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Update to Estimation Methods for Geoduck (*Panopea generosa*) Stock Index

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

The stock index in the British Columbia (BC) Geoduck fishery is estimated on a by-Geoduck-bed basis and is defined as the ratio of current biomass (B_c) to unfished exploitable biomass (*B*'). The limit reference point (LRP) for the BC Geoduck fishery was defined as current biomass being equal to 40% of *B*'. When biomass is estimated for a bed, the stock index is also estimated and beds for which the stock index is below 0.4 are closed to fishing. To date, *B*' has been back-calculated as the sum of current biomass and fishery landings on the bed. This method assumes no surplus production on a bed after fishing begins.

The methods currently used to estimate *B*' on surveyed and un-surveyed beds were reviewed. Simulations were performed to illustrate how surplus production affects estimates of *B*' and stock index over time using the current method. If surplus production occurs, the method currently used to estimate *B*' produces biased estimates of *B*' and stock index. Density dive survey data, for beds surveyed more than once, showed that surplus production may be taking place on harvested Geoduck beds in BC and that therefore the assumption of no surplus production is likely not met.

Alternative options of estimating *B*' on surveyed and un-surveyed Geoduck beds were proposed and evaluated. Data requirements, assumptions, applicability, advantages and disadvantages of each proposed option were reviewed. The performance of each option for surveyed beds was evaluated for beds where early estimates of *B*' were available. Estimating *B*' as biomass from the first survey plus the landings before 1989 was recommended because it has few assumptions, the assumptions are believed to be reasonable, it is applicable to all surveyed beds and is simple to implement.

Few alternative *B*' estimation options were available for un-surveyed beds because less data is available for those beds. For un-surveyed beds, the recommendation was to use estimates of unfished exploitable density from surveyed beds to extrapolate unfished exploitable biomass on un-surveyed beds.

Methods for estimating the stock index at the by-sub-bed spatial scale were presented along with advantages and disadvantages of this approach. An evaluation of the possible impact of changing the spatial scale at which the stock index is calculated was presented. A recommendation was made to implement calculation of stock index at the by-sub-bed spatial scale.

Mise à jour des methods d’estimation de l’indice de la taille du stock de panope (*Panopea generosa*)

RÉSUMÉ

L'indice du stock dans la pêche à la panope en Colombie-Britannique (C.-B.) est estimé par gisement de panope et est défini comme le rapport entre la biomasse actuelle (B_c) et la biomasse exploitable avant le début de la pêche (*B*’). Le point de référence limite (PRL) de la pêche à la panope en C.-B. est défini comme la biomasse actuelle correspondant à 40 % de *B*’. Lorsque la biomasse est estimée pour un gisement, l'indice du stock est également estimé, et les gisements pour lesquels l'indice du stock est inférieur à 0,4 sont fermés à la pêche. À ce jour, *B*’ a été rétrocalculé comme étant la somme de la biomasse actuelle et des débarquements de pêche sur le gisement. Cette méthode ne suppose aucune production excédentaire sur un gisement après le début de la pêche.

On a examiné les méthodes actuelles d'estimation de *B*’ des gisements qui ont fait ou non l'objet d'un relevé. Des simulations ont été effectuées pour illustrer la façon dont la production excédentaire a une incidence sur les estimations de *B*’ et l'indice du stock au fil du temps, à l'aide de la méthode actuellement utilisée. S'il y a production excédentaire, la méthode actuellement utilisée pour estimer *B*’ donne des estimations biaisées de *B*’ et de l'indice du stock. Les données de densité des relevés par plongée, pour les gisements qui ont fait l'objet de relevés plus d'une fois, ont démontré que la production excédentaire peut avoir lieu sur des gisements de panopes exploités en Colombie-Britannique et que, par conséquent, l'hypothèse de l'absence de production excédentaire n'est probablement pas satisfaite.

D'autres options d'estimation de *B*’ sur les gisements de panope qui ont fait ou non l'objet d'un relevé ont été proposées et évaluées. Les exigences en matière de données, les hypothèses, l'applicabilité, les avantages et les inconvénients de chaque option proposée ont été examinés. Le rendement de chaque option sur des gisements qui ont fait l'objet d'un relevé a été évalué dans le cas des gisements pour lesquels de premières estimations de *B*’ étaient disponibles. L'estimation de *B*’ comme la biomasse d'après le premier relevé, plus les débarquements d'avant 1989, est recommandée, car elle a peu d'hypothèses, ces hypothèses sont jugées raisonnables, elle est applicable à tous les gisements qui ont fait l'objet d'un relevé et est simple à mettre en œuvre.

Peu d’options pour estimer *B*’ étaient disponibles pour les gisements qui n'ont pas fait l'objet d'un relevé étant donné que moins de données sont disponibles pour ces gisements. Pour les gisements qui n'ont pas fait l'objet d'un relevé, la recommandation visait à utiliser les estimations de densité exploitable avant le début de la pêche des gisements qui ont fait l'objet d'un relevé pour extrapoler la biomasse exploitable sur les gisements qui n'ont pas fait l'objet d'un relevé.

Les méthodes d'estimation de l'indice du stock par sous-gisement ont été présentées, de même que les avantages et les inconvénients de cette approche. On a présenté une évaluation de l'incidence possible du changement de l'échelle spatiale à laquelle l'indice du stock est calculé. On a recommandé de mettre en œuvre le calcul de l'indice de biomasse du stock par sous-gisement.

1 INTRODUCTION

The Pacific Geoduck (*Panopea generosa*) is an infaunal bivalve found in soft substrates from Alaska to Baja California, in depths ranging from 0 to 100m (Jamison et al. 1984). A dive fishery for Geoducks started in British Columbia (BC) in 1976 and has been one of the highest valued fisheries in the province for several years (CAD $44.7 million for 2016-17 fishing season, J. Austin, pers. comm). History of the fishery was reviewed in the 2011 stock status update (DFO 2012). Geoducks are hand-picked by divers who release Geoducks from the substrate using a water jet. The fishery is limited entry and managed with a total allowable catch, area quotas, vessel quotas and scheduled openings. The fishery operates on a three year rotation in the North Coast and Inside Waters, mostly for logistical reasons (e.g., paralytic shellfish poisoning sampling and monitoring, number of landing ports and packing). The fishery operates annually on the West Coast of Vancouver Island (WCVI) (Figure 1).

History of stock assessment was presented in the 2008 stock assessment framework (Bureau et al. 2012). The fishery is currently assessed at a by-Geoduck-bed spatial scale. There are currently 2,852 Geoduck beds (made up of 5,214 sub-beds) identified on the BC coast ranging in size from 0.03 Ha to 573.3 Ha (average 7.8 ± 0.5 Ha). Current biomass for each Geoduck bed is estimated as the product of bed area, Geoduck current density and Geoduck mean weight (Bureau et al. 2012). Precautionary regional annual exploitation rates of 1.2 to 1.8% (Zhang and Hand 2006, 2007) are applied to current biomass estimates to yield harvest options.

The Limit Reference Point (LRP) for the Geoduck fishery is defined as current biomass being equal to 40% of estimated virgin biomass (Zhang and Hand 2007) and has been applied on a by-bed basis. Virgin biomass (B_0) is generally defined as a theoretical equilibrium biomass in the absence of fishing and is not a measured value, but typically inferred from models (NOAA Fisheries Glossary). To date, in the BC Geoduck assessments frameworks (Hand and Bureau 2012, Bureau et al. 2012), estimated unfished exploitable biomass was referred to as virgin biomass (B_0). To avoid confusion between different definitions of virgin biomass, B_0 will now be used to refer to the theoretical B_0 and the term B' is introduced to refer to estimated unfished exploitable biomass. In the definition of B', “unfished” means before commercial harvest began, while “exploitable” refers to the fact that Geoduck biomass is only estimated for the exploitable portion of the population. Geoducks that are too small for survey divers to see and count are not included in biomass estimates and neither are geoducks found in harvest refugia, i.e., too shallow or too deep to harvest, in substrate where harvest is not possible, etc. Geoduck harvesting and density dive surveys typically occur between 3 m and 18 m depth.

From here on, B' will be used to refer to estimated unfished exploitable Geoduck biomass. When Geoduck biomass is estimated for a bed, the stock index, defined as the ratio of current biomass (B_c, mean estimate) to unfished exploitable biomass (B') is also calculated (Bureau et al. 2012).

$$Stock\ Index = \frac{B_c}{B'} \qquad \text{Equation 1}$$

If the stock index for a bed is less than 0.4, the bed is closed to harvest. Few Geoduck beds have been surveyed before they were first harvested, therefore, surveyed estimates of unfished exploitable biomass are available for few beds. For most surveyed beds, the first survey occurred after the start of harvest and unfished exploitable biomass has been back-calculated as the sum of survey biomass and landings before the survey, with the assumption that recruitment and natural mortality are in balance (Bureau et al. 2012). In other words, it is assumed that there is no surplus production on harvested beds after they are first fished.

The current method of estimating unfished exploitable biomass in the Geoduck stock assessment framework (Bureau et al. 2012) results in an increase in estimated unfished exploitable biomass if surplus production occurs between surveys, which could eventually lead to all harvested Geoduck beds reaching the LRP, irrespective of the actual stock status. There is concern that the increase in the estimate of unfished exploitable biomass is an artefact of the current methodology used for estimating unfished exploitable biomass and may not be reflective of the stock. This could lead to premature closure of some Geoduck beds and translate to loss of fishing opportunity for the industry. Un-surveyed beds will reach the LRP once 60% of estimated unfished exploitable biomass on that bed has been harvested, regardless of the actual dynamics of the stock on the bed, again with the potential of prematurely closing beds to harvest.

The Geoduck stock index has historically been calculated at the finest spatial scale possible based on available data, i.e., at the by-bed spatial scale. Since 2006, the Geoduck fishery has been managed at the by-sub-bed spatial scale thereby increasing the spatial accuracy of landings data. The increased spatial accuracy of landings data may allow for improvements to the current biomass estimation methods thereby also providing improvements to stock index estimates.

