.5 |
| MacIntoch Rock [1] | 24-6-9 | 529 | 4.4 | 11.5 | 7.1 | +161.4 |
| E of Morfee Island | 24-6-26 | 519 | 95.5 | 79.0 | -16.5 | -17.3 |
| Dunlap Island | 24-6-31 | 520 | 11.6 | 6.0 | -5.6 | -48.3 |
| N Thormanby Island | 16-2-1, 16-1-1 | 168 / 169 | 343.9 | 224.1 | -119.8 | -34.8 |
| Round Island [2] | 17-16-1&2 | 315 / 333 | 14.2 | 27.0 | 12.8 | +90.1 |
| Boatswain Bank | 18-7-1 | 366 | 50.6 | 31.0 | -19.6 | -38.7 |
| Comox Bar | 14-13-5, 14-10-1 | 120 / 180 | 1392.6 | 907.0 | -485.6 | -34.9 |
| Marina Island | 13-15-1&2 | 223 / 224 | | | | |
| Gabriola Island | 17-10-7 | 314 | 117.2 | | | |
| Valdes Island | 29-5-2&3 | 323 / 324 | 21.1 | 21.1 | 0.0 | 0 |
| Kulleet Bay | 17-5-1 | 335 | 57.6 | 40.5 | -17.1 | -30.0 |

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[1] Old and new areas are not comparable because the bed codes were redefined with the survey results.

[2] The 1998 area based on fisher's charts was 51.29 ha.

*Table 4. Mean geoduck weight estimates, by PFM Area, from combined 1997 to 2001 logbook piece-count data.*

| PFM Area | MeanWt (lb) | # Samples | Range, by bed (lb) | | 95% CI |
|---|---|---|---|---|---|
| | | | Min | Max | |
| 1 | 2.468 | 58 | 2.286 | 2.948 | 0.110 |
| 2 | 2.735 | 2359 | 1.456 | 4.650 | 0.021 |
| 3 | 2.162 | 73 | 1.948 | 2.370 | 0.075 |
| 4 | 2.597 | 221 | 2.110 | 3.564 | 0.059 |
| 5 | 2.400 | 459 | 1.854 | 3.006 | 0.035 |
| 6 | 2.505 | 768 | 1.822 | 3.446 | 0.032 |
| 7 | 2.432 | 1438 | 1.779 | 3.303 | 0.024 |
| 8 | 2.625 | 280 | 1.922 | 3.092 | 0.060 |
| 9 | 2.350 | 86 | 1.937 | 2.846 | 0.092 |
| 10 | 2.108 | 78 | 1.908 | 2.328 | 0.089 |
| 12 | 2.503 | 155 | 2.169 | 3.047 | 0.057 |
| 13 | 2.420 | 232 | 1.803 | 3.237 | 0.065 |
| 14 | 2.458 | 864 | 2.221 | 3.470 | 0.030 |
| 15 | 2.322 | 774 | 1.778 | 3.047 | 0.037 |
| 16 | 2.180 | 196 | 1.781 | 2.470 | 0.052 |
| 17 | 2.319 | 160 | 1.551 | 3.303 | 0.075 |
| 18 | 2.049 | 3 | 2.049 | 2.049 | 0.880 |
| 19 | 2.903 | 95 | 2.797 | 2.945 | 0.073 |
| 23 | 2.278 | 293 | 1.938 | 2.918 | 0.047 |
| 24 | 2.461 | 2089 | 1.554 | 3.131 | 0.019 |
| 25 | 2.389 | 513 | 1.816 | 3.076 | 0.037 |
| 26 | 2.168 | 247 | 1.733 | 3.232 | 0.045 |
| 27 | 2.215 | 381 | 1.644 | 3.067 | 0.043 |
| 106 | 2.482 | 37 | 2.346 | 2.563 | 0.093 |
| Combined | 2.397 | 11,859 | 1.456 | 4.650 | |