Fisheries and Oceans Canada (DFO) Fisheries and Aquaculture Management Branch therefore requested advice on the following four topics from DFO Science Branch:

- A review of the methods currently used to estimate Geoduck unfished exploitable biomass, for surveyed and un-surveyed Geoduck beds.
- Alternative methods for estimating Geoduck unfished exploitable biomass, for both surveyed and un-surveyed Geoduck beds, including evaluation of the relative advantages and disadvantages of each method.
- Provide methods for estimating Geoduck stock index on a by-Geoduck-sub-bed basis. Describe the advantages and disadvantages associated with this approach.
- Identify and discuss uncertainties and knowledge gaps in the available data and proposed estimation methods.

This paper is intended to provide advice on alternative Geoduck unfished exploitable biomass and stock index estimation methods only and is not intended to be a review of the LRP currently in place for the Geoduck fishery. Furthermore, this paper is not intended to be a new Geoduck fishery assessment framework, rather, the purpose is to update Geoduck unfished exploitable biomass and stock index estimation methods within the existing Geoduck fishery stock assessment framework (Bureau et al. 2012).

2 REVIEW OF CURRENT METHODS TO ESTIMATE UNFISHED EXPLOITABLE BIOMASS

In this document, the term “surveyed” refers to Geoduck beds on which a fishery-independent density dive survey took place to estimate Geoduck density. The survey protocol was developed by DFO in the 1990’s (Campbell et al. 1998). Density survey analysis methods were detailed in Bureau et al. (2012). The term “landings” will refer to commercial Geoduck fishery landings as recorded on harvesters log books. Averages will be presented ± one standard error. Definitions of variables used in the equations and their units are provided in Appendix 1.

2.1 CURRENT METHODS TO ESTIMATE *B'* ON SURVEYED BEDS

For surveyed Geoduck beds, unfished exploitable biomass (B') has been estimated as the sum of estimated current biomass (B_c) and total historical landings (L_t) (Bureau et al. 2012):

$$B' = B_c + L_t \qquad \text{Equation 2}$$

Where current biomass (B_c) is estimated as mean survey biomass (B_s) minus the landings post-survey (L_{ps}). Survey biomass (B_s) is estimated as the mean survey density for the bed (D_s) multiplied by the bed area (A) and mean Geoduck weight for the bed (W). Mean survey density (D_s) is estimated from the latest survey of a bed. Thus:

$$B_c = B_s - L_{ps} = D_s AW - L_{ps} \qquad \text{Equation 3}$$

Total landings (L_t) are the sum of landings post-survey (L_{ps}) and landings before-survey (L_{bs}).

$$L_t = L_{ps} + L_{bs} \qquad \text{Equation 4}$$

Therefore,

$$B' = D_s AW - L_{ps} + L_{ps} + L_{bs} \qquad \text{Equation 5}$$

or:

$$B' = D_s AW + L_{bs} = B_s + L_{bs} \qquad \text{Equation 6}$$

The impact of survey density estimates on unfished exploitable biomass estimates can best be explored if Geoduck bed area (A) and mean weight (W) are assumed to stay constant over time. Unfished exploitable biomass (B') estimates are then dependent on values of survey density (D_s) and landings before the survey (L_{bs}). Dividing Equation 6 by Geoduck bed area and mean weight yields:

$$\frac{B'}{AW} = \frac{D_s AW}{AW} + \frac{L_{bs}}{AW} \qquad \text{Equation 7}$$

Or:

$$D' = D_s + D_r \qquad \text{Equation 8}$$

Where D' is unfished exploitable density and D_r corresponds to the density removed by harvest before the survey.

The current method of estimating unfished exploitable biomass assumes that recruitment and natural mortality on Geoduck beds are equal, in other words, that there is no surplus production. Since Geoduck biomass is estimated for the exploitable portion of the population only, the term “recruitment” will refer to recruitment to the fishery, as opposed to larval settlement. Geoducks start recruiting to the fishery at age 4 and can be assumed to be fully recruited by age 8-10 years (Orensanz et al. 2004). Simulations can be performed to illustrate how survey density estimates (D_s) and various surplus production scenarios affect estimated unfished exploitable density compared to true unfished exploitable density over time. Simulations are presented in Section 3 to illustrate the issue with the currently-used unfished exploitable biomass estimation method.

2.2 CURRENT METHODS TO ESTIMATE *B'* ON UN-SURVEYED BEDS

For un-surveyed beds, the current method of estimating *B*' has been to sum estimated current biomass (B_c) and historical landings on the bed (Equation 2). However, the estimation of B_c for un-surveyed beds differs from surveyed beds due to the lack of survey data. Estimation of B_c on un-surveyed beds relies on extrapolation methods where current density estimates from nearby surveyed beds are used to estimate a range of current biomass estimates for each un-surveyed bed (Bureau et al. 2012). *B*' for an un-surveyed bed is then estimated by adding total landings on the bed to the mean estimate of extrapolated current biomass (B_c).

Using the current method, un-surveyed beds will reach the LRP once 60% of estimated unfished exploitable biomass on the bed has been harvested. Dividing Equation 2 by *B*' yields:

$$1 = \frac{B_c}{B'} + \frac{L_t}{B'} \qquad \text{Equation 9}$$

Which can be re-arranged as:

$$Stock\ Index = \frac{B_c}{B'} = 1 - \frac{L_t}{B'} \qquad \text{Equation 10}$$

Although the number of un-surveyed beds is relatively large (1,520 of 2,852 beds), only 11.0 to 11.9% of Geoduck landings in the three full rotation cycles, between 2006 and 2014, have come from un-surveyed beds. Furthermore, dive surveys have covered the majority (73.5%) of the bed area open to harvest (excluding areas occupied by Sea Otters (*Enhydra lutris*), i.e., Pacific Fishery Management Areas (PFMAs) 25 to 27 on the WCVI and PFMAs 7 (except 7-31) and 8 on the Central Coast). The impact of the uncertainties associated with un-surveyed beds on the fishery may therefore not be major. Prioritizing un-surveyed beds to be surveyed in the future would help minimize the uncertainties around biomass estimates on un-surveyed beds.

3 SIMULATIONS OF ESTIMATED UNFISHED EXPLOITABLE DENSITY OVER TIME

Issues with the current method used to estimate *B*' (or *D*' when bed area and Geoduck mean weight are assumed constant) are most evident when looking at simulations of Geoduck beds surveyed more than once. For illustrative purposes in the simulations, relative true unfished exploitable density was set at 1.0. For the short term simulations, a yearly harvest rate of 2% of current density in the previous year was applied to estimate the landings in the current year. Current density for a given year was estimated as current density the previous year minus landings during the current year. For the long term simulations, a yearly harvest of 2% of previous survey density was applied between surveys. The simulations assume that true *B*' is known, that beds are re-surveyed every ten years and that survey density estimates are accurate. For the purpose of the simulations, survey densities are assumed to reflect density of exploitable Geoducks.

3.1 SIMULATION WITH NO SURPLUS PRODUCTION

The current Geoduck biomass estimation method uses only the most recent survey of a bed and assumes that recruitment and natural mortality are in balance on the bed. In other words, the method assumes that there is no surplus production. If this held true, survey densities would be expected to decrease by an amount equal to the density removed by harvest on the bed between surveys, so that density on a second survey (D_{s2}) would be equal to density on the first survey (D_{s1}) minus the density removed by harvest between the two surveys (D_{rb}).

$$D_{s2} = D_{s1} - D_{rb} \quad \text{Equation 11}$$

Where D_{rb} is estimated as:

$$D_{rb} = \frac{L_{rb}}{AW} \quad \text{Equation 12}$$

And L_{rb} are the landings removed between surveys.

The first simulation illustrates how estimated unfished exploitable density is affected by subsequent surveys when the assumption of no surplus production is met. Under the assumption of no surplus production, estimates of *D*' from survey to survey would remain constant (Table 1, Figure 2A) and estimates of stock index would therefore be accurate. Consequently, the method currently used is adequate as long as the assumption of no surplus production is met. Under the assumption of no surplus production, a Geoduck bed would reach the LRP once 60% of the estimated unfished exploitable biomass on the bed has been harvested which eventually would lead to the closure of all Geoduck beds.

However, the assumption of no surplus production may not be valid and may not be reflective of what is happening on Geoduck beds after they are harvested. The following section illustrates how surplus production would affect estimates of *D*' using the current estimation method.

3.2 SIMULATIONS WITH SURPLUS PRODUCTION

Several simulations were conducted to illustrate how surplus production on a Geoduck bed, as evidenced by survey density data, would affect the estimation of unfished exploitable density. If surplus production occurred on a bed between surveys, density on the second survey would be greater than density on the first survey (D_{s1}) minus the density removed by harvest between the two surveys (D_{rb}).

$$D_{s2} > D_{s1} - D_{rb} \;\; if\ surplus\ production\ occurred \quad \text{Equation 13}$$

This situation would result in a greater estimate of *B*' based on the last survey since surplus production between surveys would now be included in the estimate of *B*'. Two test cases where surplus production occurs between surveys were simulated. In the first case (Table 2, Figure 2B), survey densities were set to be greater than *D*' minus D_r but below *D*', in other words density decreased over time but not as much as under the assumption of no surplus production. In the second test case (Table 3, Figure 2C), survey densities were set to be constant over time and equal to *D*', in other words surplus production was set to be equal to fishery removals.

Simulation results show that when surplus production occurs, estimates of *D*' increase, i.e., become biased, after each survey since the surplus production (between surveys) is then included in the estimates of *D*'. The increases in *D*' estimates are thus an artefact of the estimation method due to the fact that surplus production is not accounted for in the current method. The increase in estimated *D*' from survey to survey results in biases in the calculation of the stock index causing the stock index to decrease faster than if the true *D*' was used (Table 2 and Table 3, Figure 2 B & C and Figure 3) and causing beds to approach the LRP faster and possibly close when closure may not be warranted.

Another artefact of the current method, when surplus production occurs between surveys, is that the density that has to be maintained on a bed for it to remain above the LRP increases over time. If bed area and Geoduck mean weight on a bed are assumed to be constant over time, biomass is proportional to density and the LRP can then be expressed in terms of density where the Limit Reference Density (LRD) equals 0.4 x *D*'. As estimated *D*' increases, so does the LRD.

If survey density was to remain constant on a bed where harvest is taking place, i.e., surplus production equal to fishery removals, there would be a point in time where the LRD would be equal to true *D*’ (Table 4, Figure 3A) resulting in a bed closure (stock index < 0.4) despite the fact that density has not changed over time. If survey densities go down over time, with surplus production taking place at a lower level, the LRP is reached sooner, but the rate of increase in LRD slows over time (Table 5, Figure 3B).

3.3 SIMULATION WITH NET MORTALITY

Conversely, issues also occur if the second survey density (D_{s2}) on a bed is lower than the first survey density (D_{s1}) minus density removed between surveys (D_{rb}), i.e., if net mortality has occurred on a bed between surveys.

$$D_{s2} < D_{s1} - D_{rb} \;\; if\ net\ mortality\ occurred \qquad \text{Equation 14}$$

Simulations show that in this case, the estimated *D*’ would decrease after the second survey and would lead to a greater stock index than that based on the true *D*’, potentially keeping a bed above the LRP when it should not (Table 6, Figure 2D).

4 IS THE ASSUMPTION OF NO SURPLUS PRODUCTION VALID?

Simulations presented in the previous section indicated that the current method for estimating Geoduck unfished exploitable biomass was appropriate when the assumption of no surplus production was met but that the current method produced biased estimates of *B*’ and stock index when surplus production (or net mortality) occurs. Whether the current Geoduck unfished exploitable biomass estimation method is adequate then depends on whether or not the assumption of no surplus production is valid.

The current Geoduck assessment framework assumes that populations were in equilibrium at the start of the fishery and that *B*’ on a bed is the exploitable carrying capacity on that bed. The assumption that “recruitment and natural mortality are in balance”, after harvest first occurred on a bed, assumes no surplus production after the stock abundance decreases below the carrying capacity because of harvest; contrary to many population growth (e.g. logistic or Schafer models) and fishery stock assessment models (e.g. Ricker or Beverton-Holt models). The assumption that no surplus production occurs as the stock is fished down essentially assumes that no recovery from fishing is expected. Including some estimate of surplus production into the estimation of Geoduck *B*’ may bring the model more in line with traditional population growth and fishery stock assessment models.

When the Geoduck stock assessment framework was developed, few beds had been surveyed more than once and the issues described above were not detected. Furthermore, little data was available to estimate surplus production on harvested Geoduck beds at the time. The current method allowed the fishery to proceed in a precautionary manner with limited knowledge of Geoduck productivity.

In the early years of the Geoduck survey program, the focus was on estimating density from as many beds as possible throughout the BC coast. As survey coverage of Geoduck beds increased over the years, survey focus changed from targeting un-surveyed beds to re-surveying beds that have not been surveyed for 10 years or more. A total of 1,317 Geoduck beds have been surveyed at least once since 1992, of those, 298 (22.6% of surveyed beds) have now been surveyed more than once. As more Geoduck beds get re-surveyed, the impacts of the artefacts described in Section 3 increase, if surplus production is occurring. Since beds selected for re-survey are often considered to be productive and important beds for the fishery, the estimation artefacts may disproportionately impact "important" beds. A new way to estimate *B*' free of the artefacts and bias described above is therefore desired if surplus production is occurring.

Survey density and landings data for beds that have been surveyed more than once was reviewed to determine if there is evidence for surplus production on commercially harvested Geoduck beds in BC. In other words, is the assumption of no surplus production on Geoduck beds after the start of harvest valid?

4.1 COMPARISON OF FIRST AND LAST DENSITY ESTIMATES FOR RE-SURVEYED BEDS

To date, 228 Geoduck beds on the BC coast have been surveyed more than once, excluding beds in Sea Otter occupied areas. A further seven beds were excluded because the first and last surveys did not cover the same portions of the bed. A total of 221 beds were therefore used in this analysis.

The average time between surveys, in portions of the coast where the fishery operates on a three year rotation (Inside Waters and North Coast), was 12 years (Table 7A). Beds in these regions may therefore have been open to harvest, on average, up to four times between surveys. On the WCVI, the fishery was rotational between 1989 and 2001 and returned to an annual fishery in 2002, the average time between surveys was 10 years. The number of times a bed on WCVI may have been harvested between surveys will vary depending on the timing of surveys.

Density results from first and last survey on a bed were compared. Densities were estimated using only transects that fall on beds for the comparisons (See Run 4 in Bureau et al. 2012). Since the number of years between first and last surveys varies from bed to bed, trends in density are discussed in terms of change per year so that results are comparable between beds with different survey intervals.

Overall, average survey density was greater for the second survey (paired t-test, df = 220, t = -3.262, p = 0.001) (Table 7 A). Data from beds that have been re-surveyed show an average rate of increase in survey density of 0.023 ± 0.000 Geoducks/m^2/year between surveys (one sample t-test, df = 220, t = 4.028, p < 0.001, Table 7 A), while an average 0.017 ± 0.002 Geoducks/m^2/year were removed by harvest between surveys (Table 7 A), suggesting that surplus production is indeed occurring.

By region, the rate of density change (between surveys) ranged from -0.038 ± 0.010 Geoducks/m^2/year in the Central Coast to 0.050 ± 0.012 Geoducks/m^2/year in the Prince Rupert region (Table 7 A). The Central Coast showed a negative trend in density between surveys (one sample t-test, df = 27, t = -3.876, p = 0.001), even when Geoduck beds in areas occupied by Sea Otters were excluded. The rate of density change between surveys was positive and significantly different than zero for the Prince Rupert (one sample t-test, df = 76, t = 4.270, p < 0.001) and WCVI (one sample t-test, df = 30, t = 2.200, p = 0.036) regions; but not significantly different than zero for Inside Waters (one sample t-test, df = 31, t = 1.876, p = 0.070) and Haida Gwaii (one sample t-test, df = 52, t = 1.669, p = 0.101) regions. By region, yearly density removed by harvest between surveys (Table 7 B) ranged between 0.004 ± 0.001 Geoducks/m^2/year in the Inside Waters to 0.027 ± 0.006 Geoducks/m^2/year in Haida Gwaii. Yearly density removed between surveys in the Central Coast was 0.021 ± 0.004 Geoducks/m^2/year, less than the decrease observed in survey densities, suggesting that additional mortality due to factors other than harvest may have taken place in the Central Coast.

4.2 COMPARISON OF FIRST AND LAST *B'* AND STOCK INDEX ESTIMATES FOR RE-SURVEYED BEDS

For the 221 beds surveyed more than once (outside Sea Otter occupied areas), unfished exploitable biomass (*B*') was estimated based on the first and last surveys and those estimates were compared. Mean survey biomass for each bed was estimated as the product of mean survey density, bed area and Geoduck mean weight. The sum of historical landings, for each bed, before each survey, was calculated from the Geoduck logbook database. Unfished exploitable biomass for each bed, based on the first and last survey, was then estimated using Equation 6. The ratio of *B*' from last survey over *B*' from first survey was then calculated for each bed.

The average ratio of *B*' from last survey to *B*' from first survey was 1.256 ± 0.036 and was significantly different from 1.0 (one sample t-test, df = 220, t = 7.222, p <0.001) with an average of 11.9 ± 0.3 years between surveys (Table 7 A & B). By region, the ratio of *B*' from last survey to *B*' from first survey ranged from 0.942 ± 0.062 in the Central Coast to 1.347 ± 0.063 in Prince Rupert region and was above and significantly different than 1.0 for all regions (one sample t-tests: Haida Gwaii, df = 52, t = 3.673, p = 0.001; Prince Rupert, df = 75, t = 5.509, p < 0.001; Inside Waters, df = 31, t = 2.452, p = 0.020; WCVI, df = 30, t = 3.728, p = 0.001) except the Central Coast (one sample t-test, df = 27, t = -0.944, p = 0.353). Since density between surveys increased on average, coupled with harvest taking place between surveys, estimates of B' from the second surveys were expected to, on average, be greater than B' estimated from the first surveys. Again these results suggest that surplus production may be occurring on harvested Geoduck beds. If no surplus production was taking place, the expected *B*' ratio would be 1.0.

Stock indices for each re-surveyed bed were calculated in two ways, i.e., using the *B*' estimated from first and last surveys, with both calculations using the latest survey biomass as the estimate of current biomass (B_c). The average stock indices were 0.934 ± 0.038 and 0.718 ± 0.013 when *B*' was estimated from first and last survey, respectively and were significantly different from each other (paired t-test, df = 220, t = 6.989, p < 0.001). This result was expected because the estimates of *B*' from the last survey were on average greater than those estimated from the first survey (Table 7 B) which translates into lower stock index values. The regional average of stock index based on the last survey was lower and significantly different than that based on the first survey for all regions (paired t-tests: Haida Gwaii, df = 52, t = 3.310, p = 0.002; Prince Rupert, df = 76, t = 5.654, p < 0.001; Inside Waters, df = 31, t = 2.235, p = 0.033; WCVI, df = 30, t = 3.116, p = 0.004) except the Central Coast, where there was no difference (paired t-test, df = 27, t = -0.700, p = 0.490).

4.3 ESTIMATES OF SURPLUS PRODUCTION RATES FOR RE-SURVEYED BEDS

4.3.1 Surplus Production Rates Between First and Last Surveys

The yearly surplus production rate (kg/year) for each bed, between the first and last surveys, was estimated for the 221 Geoduck beds that were surveyed more than once (excluding beds in areas occupied by Sea Otters) using Equation 18. The surplus production rate was then converted to yearly surplus production density (Geoducks/m^2/year) by dividing the yearly surplus production rate by the bed area and mean Geoduck weight for each bed. The average yearly surplus production density was 0.039 ± 0.006 Geoducks/m^2/year (Table 7 B) and was significantly different from zero (one sample t-test, df = 220, t = 6.712, p < 0.001). The positive overall yearly surplus production density again supports that surplus production likely has been taking place on harvested Geoduck beds, for most regions, in BC.

By region, average yearly surplus production density ranged from -0.017 ± 0.011 Geoducks/m^2/year in the Central Coast to 0.067 ± 0.012 Geoducks/m^2/year in Prince Rupert region (Table 7 B). The average yearly surplus production density for the Central Coast was negative but not significantly different than zero (one sample t-test, df = 27, t = -1.538, p = 0.136). Regional average surplus production densities were significantly different from zero for all other regions of the BC coast (one sample t-test results: Haida Gwaii, df = 52, t = 3.790, p < 0.001; Prince Rupert, df = 76, t = 5.675, p < 0.001; Inside Waters, df = 31, t = 2.238, p = 0.033; WCVI, df = 30, t = 2.732, p = 0.01). Excluding the Central Coast, surplus production densities were lower in southern BC (Inside Waters and WCVI) than in northern BC (Haida Gwaii and Prince Rupert regions).