*Table 5. Comparison of mean geoduck weight estimates from harvest log piece-count data and from biological sampling for all surveyed beds.*

| Survey | | Mean Geoduck Weight (lb) | | |
|---|---|---|---|---|
| | PFM Area | Piece-count | Biosample | % Difference |
| Cumshewa Inlet | 2 | 3.06 | 2.43 | 26 |
| Selwyn/Dana/Logan Inlets | 2 | 2.59 | 2.16 | 20 |
| Hotspring Island | 2 | 2.46 | 2.00 | 23 |
| Burnaby Island | 2 | 3.39 | 3.17 | 7 |
| Houston Stewart Ch. | 2 | 2.50 | 2.03 | 23 |
| Gowgaia Bay | 2 | 3.17 | 3.34 | -4 |
| Hippa Island | 2 | 2.26 | 1.70 | 34 |
| Dundas Island | 3 | 2.12 | 1.70 | 25 |
| Principe Channel | 5 | 2.31 | 1.88 | 23 |
| Otter Pass | 6 | 2.24 | 1.89 | 24 |
| Anderson/Laredo | 6 | 2.40 | 1.97 | 31 |
| West Aristazabal Island | 6 | 2.61 | 2.25 | 18 |
| West Higgins Pass | 6 | 2.49 | 2.03 | 23 |
| Kitasu Bay | 6 | 2.35 | 2.25 | 6 |
| Price Island | 6 | 2.37 | 2.12 | 12 |
| Moore Islands | 106 | 2.50 | 2.22 | 13 |
| Goose/Wurtele/Seaforth | 7 | 2.06 | 1.46 | 41 |
| S Bardswell/Prince Group | 7 | 2.18 | 1.90 | 20 |
| Hakai Passage | 8 | 2.64 | 3.00 | -6 |
| Duncan Island | 12 | 2.95 | 2.10 | 40 |
| Goletas Channel | 12 | 2.48 | 2.30 | 9 |
| Comox 1993 | 14 | 2.22 | 2.04 | 9 |
| Comox 1998 | 14 | 2.22 | 1.72 | 29 |
| Oyster River | 14 | 2.44 | 2.07 | 18 |
| Thormanby Island | 16 | 1.93 | 1.63 | 18 |
| Round Island | 17 | 2.20 | 1.61 | 37 |
| Valdes Island | 17 | 2.01 | 1.43 | 40 |
| Boatswain Bank | 18 | 2.05 | 1.49 | 38 |
| Barkley Sound | 23 | 2.43 | 2.12 | 15 |
| Millar Channel | 24 | 2.07 | 1.63 | 27 |
| Elbow Bank | 24 | 2.49 | 3.29 | -24 |
| Tofino | 24 | 2.49 | 2.68 | -7 |
| Yellow Bank | 24 | 2.40 | 2.10 | 14 |
| Nootka Sound | 25 | 2.22 | 1.69 | 35 |
| Kyuquot | 26 | 1.86 | 1.60 | 16 |
| Winter Harbour | 27 | 2.26 | 1.70 | 33 |
| **Overall Average** | | 2.44 | 2.11 | 20 |