Zhang and Hand (2006) showed that the highest average recruitment rates were in the Prince Rupert and Central Coast regions while recruitment rates were intermediate in Haida Gwaii and the WCVI and lowest for the Inside Waters. Surplus production rates estimated here followed a similar pattern (Table 7 B), except for the Central Coast.

4.3.2 Do Surplus Production Rates Change Over Time?

Some population growth and fishery models predict that, as a population is fished down from equilibrium levels, surplus production rates will increase up to a maximum surplus production, generally referred to as Maximum Sustainable Yield (MSY). Different models predict different shapes for the surplus production curve. Geoduck populations were assumed to be at equilibrium levels (carrying capacity) when the fishery began. Whether surplus production rates vary as a Geoduck stock is fished down can be investigated with beds that were surveyed three times, providing two between-survey intervals for which surplus production rates can be estimated.

Thirty-eight Geoduck beds were surveyed three times, 17 of which were located outside areas occupied by Sea Otters. For these 17 beds, the surplus production rates for each of the two between-survey intervals were estimated as described above. The average surplus production rates for survey interval 1 (between first and second survey) and survey interval 2 (between second and third survey) where then estimated.

For the 17 beds outside Sea Otter occupied areas, the average yearly surplus production densities were 0.072 ± 0.039 and 0.042 ± 0.021 Geoducks/m^2/year for the first and second survey intervals respectively but were not significantly different (paired t-test, df = 16, t = 0.631, p = 0.537). Average survey intervals were 9.9 and 8.1 years for the first and second intervals respectively (Table 8). Population growth models would have predicted a higher yearly surplus production density for the second survey interval than the first, if densities had gone down over time. However, average densities increased over time. The lack of significant difference may be due to the low sample size, or environmental factors may have affected Geoduck productivity. Zhang and Hand (2006, 2007) showed long-term variability in Geoduck recruitment rates in BC, with increasing recruitment between 1930 and 1950 followed by a period of generally decreasing recruitment between 1950 and the mid 1980’s and increased recruitment rates since the mid 1980’s. Valero et al. (2004) showed that long-term trends in Geoduck recruitment were consistent with long-term trends in sea surface temperatures. Factors other than stock size may thus be affecting Geoduck recruitment.

4.4 EVIDENCE FOR GEODUCK SURPLUS PRODUCTION IN OTHER REGIONS

In Washington State, Geoducks are harvested on “tracts” that are harvested at a higher rate than in the BC Geoduck fishery (Orensanz et al. 2004). Once fished, a tract is not fished again until survey data shows that densities have recovered (Goodwin and Bradbury 2000).

Recruitment rates on harvested tracts were calculated, from tracts where two post-fishing surveys were available, and averaged 0.054 Geoducks/m^2/year, confirming that post-fishing recruitment occurs (Goodwin and Bradbury 2000). Orensanz et al. (2004) identified two tract recovery trajectories; on fast-recovery tracts, the average annual recovery rates ranged from 0.061 to 0.134 Geoducks/m^2/year while on slow-recovery tracts, the average annual recovery rates ranged from 0.012 to 0.031 Geoducks/m^2/year. These results suggest that recovery rates (or surplus production) can be variable between tracts. The average annual recovery rate on fast-recovery tracts was 0.099 Geoducks/m^2/year while on slow-recovery tracts, the average annual recovery rate was 0.022 Geoducks/m^2/year (calculated from data in Table 9 in Orensanz et al. 2000).

5 OPTIONS FOR IMPROVEMENT FOR SURVEYED BEDS

Analysis of data from re-surveyed Geoduck beds presented in Section 4 indicated that the assumption of no surplus production after the start of harvest is likely not valid. Therefore, unfished exploitable biomass estimates may be susceptible to the biases described in the simulations presented in Section 3. An alternative unfished exploitable biomass estimation method is therefore desirable. Possible options are described in the next sections and outlined in the table below.

Option	Unfished exploitable biomass (*B*') =
1	1^{st} survey + prior landings
2A	1^{st} survey + prior landings - fixed surplus production from literature
2B	1^{st} survey + prior landings - surplus production from surveys
2C	1^{st} survey + prior landings - fixed regional surplus production
3A	1^{st} survey
3B	1^{st} survey + pre-1989 landings
4A	Hybrid with fixed surplus production from literature
4C	Hybrid with fixed regional surplus production

All options that include estimates of historical landings rely on the assumption that landings history is complete and accurate. Because of issues with under-reporting of landings in the early years of the fishery and poor geo-referencing of harvest events before 2000, landings history is not likely complete and accurate for at least some Geoduck beds (see Uncertainties section for details).

5.1 OPTION 1 – UNFISHED EXPLOITABLE BIOMASS = BIOMASS FROM FIRST SURVEY + LANDINGS BEFORE FIRST SURVEY

One option to minimize the bias described for re-surveyed beds would be to estimate *B*’ from the first survey of each bed, instead of from the latest survey. This method would eliminate surplus production after the first survey from the *B*’ estimations, possibly resulting in a more accurate estimate of *B*’ and could be a better long term approach. This would be the same approach (to estimate *B*’) used for beds surveyed only once and would therefore be an improvement only for beds surveyed more than once. In this case *B*’ would be calculated as:

$$B' = B_{s1} + L_{bs1} \quad \text{Equation 15}$$

Where B_{s1} is biomass based on first survey and L_{bs1} are the landings before the first survey. This option assumes no surplus production between the first harvest of a bed and the first survey. However, if surplus production did occur between the first year of harvest and the first survey, it would be included in the estimate of *B*’. While this may not have a large impact on *B*’ for beds that were surveyed soon (a few years) after harvest began, the impact may be greater for beds that were harvested for many years before being first surveyed. Surplus production, between start of harvest and the first survey, would be included in *B*’ estimates resulting in an increased (biased) *B*’ which in turn would translate into lower biased stock index values.

The Geoduck density dive survey program started in 1992 while the fishery started in 1976. The overall average difference between the year first surveyed and year first harvested for Geoduck beds on the BC coast is 12.1 ± 0.2 years (n = 1,277). By region, the average difference between the year first surveyed and year first harvested was 19.9 ± 0.9 years for the Inside Waters (n = 114), 18.3 ± 0.7 years for the WCVI (n = 112), 10.8 ± 0.3 years for the Central Coast (n = 443) and 10.4 ± 0.4 years for both Prince Rupert (n = 337) and Haida Gwaii (n = 271) regions. The lower differences observed in the North Coast were expected as the fishery first developed in the South Coast (Inside Waters and WCVI) in the late 1970’s and then expanded to the North Coast during the 1980’s.

Because of the high average number of years between first harvest and first survey, surplus production between first harvest and the first survey may not be negligible and thus, Option 1 may still lead to over-estimates of *B*’.

The biases in *B*’ estimates, associated with adding landings before the first survey to biomass estimated from the first survey, would be even greater for beds that have not yet been surveyed. On average, un-surveyed beds have been harvested on 3.3 ± 0.1 years since the start of the fishery while the average number of years since first harvest (i.e., 2017 – year of first harvest) is 18.9 ± 0.3 (n = 1,365). By region, the average number of years un-surveyed beds were harvested ranges from 2.5 ± 0.1 years in the Prince Rupert region (n = 219) to 4.1 ± 0.2 years on WCVI and Inside Waters (n = 285 and n = 236 respectively) (Table 9) while the average number of years since first harvest ranges from 13.9 ± 0.5 years in the Prince Rupert region (n = 219) to 27.0 ± 0.6 years in the Inside Waters (n = 236). Since many un-surveyed beds were first harvested many years ago, the first survey, when it takes place, may include a non-trivial amount of surplus production in the estimate of *B*’, if option 1 is used.

The average yearly density removed from all un-surveyed beds (divided by number of years since first fished) is 0.015 ± 0.001 Geoducks/m^2/year (n = 1,365). By region, the average yearly density removed from un-surveyed beds ranged from 0.006 ± 0.001 Geoducks/m^2/year in the Inside Waters (n = 236) to 0.020 ± 0.001 Geoducks/m^2/year in the Central Coast (n = 412) (Table 9). Overall average of density removed from un-surveyed beds (all years) was 0.261 ± 0.011 Geoducks/m^2 and by region, ranged from 0.159 ± 0.015 Geoducks/m^2 (n = 236) in the Inside Waters to 0.343 ± 0.029 Geoducks/m^2 (n =285) on the WCVI.

5.2 OPTION 2 – UNFISHED EXPLOITABLE BIOMASS = BIOMASS FROM FIRST SURVEY + LANDINGS BEFORE FIRST SURVEY – SURPLUS PRODUCTION BEFORE FIRST SURVEY

A possible improvement over option 1 would be to attempt to account for surplus production to a bed since it was first harvested. Four options to include surplus production in the estimation of *B*’ were evaluated. For beds surveyed only once, a fixed estimate of surplus production would be required. Fixed surplus production rates could be obtained from the literature or using data from beds surveyed more than once. For beds surveyed more than once, a fixed estimate could be used or surplus production could be estimated from survey and harvest data. Age frequency distributions could be used, for beds where biological samples were collected during surveys, to estimate recruitment since the beginning of fishing on a bed.

5.2.1 Option 2A – Using a Fixed Surplus Production Rate Estimate

A number of studies have estimated recruitment rates of Geoducks in BC (Campbell et al. 2004, Zhang and Campbell 2004, Zhang and Hand 2006, 2007) and Washington (Orensanz et al. 2000, 2004, Goodwin and Shaul 1984). The definition of recruitment varied between the studies. Zhang and Campbell (2004) found no long term negative impacts of Geoduck harvest on subsequent recruitment in experimental harvest plots and estimated mean yearly recruitment density (of 1 year-olds, over 10 years) at 0.22 Geoducks/m^2/year at a location on the WCVI and 0.016 Geoducks/m^2/year at a location in the Strait of Georgia. Zhang and Hand (2006, 2007) back-calculated Geoduck recruitment history from Geoduck age frequencies using a range of mortality rates. They found that Geoduck recruitment history was similar between regions, especially in Northern BC, but with variability within regions. Zhang and Hand (2006, 2007) showed relatively lower recruitment rates for the Strait of Georgia than for other regions of the BC coast. The lowest natural mortality rate used in their model (M = 0.016) yielded lower recruitment estimates which could be used as conservative estimates. Historical Geoduck recruitment rates were generally above 0.02 Geoducks/m^2/year for all regions except in the Strait of Georgia where recruitment rate was below 0.01 Geoducks/m^2/year until the 1990's. Maximum recruitment rate estimated was above 0.12 Geoducks/m^2/year in the Prince Rupert region around 1948.

Orensanz et al. (2004) reported Geoduck recruitment in harvested "tracts" in Washington State between 0.013 and 0.150 Geoducks/m^2/year. Goodwin and Shaul (1984) reported young-of-the-year densities ranging from 0.60 to 1.60/m^2 between 1977 and 1981 at an un-harvested location in Washington State. Density of 0-4 year old Geoducks in six harvested and six un-harvested sites in Washington State ranged from 0.00 to 1.30 Geoducks/m^2 and 0.18 to 2.50 Geoducks/m^2 respectively (Goodwin and Shaul 1984).

Results presented here for 221 re-surveyed beds in BC (Section 4.3) showed average estimates of yearly surplus production density of 0.039 ± 0.006 Geoducks/m^2/year between first and last surveys.

The *B*' estimation formula in option 1 could be modified to account for recruitment between first harvest and first survey on a bed as follows:

$$B' = B_{s1} + L_{bs1} - P_{h1-s1} \qquad \text{Equation 16}$$

Where B_{s1} is biomass based on first survey, L_{bs1} are the landings before the first survey and P_{h1-s1} is the estimated surplus production from year first harvested to year first surveyed (i.e., before first survey). Since Geoduck recruitment is variable in time and space, a conservative estimate of mean annual surplus production rate should be chosen. Based on published data and analyses presented here, a surplus production rate of 0.01 Geoducks/m^2/year appears to be conservative. This surplus production value is below that which would support the increases in density observed on re-surveyed beds. An option to account for surplus production between first harvest and first survey in the estimation of *B*' could thus be:

$$B' = B_{s1} + L_{bs1} - 0.01(Y_{s1} - Y_{h1})AW \qquad \text{Equation 17}$$

Where Y_{s1} is the year first surveyed, Y_{h1} is the year first harvested, *A* is the bed area and *W* is the mean weight estimate for that bed. Using equation 17, *B*' would be estimated in the same manner for all surveyed beds, irrespective of how many times they were surveyed.

Several authors have reported long term trends in Geoduck recruitment in BC and Washington State, including a decades-long decrease in Geoduck recruitment rates before the start of the fishery, with a low in the 1970's, followed by a rebound to pre-decline levels in the 1980's and

1990's (Bradbury and Taggart 2000, Orensanz et al. 2000, 2004, Valero et al. 2004, Zhang and Hand 2006, 2007).

Zhang and Hand (2006, 2007) showed an increasing trend in Geoduck recruitment in the 1990's, using data from Geoduck biological samples collected in BC between 1993 and 2003. Geoducks younger than 5 years are likely under-represented in biological samples (Bureau et al. 2002, 2003) and therefore, recruitment history since the late 1990's is unknown. Since 2005, advances in sample preparation and age determination techniques, i.e., cross-dating (Black et al. 2008, Lochead et al. 2012) have improved the accuracy of Geoduck age estimates. Lochead et al. (2012) compared recruitment estimates for two samples aged using both the old and new methods. They showed that recruitment strength can be greater when using cross-dating (new method), as uncertainty in ages estimated using the old method tended to "smudge" single-year recruitment events over more than a year resulting in lower, albeit wider, recruitment peaks. Analysis of biological samples collected since 2004 would improve our knowledge of Geoduck recruitment patterns between the late 1990's and the late 2000's.

5.2.2 Option 2B – Estimating Surplus Production from Survey Data

For beds surveyed more than once, it may be possible to estimate surplus production from survey data. This would assume that survey density estimates are accurate (see Uncertainties, Section 7). Analysis of yearly surplus production density between survey intervals (for beds surveyed three times, Section 4.3.2) showed no evidence of difference in yearly surplus production density between survey intervals. The surplus production rate between first and last surveys could be estimated as:

$$R_j = \frac{B_{sl} - B_{s1} + L_j}{T_j} \qquad \text{Equation 18}$$

Where:

R_j is the average yearly surplus production rate, i.e., weight/year, during time interval *j*.

B_{sl} is the biomass based on the last survey, while B_{s1} is the biomass based on the first survey.

L_j are the landings between first and last surveys, during time interval *j*.

T_j is the time, in years, between first and last surveys, during time interval *j*.

Unfished exploitable biomass could then be estimated as:

$$B' = B_{s1} + L_{bs1} - R_j(Y_{s1} - Y_{h1}) \qquad \text{Equation 19}$$

Estimating surplus production rates from survey data may initially appear preferable to using a blanket fixed value of surplus production as it makes the best use of available survey data and may reflect geographical differences. However, assumptions regarding survey density estimates need to be considered. Survey density estimates are assumed to be accurate under Option 2B. However, confidence bounds around Geoduck survey density estimates are generally wide, indicating low precision. Surplus production rates estimated using Equation 18 are therefore susceptible to the low precision of the density estimates and may not be truly reflective of actual surplus production. The assumption of accurate density estimates may not be met and therefore, applying surplus production rates estimated using Equation 18 to individual beds should be done with caution, if at all. This option also assumes that the average surplus production rate before the first survey was equal to the average surplus production rate between the first and last surveys. Considering the documented variability in Geoduck recruitment rates over time (Orensanz et al. 2000, 2004, Zhang and Hand, 2006, 2007), this last assumption may also not be valid.

Option 2B could only be applied to beds surveyed more than once. Another method would thus be required to estimate *B*' for beds surveyed only once.

5.2.3 Option 2C – Using Regional Surplus Production Rates Based on Survey Data

Another option, between options 2A and 2B, would be to estimate regional average surplus production rates using data from beds surveyed more than once. These regional surplus production rates could then be applied to all surveyed beds within each region. Unfished exploitable biomass could be estimated as:

$$B' = B_{s1} + L_{bs1} - \overline{D_{P_R}}(Y_{s1} - Y_{h1})AW \qquad \text{Equation 20}$$

where $\overline{D_{P_R}}$ is the average surplus production density, in Geoducks/m^2/year, estimated from beds surveyed more than once in region *R*.

This option may have the advantage of incorporating differences in surplus production rates between regions (as determined from re-surveyed beds). However, it is subject to the same caveats as option 2B regarding the accuracy of density estimates and the surplus production rates derived from them. Option 2C assumes that the average surplus production rate on a bed before the first survey was equal to the average regional surplus production rate between first and last surveys. Using this method, *B*' would be estimated in the same manner for all surveyed beds, irrespective of how many times they were surveyed.

5.2.4 Option 2D – Use of Survey and Age Frequency Distribution Data to Estimate Surplus Production

Hand and Dovey (1999) proposed a method to estimate *D*' for surveyed beds where biological samples of age frequency distributions are available. The method involved the use of age frequency data to determine the proportion of the population that has recruited to a bed after the beginning of the fishery on that bed. The density of Geoducks that have recruited since the start of the fishery was then estimated as the product of the proportion of recruits and survey density. *D*' was then estimated as survey density minus the density recruited since the start of the fishery plus density removed by harvest. Using a similar approach, *B*' could be estimated as:

$$B' = B_{s1} + L_{bs1} - p_r D_{s1} AW \qquad \text{Equation 21}$$

where p_r is the is the proportion of Geoducks recruited after the start of the fishery on a bed based on the age frequency distribution of the biological sample.

This method assumes that the age frequency distribution of the biological sample is representative of the exploitable population on the bed. The method further assumes that landings history is accurate and that Geoducks removed by harvest had recruited to the bed before the start of the fishery. This method could be an alternative to option 2B to include estimates of recruitment in the estimation of *B*'.

Between 1993 and 2016, 86 biological samples of Geoduck age frequency distributions have been collected throughout the BC coast (from 161 surveyed beds). The size of each of the 86 samples varied between 300 and 500 Geoducks. Some samples have shown recruitment to Geoduck beds after the start of the fishery (Bureau et al. 2002, 2003). However, age frequency distributions are available for only a small portion (12%) of surveyed beds. The Geoduck biological sampling program was scaled back after 2010 from three to five samples a year (1,500 to 2,500 Geoducks a year) to one or two samples a year (500 to 1,000 Geoducks a year) when the focus of the sampling program changed. Due to the low number of surveyed beds with age frequency distributions, this method may not be as representative of conditions throughout the coast compared to methods that do not rely on age frequency distributions (i.e. methods where more beds have the necessary data available). Because data required for Option 2D are available for few beds, this option was not considered further.

5.3 OPTION 3A – UNFISHED EXPLOITABLE BIOMASS = BIOMASS FROM FIRST SURVEY

Another option for the estimation of *B*' would be to simply use the density estimate from the first survey of a bed (D_{s1}) as the estimate of unfished exploitable density (*D*'). In this case, landings between the first harvest and first survey of a bed would not be added to the biomass estimated from the survey.

$$B' = B_{s1} = D_{s1}AW \qquad \text{Equation 22}$$

This method would assume that surplus production between the beginning of harvest on a bed and the first survey is equal to fishery removals and would result in a lower estimate of *B*' than the method presently used (where removals would be added to B_{s1}). Since, on average, data from re-surveyed beds showed an increase in density between first and last surveys, i.e., surplus production greater than fishery removals, then the assumption of surplus production equal to removals before the first survey may be reasonable.

Using option 3A, *B*' would be estimated in the same manner for all surveyed beds, irrespective of how many times they were surveyed. Option 3A does not rely on landings estimates and therefore does not rely on the assumption that landings history is accurate. Also, since surplus production is not included in option 3A, it does not rely on assumptions of constant surplus production across time and within a region.

Harvest on beds that remain un-surveyed to this day has, on average, started 18.9 years ago. Surplus production since the beginning of the fishery on the un-surveyed beds may therefore not be negligible and consequently adding removals to B_{s1} estimates may lead to inflated estimates of *B*' which may not be warranted. Since data from re-surveyed beds suggest that, overall, surplus production was greater than removals, using density from the first survey without adding removals may be more justifiable than the current method where removals are added. Estimating *B*' directly from the first survey density without incorporating surplus production and removals relies on fewer assumptions also and has the advantage of being simple to implement.