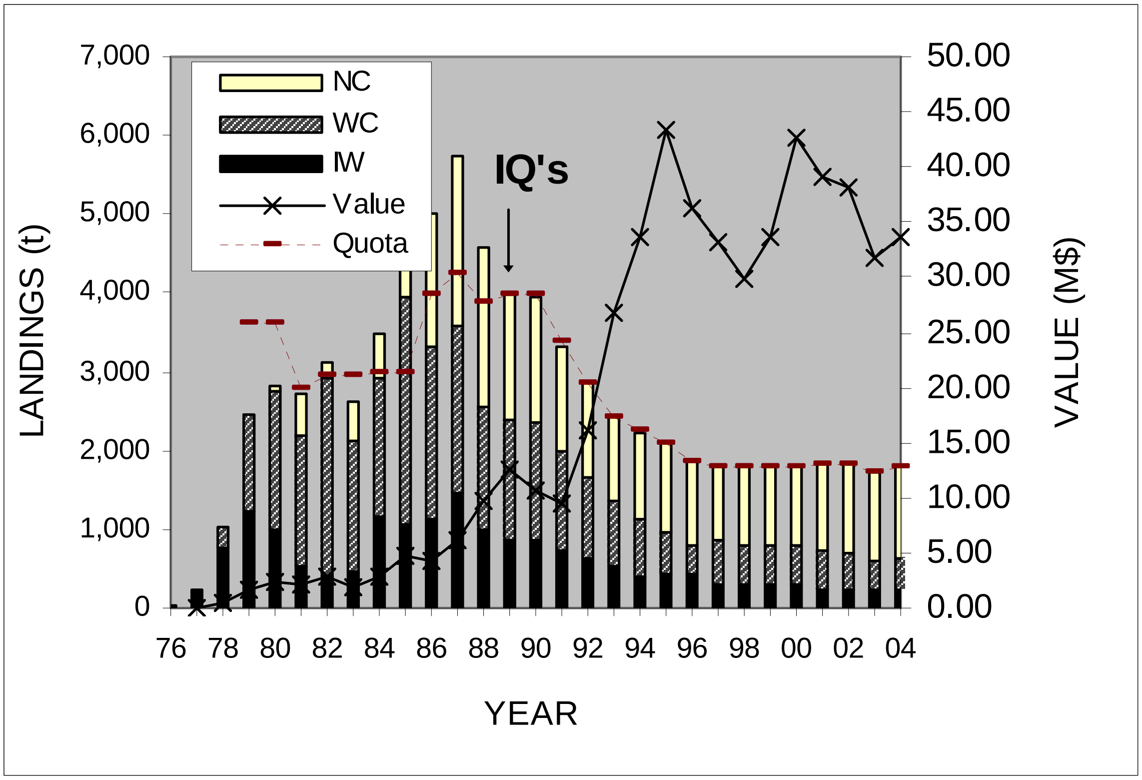


*Figure 1. Summary of quota (t), landings by region (t) and fishery value (millions of dollars), by year, for the geoduck fishery.*

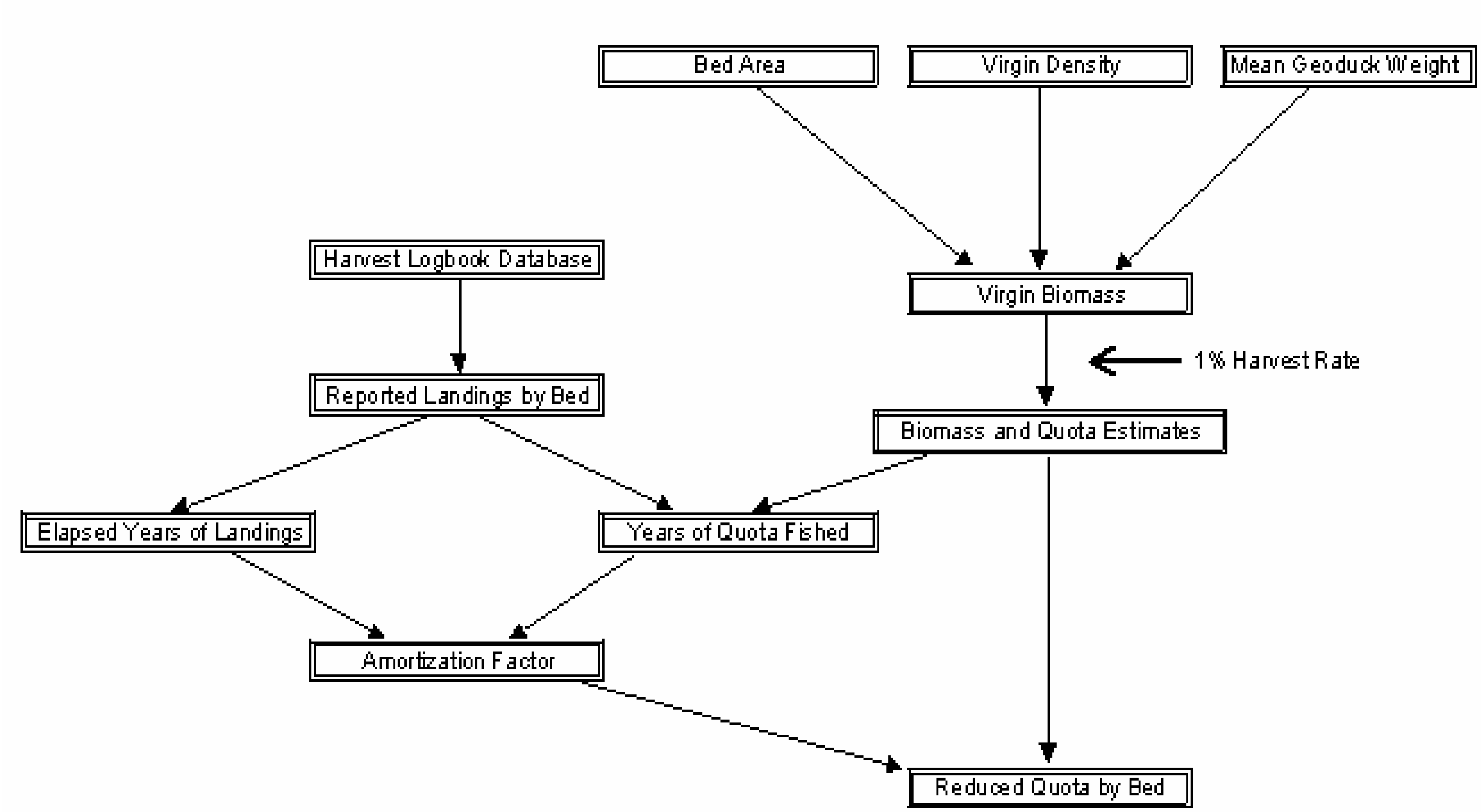