5.4 OPTION 3B – UNFISHED EXPLOITABLE BIOMASS = BIOMASS FROM FIRST SURVEY + LANDINGS BEFORE 1989

The main assumption under option 3A is that surplus production before the first survey is equal to commercial landings before the first survey. Whether this assumption is reasonable for the whole history of the fishery is therefore worth investigating. The BC Geoduck fishery developed rapidly starting in 1976, landings peaked in 1987 and then gradually decreased through management actions, landings since 1996 have been relatively stable (Figure 4). Under option 3A, the years with greater landings are assumed to have correspondingly high surplus production. The fishery first developed in Southern BC (Inside Waters and WCVI) and landings predominantly came from there until 1994. Since 1995, the majority of landings have come from the North Coast.

Harbo et al. (1992) reviewed the early management history of the fishery. In 1976 only the Strait of Georgia was open to harvest with expansion to the entire coast in 1977. There were no quotas before 1979. Area management started in 1979 with only two management areas (South Coast and North Coast). The number of management areas increased to 44 in 1988 (Harbo et al. 1992). During the 1989-1991 rotation, the first of the three year rotations, the BC coast was divided into 78 Geoduck Management Areas (GMAs) (Harbo et al. 1995). The number of GMAs increased over the years as some GMAs were split to distribute fishing effort. Beds preferred by harvesters, because of density, quality and/or ease of harvest, could therefore be harvested more intensely in the early years of the fishery than after bed-by-bed management was implemented. Bed-by-bed management was first informally implemented by fishery on-grounds monitors in the mid 1990's.

Zhang and Hand (2006, 2007) reported low Geoduck recruitment in BC between 1950 and the mid 1980's followed by increased recruitment after the mid 1980's. The combination of low recruitment and high harvest rate in the 1980's makes it less likely that surplus production was equal to landings during those years. In other words, the underlying assumption for option 3A is unlikely to be valid during the 1980's. Option 3A may then underestimate *B*' for beds that were heavily harvested in the early years of the fishery. Assuming that surplus production has been equal to fishery removals for only a more recent portion of the fishery history may therefore be a more reasonable assumption. A new option to address this issue could be to add a portion, but not all, of historical landings on a bed to the estimated biomass from the first survey. Considering that by 1989 recruitment was on the rise and harvest rates were on a downward trend, 1989 was chosen as the cut-off year. Unfished exploitable biomass (*B*') could then be estimated as the biomass from the first survey plus landings before 1989.

$$B' = B_{s1} + L_{b1989} \qquad \text{Equation 23}$$

Where L_{b1989} are landings before 1989. Option 3B is then an intermediate between option 1 and option 3A. Equation 23 relies on assumptions of both options 1 and 3A for different periods of the fishery. For the years before 1989, the assumption from option 1 applies, i.e., it is assumed that there is no surplus production. This may be a reasonable assumption for the period of the fishery when landings were high and recruitment low. For the period from 1989 onwards, the assumption from option 3A applies, i.e., surplus production is assumed to be equal to fishery landings for the years between 1989 and the first survey.

One drawback of using landings before 1989 is that geo-referencing of fishing events during that period was poor, leading to uncertainties in the landings for each bed (see Uncertainties section). However, only 25% (725 out of 2,852) of beds were harvested before 1989. Option 3B would therefore yield the same results as option 3A for 75% of the beds. The majority (434 beds or 60%) of beds harvested before 1989 are located in the South Coast (Inside Waters and WCVI regions).

The density of Geoducks removed by year, for each bed, was estimated from landings data (up to 2014), mean Geoduck weight estimates and bed area estimates. Outliers where density removed from a bed in a given year was greater than 2 Geoducks/m^2 were excluded (13 of 12,845 cases). The outliers occurred mostly on very small beds. The average yearly density removed was then estimated by region. The average yearly density removed for the Inside Waters region was 0.052 and 0.033 Geoducks/m^2/year for the periods before and after 1989 respectively. For the WCVI, the average of yearly density removed was 0.125 and 0.044 Geoducks/m^2/year for the periods before and after 1989 respectively. In the North Coast, the average of yearly density removed was 0.162 and 0.086 Geoducks/m^2/year for the periods before and after 1989 respectively.

5.5 OPTION 4 – HYBRID APPROACH BASED ON DATA AVAILABLE

Since the number of times a bed has been surveyed varies from bed to bed, a hybrid approach could be used to make the best use of available data for each bed. For beds with a single survey, a fixed surplus production rate could be used while, for beds with multiple surveys, a survey-derived estimate of surplus production rate could be used. Unfished exploitable biomass could be calculated as:

$$B' = B_{s1} + L_{bs1} - min(rT_1, L_{bs1}) \qquad \text{Equation 24}$$

Where T_1 is the time, in years, between the first survey and the first year of harvest, and r is the surplus production rate before the first survey defined as:

(1) If there is only one survey for a bed, r = 0.01 A W, where 0.01 Geoducks/m^2/year is a precautionary estimate of surplus production density based on published literature. Alternatively, average regional estimates of surplus production density, estimated from re-surveyed beds, could be used so that $r = \overline{D_{P_R}}\ A\ W$, where $\overline{D_{P_R}}$ is the average surplus production density between surveys for region R.

(1) If there are two or more surveys for a bed:

    (2) If $R_j \geq 0$ then $r = R_j$

    (2) Else (i.e., $R_j < 0$), $r = 0$

There are therefore two alternatives to option 4 depending on whether a coastal fixed surplus production rate based on the literature is used (option 4A), as in option 2A; or regional fixed average surplus production rates estimated from survey data (option 4C), as in option 2C, are used for beds surveyed only once.

In Equation 24, the minimum of surplus production before the first survey (rT_1) or landings before the first survey (L_{bs1}) is chosen to be subtracted from $B_{s1} + L_{bs1}$. In other words, the maximum value subtracted from $B_{s1} + L_{bs1}$ is L_{bs1}. This does not allow surplus production to be greater than the value of landings before the first survey (L_{bs1}), thereby not allowing estimated B' to fall below B_{s1}. If surplus production is greater than removals before the first survey (i.e., if $rT_1 > L_{bs1}$), then:

$$B' = B_{s1} + L_{bs1} - L_{bs1} = B_{s1} \qquad \text{Equation 25}$$

Which is equivalent to option 3A above. The estimated unfished exploitable biomass (B') would thus not be allowed to fall below the first survey estimate, which is more precautionary (greater B' translates into lower stock index) than allowing B' to fall below B_{s1}.

If surplus production is less than removals before the first survey ($rT_1 < L_{bs1}$), then:

$$B' = B_{s1} + L_{bs1} - rT_1 \qquad \text{Equation 26}$$

Which is similar to option 2 above, with flexibility built in around the number of surveys on a bed and maximizing use of available survey data for each bed. In this case, the estimate of unfished exploitable biomass (B') would be higher than the first survey estimate but lower than the method currently used.

If the estimated surplus production rate is 0 or less (for beds with two or more surveys), r would be set to 0 and:

$$B' = B_{s1} + L_{bs1} - 0 \quad \text{Equation 27}$$

Which is equivalent to option 1 above.

Option 4 would be more complicated to implement than options 1, 2 or 3, but has the advantage of providing a flexible approach that maximizes use of available survey data for each bed while being more precautionary when less data is available. However, for beds surveyed more than once, and if regional surplus production rates used are based on survey data, the caveats regarding survey densities and the surplus production rates derived from them described in Section 5.2.2 also apply here. Under Option 4, the *B'* estimation method would vary between beds, based on data available, the assumptions associated with *B'* estimation would therefore also vary from bed to bed. It could be argued that simpler methods where *B'* is estimated in a consistent manner for all surveyed beds and under a common set of assumptions may be preferable.

5.6 SELECTION CRITERIA AND EVALUATION

Several criteria can be considered to select which of the options outlined above should be chosen. First, are the assumptions behind each method likely to be valid or not? Methods that rely on fewer assumptions or where assumptions are more likely to be met may be preferable. Second, use of available data could also be considered, methods that maximize the use of available data for a given bed may be preferable over methods that are based on more generalizations. Third, the level of precaution built into the methods could be considered. Methods that are more precautionary for cases where uncertainty is greater may be preferable. Fourth, the number of beds that the method is applicable to could be considered. Methods that are applicable to more beds may be preferable to methods that are applicable to fewer beds. Fifth, ease of implementation can be considered, easily implemented methods may be preferable in some respects. A summary of assumptions, applicability, advantages and disadvantages of each option are provided in Table 10 for surveyed beds.

Lastly, an evaluation of the performance of each option can be done for re-surveyed beds where the first survey occurred before, or soon (within two years) after the start of harvest, which will be referred to in the next section as “early surveys”. Using data from these beds, the performance of the various *B'* estimation options can be evaluated by using data from the second surveys to estimate *B'* using each option and comparing those to the early survey *B'* estimates.

5.6.1 Comparison of Options for Beds where Early Survey Estimates are Available

Throughout the BC coast, 25 beds were harvested only once, in the year or two before being first surveyed, and were subsequently re-surveyed. These beds were surveyed as part of three pairs of surveys. Seven Geoduck beds in the Moore Islands were first harvested in 1996 and surveyed in 1998 and 2014. Ten beds in Principe Channel were first harvested in 1996 and surveyed in 1997 and 2012. Eight beds in Tasu Sound were first harvested in 2000 and surveyed in 2001 and 2008.

For beds harvested only once, a year or two before being first surveyed, the current method of estimating *B'* is expected to be relatively accurate because little settlement is expected to have occurred in the time between first harvest and the first (early) survey (within two years). Furthermore, if settlement had occurred between the first harvest and first survey, the newly settled Geoducks would have been too small for survey divers to see and count on the first survey. The assumption of no surplus production may thus be valid on the small temporal scale of a year or two between first harvest and first survey. For these beds, *B*' from the early survey was estimated with the current method using density estimates from the early survey.

An additional 22 beds were surveyed before first being harvested and subsequently re-surveyed, of these, eight were located in areas occupied by Sea Otters and were excluded from analyses. For the 14 remaining beds that were surveyed before being first harvested, the biomass estimate from the first survey was used as the early survey *B*' estimate.