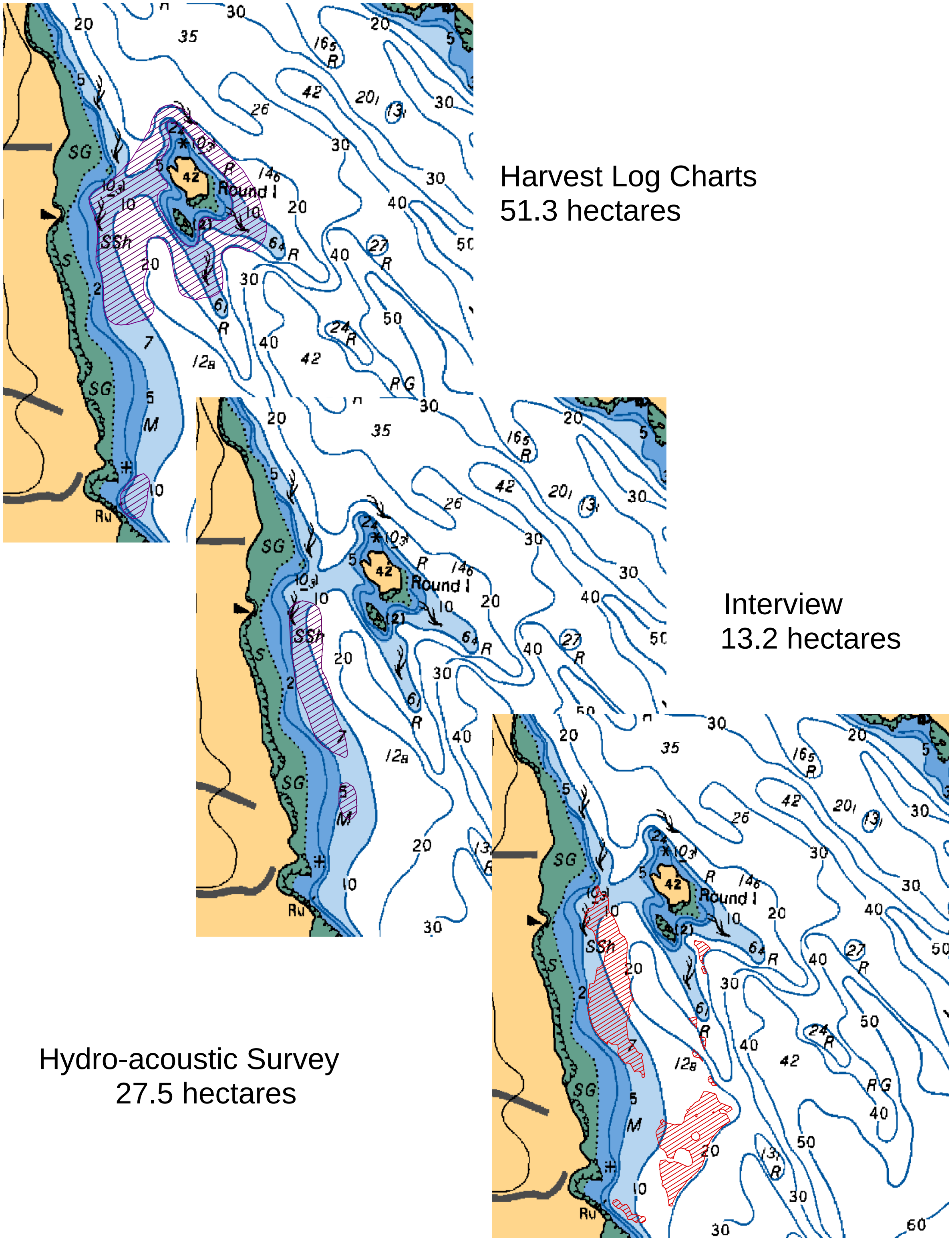