Estimates of *B'* based on early surveys are thus available for 39 Geoduck beds. The average time between the first survey (that provided the early *B'* estimate) and second survey was 13.2 ± 0.6 years. *B'* on these beds was then re-estimated using density data from the second survey (considering it as the first post-harvest survey) and each option described above. *B*' estimates from the second survey were then compared to the early *B'* estimates to evaluate the performance of the various *B'* estimation options proposed (Table 11).

Using option 1 (Equation 15), *B'* based on the second survey is estimated as survey biomass + landings pre-survey. This method is equivalent to the current method used for beds surveyed only once. The average ratio of *B'* estimated using option 1 to early *B'* was 1.177 ± 0.063, significantly different from 1.0 (one sample t-test, df = 38, t = 2.798, p = 0.008), suggesting that option 1 lead to overestimates of *B'*, as was expected (Table 11A).

Option 2 introduces some measure of surplus production in the estimation of *B'*. Three alternatives were suggested to estimate surplus production, i.e., 2A – using a fixed coast wide surplus production rate from the literature, 2B – estimating bed-specific surplus production from survey data, or 2C – using fixed regional surplus production rates based on survey data.

For option 2A, a fixed surplus production rate of 0.01 Geoducks/m^2/year was incorporated in the calculations (Equation 17), the average ratio of second survey *B'* to early *B'* was 1.102 ± 0.063 (Table 11A) but was not significantly different from 1.0 (one sample t-test, df = 38, t = 1.611, p = 0.116). As expected this ratio is lower than that obtained from option 1 since a fixed estimate of surplus production was subtracted from the *B'* estimated in option 1. A disadvantage of option 2A is that it assumes a constant surplus production rate over time and for the entire BC coast. Surplus production rates are unlikely to be constant over time and results presented in Section 4.3 (Table 7) showed variability in surplus production rates between regions of the BC coast.

Option 2B could not be evaluated because none of the 39 beds with early *B'* estimates were surveyed three times. When the first survey of those beds is used to estimate early *B'* and the second survey is considered to be the first post-harvest survey, a third survey would be necessary to evaluate how option 2B performs.

For option 2C, the regional average surplus production rates estimated from re-surveyed beds (Table 7) were used in the estimations of *B'* (Equation 20). The average surplus production rate estimated for the Central Coast was not significantly different from zero (Section 4.3.1). Zhang and Hand (2006) reported high recruitment rates for the Central Coast. The surplus production rate for this analysis was therefore set to zero for the Central Coast. The average ratio of *B'* estimated from the second survey to early *B'* was 0.766 ± 0.080 and was significantly different from 1.0 (one sample t-test, df = 38, t = -2.576, p = 0.014) making option 2C the least accurate and least precise of the options evaluated (Table 11A). Furthermore, on average, option 2C under-estimated *B'* by at least 20% and is therefore not considered to be precautionary enough. A lower ratio was expected for option 2C than for option 2A because the surplus production rates used in option 2C are, on average, higher. For four beds, *B'* was negative when using option 2C implying that surplus production was greater than the sum of survey biomass and landings before the survey which seems unlikely. Regional average surplus production rates estimated from re-surveyed beds therefore did not appear to be a good option to extrapolate surplus production to all beds within entire regions.

Option 3A consists of using the first survey biomass estimate as the estimate of *B'* (Equation 22). When the second survey is considered as the first post-harvest survey (for beds with an early *B'* estimates), the average ratio of *B'* from the survey to early *B'* was 0.997 ± 0.054 (Table 11B) and was not significantly different from 1.0 (one sample t-test, df = 38, t = -0.052, p = 0.959). This ratio is closer to 1.0 than when using the other options and had the lowest standard error, suggesting that option 3A was, on average, both the most accurate and most precise method to estimate *B'*.

Results presented in Table 11 suggested that option 3A performed well to estimate *B*'. However, data available to produce the comparisons presented in Table 11 were only available for the North Coast and the first survey, for the earliest surveyed bed, took place in 1993. No beds for which harvest began in the early 1980's had an early survey. The performance of option 3A for these beds therefore could not be evaluated. Results in Table 11 were based on lower harvest rates than those from the early years of the fishery and therefore may not be applicable to beds that were heavily harvested in the early years of the fishery.

Option 3B is similar to option 3A except that landings before 1989 are added to the estimate of biomass from the first survey (B_{s1}). None of the beds with early surveys were harvested before 1989. Therefore, in the current analysis, option 3B would have produced the same results as option 3A. Results for option 3B are therefore not presented in Table 11B.

Option 4 is a hybrid option (Equation 24), based on data available, where surplus production is estimated but not permitted to exceed landings before the first survey, thereby not allowing *B*' to fall below the biomass estimated from the first survey. For the beds analyzed in this section, the second survey was considered as the first post-harvest survey. Since none of the beds used in the analysis had three surveys, only fixed estimates of surplus production could be used. Option 4 was evaluated using a coast wide fixed surplus production rate from the literature (4A) and regional average surplus production rates estimated from survey data (4C).

For option 4A, using a coast wide fixed surplus production density of 0.01 Geoducks/m^2/year, estimated surplus production was greater than the landings before the survey for 9 of 39 beds (23.1%). The average ratio of *B'* estimated from the second survey to early *B'* was 1.112 ± 0.062 (Table 11B) and was not significantly different from 1.0 (one sample t-test, df = 38, t = 1.799, p = 0.080). As expected this option produced higher estimates of *B'* than option 2A and 2C because there was a cap on surplus production.

Option 4C, the hybrid option using regional fixed surplus production rates estimated from survey data, ranked second in accuracy and precision after option 3A (Table 11B). The average ratio of *B'* estimated from the second survey to early *B'*, when using option 4C, was 1.040 ± 0.056 and was not significantly different from 1.0 (one sample t-test, df = 38, t = 0.826, p = 0.414). Both options 2C and 4C use fixed regional surplus production rates, however, when using option 4C, surplus production is capped at the value of landings before the first survey. When surplus production is greater than landings before the first survey, option 4C results will be equal to option 3A results. Option 4C yielded the same *B'* as option 3A (and 3B) for 30 of the 39 beds where an early estimate of *B'* was available, thus explaining why option 4C results were similar to option 3A. Some drawbacks of option 4C are that more assumptions are made than for option 3A or 3B and that the method to estimate *B'* on surveyed beds is not consistent for all surveyed beds. Option 4 by default uses bed-specific estimates of surplus production rates when available (becomes equivalent to option 2B for those beds), however, no data were available to determine bed-specific surplus production rates in this analysis. The potential impact of bed-specific surplus production rates on estimates of *B'* thus remains un-quantified. Option 4C would be more complex to implement and relies on more assumptions than options 3A and 3B. Option 4C shows few advantages over options 3A and 3B and, for most beds tested, produced the same result as option 3A (and 3B). Surplus production rates estimated from survey data under both options 4A and 4C are subject to the caveats regarding survey density estimates described in Section 5.2.2. Therefore, there appears to be little benefit to choose option 4C over option 3A or 3B.

Data for beds where early estimates of *B'* were available and that were re-surveyed suggested that option 3A was the most accurate and most precise of the options proposed for estimating *B'* on surveyed beds. For the beds used in this analysis, option 3B produced the same results as option 3A because none of those beds had been harvested before 1989. Option 3A and 3B are the easiest to implement and use data from the first survey of each surveyed bed, thereby estimating *B'* in a consistent manner for all surveyed beds. Option 3A has an advantage in that it does not incorporate landings in the estimate of *B'*, uncertainties in landings history (see Uncertainties section) are eliminated from the process. However, the assumption for option 3A may not be valid for beds heavily harvested in the early years of the fishery when landings were highest and recruitment rates low. Option 3A may lead to underestimates of B' for those beds. Adding pre-1989 landings to the biomass estimate from the first survey (option 3B) may be a more defensible option since surplus production rates were unlikely to equal fishery landings at a time when landings were high and recruitment was low. Since only 25% of beds were harvested before 1989, option 3B would produce the same results as option 3A for 75% of beds. No assumptions regarding surplus production rates after the first survey are made in option 3A or 3B.

6 OPTIONS FOR UN-SURVEYED BEDS

Because less data is available for un-surveyed Geoduck beds, fewer options for improvements to the unfished exploitable biomass estimation method are available. Based on the last three full Geoduck fishery rotation cycles for which data was available (2006-2008, 2009-2011 and 2012-2014) between 88.1 to 89.0% of Geoduck landings have come from surveyed beds. The remaining 11.0 to 11.9% of landings were harvested from un-surveyed beds. Improving *B'* estimation methods for surveyed beds would therefore have the most impact for the fishery. Changes to *B'* estimation methods for un-surveyed beds are not expected to have as large an impact. A summary of the options proposed for estimation of *B'* on un-surveyed beds, along with their assumptions, advantages and disadvantages is presented in Table 12.

6.1 OPTION 1 – NO CHANGE

One option for un-surveyed beds would be to keep the *B'* estimation method as-is (i.e., using Equation 2). This may lead to overestimates of *B'*, with the effect of lowering the stock index for those beds, which is more precautionary. Since biomass on un-surveyed beds is extrapolated from nearby surveyed beds, there is likely greater uncertainty in the biomass estimates for un-surveyed beds which may warrant using a more precautionary method to estimate stock index for un-surveyed beds. Since this option requires no changes to *B'* estimation methods for un-surveyed beds, implementation would be straightforward. This option assumes that there is no surplus production and that landings history is accurate. However, this option may lead to premature closure of some beds until they get surveyed because beds would close once harvest on a bed equals 60% of estimated *B'* (Equation 10).

6.2 OPTION 2 – USE REGIONAL ESTIMATES OF UNFISHED EXPLOITABLE DENSITY TO ESTIMATE UNFISHED EXPLOITABLE BIOMASS ON UN-SURVEYED BEDS

An option to improve *B'* estimates for un-surveyed beds could be to calculate regional estimates of *D*', where *D*' would be estimated from revised *B'* estimates from the surveyed beds and use these regional *D*' estimates to extrapolate *B'* on un-surveyed beds. This option can only be evaluated once an unfished exploitable biomass estimation method for surveyed beds has been selected and implemented.

If option 3B is selected for surveyed beds, *D*' could easily be estimated for each surveyed bed from their *B*' estimates. Regional average *D*' could then be estimated from surveyed beds and average *B'* on un-surveyed beds estimated as:

$$B' = \overline{D'}_R AW \quad \text{Equation 28}$$

where $\overline{D'}_R$ is the average *D*' from surveyed beds in region R.