*Figure 2. Flowchart showing source data and sequence of computations for the calculation of geoduck quotas.*



Harvest Log Charts
51.3 hectares

Interview
13.2 hectares

Hydro-acoustic Survey
27.5 hectares

*Figure 3. Spatial extent and calculated area of a geoduck bed in the Strait of Georgia as determined from harvest log charts (top panel), interviews with harvesters (middle) and with acoustic substrate mapping (bottom panel).*

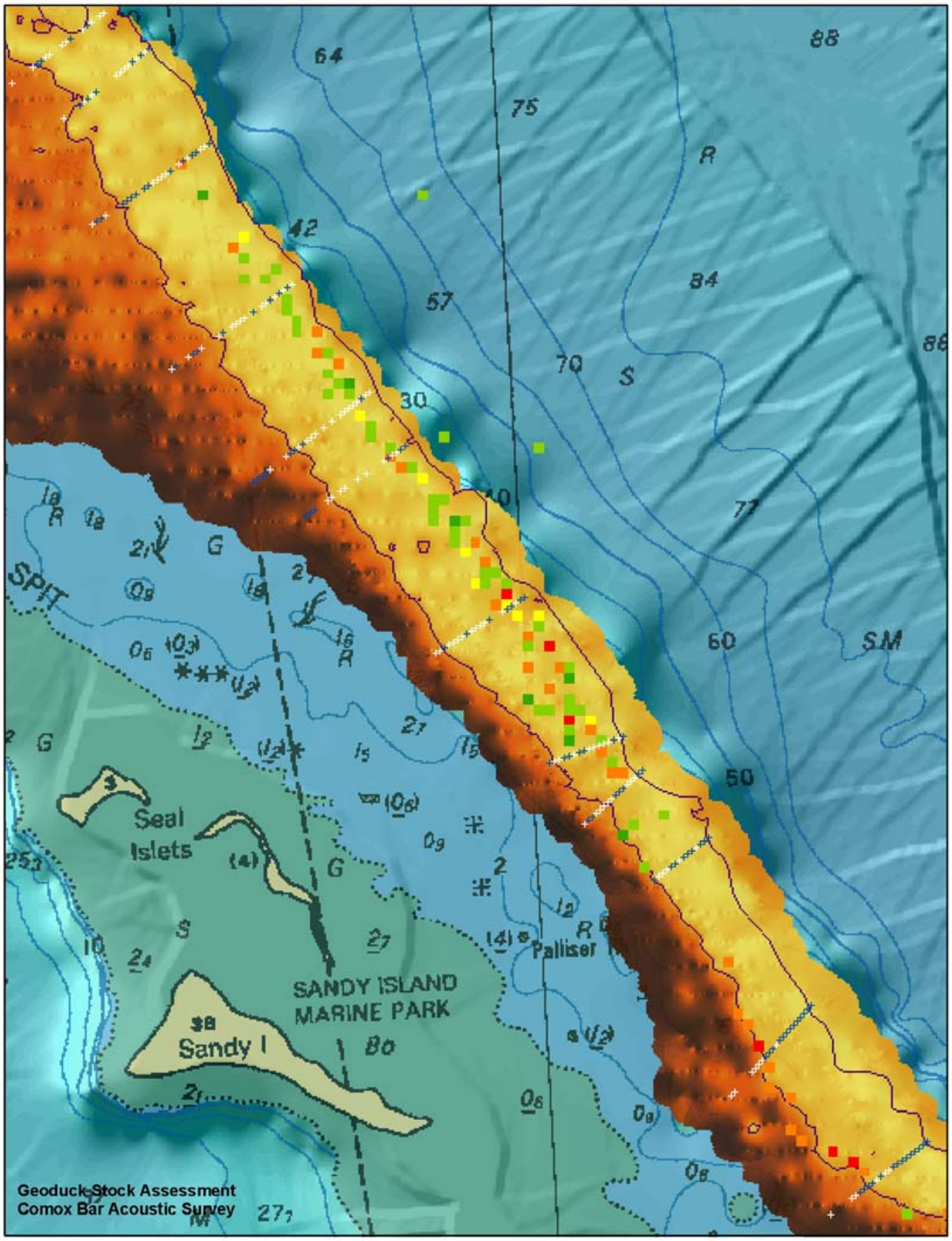


Figure 4. Substrate surface from acoustical survey at Comox Bar, overlaid with transect density data (blue or white crosses; white = 0 geoducks) and fishing events (coloured squares; red = high catch density, yellow = low). Soft substrate is yellow and bed boundary is defined by solid line.

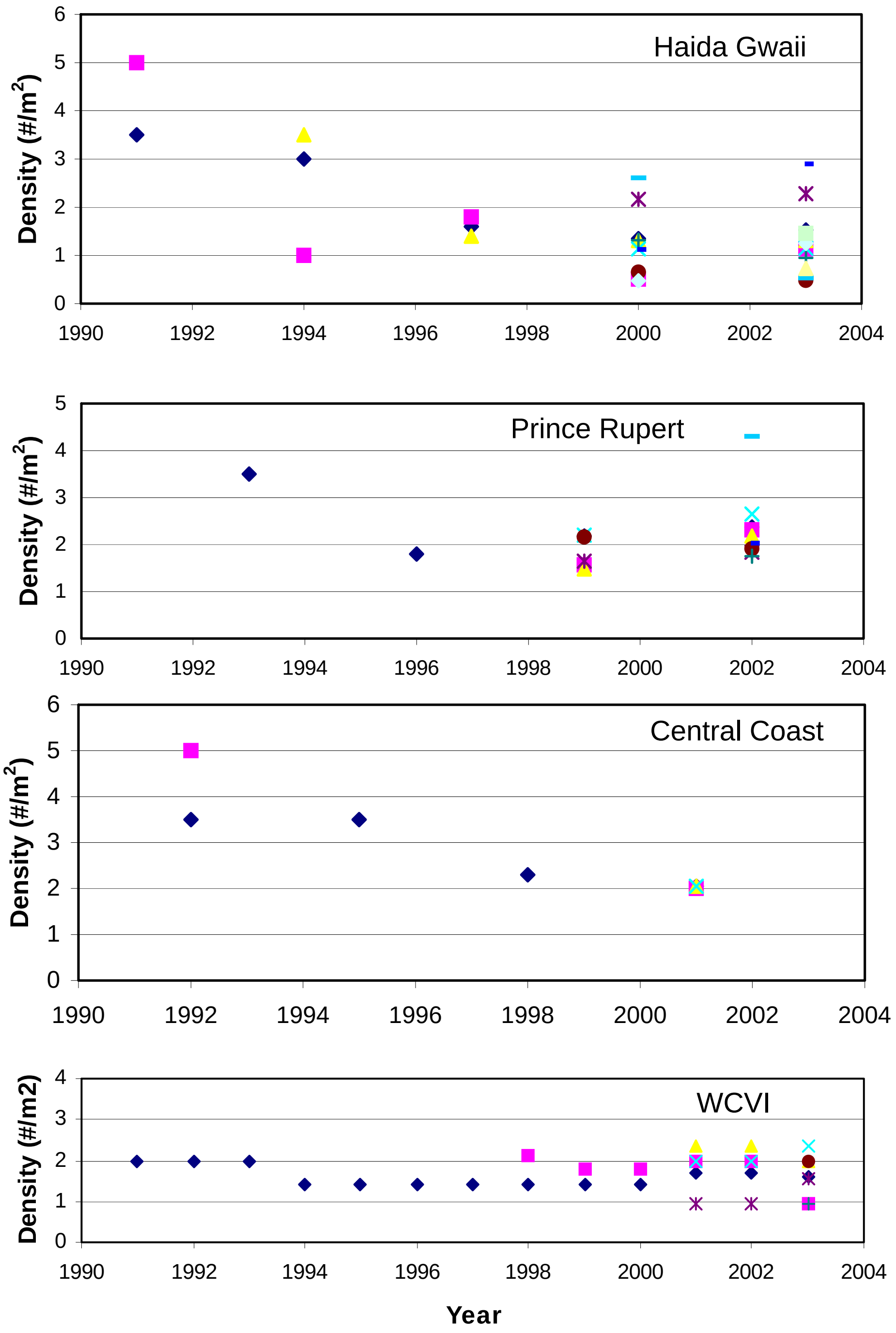


*Figure 5. Plot of estimated regional average geoduck density, by Region and year (large diamonds) with the individual survey density estimates shown in other symbols.*

## APPENDIX 1. REQUEST FOR WORKING PAPER

### PSARC INVERTEBRATE SUBCOMMITTEE

**Date Submitted:** April 26, 2002

**Individual or group requesting advice:**
J. Boutillier, C. Hand – Stock Assessment Division

**Proposed PSARC Presentation Date:**
December, 2002

**Subject of Paper (title if developed):** Geoduck Stock Assessment Framework

**Stock Assessment Lead Author:**
Claudia Hand, Shellfish Stock Assessment Division

**Fisheries Management Author/Reviewer:**
Rick Harbo, Steve Heizer, Juanita Rogers

**Rationale for request:**
The calculation of geoduck quotas has become increasingly complex as we move towards bed-by-bed assessment and management, and because of the large amount of survey, observer and fisheries data available. This framework will evaluate the current geoduck assessment program and identify and prioritize future research, and will allow for a systematic approach that insures that uncertainties are well understood so that the precautionary approach can be implemented in a meaningful way.

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

- What modifications and/or changes have occurred in the estimation of population parameters (eg. survey protocols, substrate mapping, on-grounds observer information) ?
- What new data (new or modified bed areas from logbooks, observer fisheries and substrate mapping, survey density data, biological sample data, market sample data) are available for calculating quotas ?
- How are parameter estimates extrapolated to beds where no data are available ?
- What are the future directions for the quota calculation process ?

**Objective of Working Paper:**
To clarify how density survey data, commercial piece count data, and estimates of bed area from logbook reports, from observer fisheries and from substrate mapping are used to calculate virgin biomass for individual geoduck beds. To describe the methods used to extrapolate data to beds where data aren't available. To outline the future directions of these approaches and how to get there.

**Stakeholders Affected:**
"G" Licence holders, aboriginal groups, other potential harvesters

**How Advice May Impact the Development of a Fishing Plan:**
Essential to understanding how quotas are calculated.