Since new options for *B'* estimation on surveyed beds are expected to lead to lower *B'* estimates than the current method, estimation of *D*' from surveyed beds and its application to the calculation of *B'* on un-surveyed beds is expected to lead to lower estimates of *B'* for un-surveyed beds. Using this option would make estimation methods more consistent between surveyed and un-surveyed beds.

7 UNCERTAINTIES

Estimation of *B'* on a Geoduck bed relies on several parameters: Geoduck bed area, Geoduck mean weight, Geoduck density, landings history and possibly surplus production (depending on estimation method). Uncertainties in each of these parameters can thus affect *B'* estimates. Uncertainties around estimation of Geoduck bed area, mean weight, density and landings were described in detail in Bureau et al. (2012) and these uncertainties apply to the calculation of *B*' also.

7.1 IMPACT OF GEODUCK BED AREA ON ESTIMATES OF *B'*

An estimate of bed area is available for each Geoduck bed on the BC coast. Portions of some Geoduck beds may not be harvestable due to differences in substrate throughout the bed. The portion of a Geoduck bed that is harvestable is therefore not known exactly. Geoduck bed area estimates are reviewed annually as new data from commercial harvest, dive surveys and substrate mapping become available (Bureau et al. 2012). Not all beds are updated each year. Since bed area is one of the inputs to the calculation of Geoduck biomass, a change in the area of a bed will change its estimated biomass. Changes to the area of a bed over time are generally considered to be improvements as more data is gathered about a bed. Therefore, it is justifiable to re-estimate *B'* after the area of a bed is updated (see Discussion).

7.2 IMPACT OF GEODUCK MEAN WEIGHT ON ESTIMATES OF *B'*

Similarly to bed area, Geoduck mean weight on a bed is an input to biomass calculations and mean weight estimates are reviewed annually to include the latest available data (Bureau et al. 2012). Not all beds are updated each year. Not all beds have a bed-specific estimate of mean weight. For beds where insufficient data exist to estimate a bed-specific mean weight, mean weight from a larger spatial scale is used (Bed to GMA to Statistical Sub Area, Bureau et al. 2012). However, as more data become available every year, the number of beds with bed-specific estimates of mean weight increases and more data become available for beds where a bed-specific estimate of mean weight already existed. Re-estimating *B'* when mean weight estimates are updated is justifiable as it may increase the accuracy of *B*' estimates for some beds and reduce the number of beds for which mean weight is extrapolated.

Trends in mean weight of Geoducks over time have not been investigated. Currently, the Geoduck mean weight estimation procedure uses all commercial Geoduck logbook data from 1997 onwards where true counts of Geoducks harvested were recorded. Because Geoduck mean weights are estimated from commercial landings data, they represent the mean weight of exploitable Geoducks (Geoducks that have recruited to the fishery). Every year, before updating biomass estimates, another year's commercial harvest data is added to the mean weight dataset and mean weight estimates are updated. The dataset therefore grows from year to year. Several years of data must be used to ensure sufficient data is available (geographical coverage). Because of the three-year rotational nature of the fishery, at least three years of data must be used so that data are available for all portions of the coast. Because not all beds are harvested each time an area is open (e.g. because of paralytic shellfish poisoning closures, because the area quota has been achieved, etc.) and because the number of fishing events on a bed in a single rotation may be low, using data from more than one rotation increases the number of beds for which data is available to estimate mean weight. Adding more years of data to the dataset thus increases the number of beds for which a bed-specific estimate of mean weight is available and reduces the number of beds for which mean weight is extrapolated from nearby beds, which is expected to increase the accuracy of biomass estimates. However, if mean weight changes over time, then continuing to add more years of data to the mean weight data set could result in increased uncertainty in the estimation of biomass. Analyzing trends in mean Geoduck weight over time was outside the scope of this paper.

7.3 IMPACT OF SURPLUS PRODUCTION RATES ON ESTIMATES OF *B'*

If the method chosen to estimate *B'* is one that includes surplus production, then uncertainty in surplus production rates may affect estimates of *B'*. Published estimates of Geoduck recruitment were reviewed in Section 5. Since Geoduck recruitment is variable in time and space (Bureau et al. 2002, 2003, Campbell et al. 2004, Goodwin and Shaul 1984, Orensanz et al. 2000, 2004, Zhang and Hand 2006, 2007), a conservative estimate of Geoduck surplus production rate should be chosen (if using a fixed estimate). For the *B'* estimation options where surplus production rates are used, more conservative estimates of surplus production rates lead to greater estimates of *B'* which are more precautionary as they lead to lower stock index values.

The proposed options that factor in surplus production assume constant surplus production rates over time and/or across regions and/or that surplus production before the first survey was equal to surplus production between the first and last surveys. Zhang and Hand (2006) warned that recruitment variation is large, within each geographic region in BC, which may preclude using regional index sites to represent recruitment trends in any given area. Zhang and Hand (2006, 2007) and Orensanz et al. (2000, 2004) also showed long-term trends in Geoduck recruitment strength indicating that recruitment is not constant over time.

Estimating surplus production rates from survey data, for beds surveyed more than once, relies on the assumption that survey density estimates are accurate. Uncertainty in survey density estimates translates into uncertainty in the surplus production rates derived from them.

Theoretically, according to population growth and fishery models, levels of surplus production may vary over time as density on a bed is reduced by harvest. However, data from beds surveyed three times showed no significant differences in surplus production rates between survey intervals (intervals between first and second and between second and third surveys). Factors affecting Geoduck productivity are poorly understood. Other factors, such as environmental factors may also be at play. Valero et al. (2004) showed correlations between long-term trends in Geoduck recruitment and long-term trends in sea surface temperature.

7.4 IMPACT OF LANDINGS ON ESTIMATES OF *B'*

Depending on the method chosen to estimate *B'*, uncertainty in landings history may affect *B'* estimation. Uncertainties in landings history are due poor geo-referencing and under-reporting of landings before 1989 when dock-side validation of all landings was implemented (Bureau et al. 2012, Hand and Bureau 2012). Starting in 1989, landings have been fully reported and are considered accurate. However, recording of latitude and longitude of harvest events on commercial Geoduck logbooks only began 1997 (harvest charts were used before) and "selective availability" on the Global Positioning System was only disabled in 2000. Geo-referencing of harvest events before 2000 was therefore not as accurate as it currently is. The proportion of geo-referenced landings increased between 1997 and 2005 and, since 2006 all landings have been geo-referenced. If the option selected to estimate *B'* is one that includes an estimate of landings, then the uncertainty in landings history (amount and location) may translate into greater uncertainty in estimated *B'*.

7.5 IMPACT OF DENSITY-DEPENDENT SURVIVAL

Little is known regarding density-dependent survival of Geoducks newly settled to a bed. Campbell et al. (2004) found no negative impact of harvest on subsequent Geoduck recruitment in experimentally harvested Geoduck plots in BC. Zhang and Campbell (2004) found no evidence that severe harvesting had an impact on long term Geoduck recruitment in experimental plots on the WCVI, while recruitment was highest in the most heavily harvested experimental plots in the Strait of Georgia. Whether a decrease in Geoduck density through harvest can improve survival of newly settled Geoducks, through decreased competition for space, is unknown. Whether food is a limiting factor to Geoduck survival on wild Geoduck beds is also unknown. Campbell et al. (2004) found no relationship between recruitment and density.

7.6 IMPACT OF DENSITY ESTIMATES

Uncertainty around Geoduck survey density estimates introduces uncertainty in the estimation of biomass and also in the estimation of surplus production rates derived from density estimates. Because a portion of Geoducks younger than five years are likely too small to be seen and counted by survey divers, survey density estimates consist mostly of exploitable Geoducks.

A potentially important factor that can impact the accuracy of Geoduck dive surveys is the "show-factor", i.e., the proportion of Geoducks in a bed that are "showing" (visible to survey divers) at the time of the survey (Bureau et al. 2012, Hand and Bureau 2012). Until 2012, Geoduck surveys were conducted between early May and late September based on the belief that this was the best time window for high show-factors. Since 2013, the Geoduck survey schedule has been compressed between mid-April and mid-July. Data collected from long term show-factor plots monitored monthly over two years (unpublished) showed that Geoduck show-factor decreases after mid-July. Density from Geoduck surveys conducted in August and September may therefore be lower than if the same bed was surveyed earlier in the same year.

Geoducks are not distributed uniformly throughout Geoduck beds. As a result, confidence bounds around survey density estimates can be wide. In other words, uncertainty in survey density estimates can be large (low precision). Bureau et al. (2012) reported that precision around survey density estimates has improved over time, due to improved spatial bed area estimates as a result of substrate mapping before surveying since 2003.

Geoduck beds selected for surveying are not chosen randomly. Historically, beds considered to be important to the fishery have been selected preferentially for surveying over beds that are less important to the fishery. Therefore, surveyed Geoduck beds are not a random sample of all Geoduck beds on the coast. Densities estimated from surveyed beds therefore may not be truly representative of all beds on the coast or within regions.

Furthermore, beds selected for re-survey are sometimes believed to be productive beds. Re-surveyed beds are thus also not a random sample of all beds on the coast. Because of the potential bias towards selecting beds considered to be productive for re-survey, surplus production rates estimated from re-surveyed beds may not be applicable to other beds on the coast or within regions.

7.7 INCORPORATING UNCERTAINTY

The methods presented in this paper are deterministic. The uncertainties in the parameter estimates described in the previous sections are not accounted for in the estimations of stock index since the calculations are based on mean values of biomass. A potential future improvement to the methods would be to use probabilistic methods to incorporate uncertainty in biomass estimation inputs (using the recommended *B'* and stock index estimation methods) to be carried through to the probability of the stock index being above 0.4.

8 SPATIAL SCALE AT WHICH TO ESTIMATE CURRENT BIOMASS AND STOCK INDEX

The Geoduck stock index has historically been calculated at the finest spatial scale possible, based on available data. Geoduck biomass has been estimated on a by-bed basis because density and mean weight data are available at the by-bed spatial scale. Because biomass has been calculated on a by-bed basis and landings before 1997 were only coded to the bed level, the stock index has, to date, also been calculated on a by-bed basis. A Geoduck bed can be made up of several sub-beds which are physically distinct on the seabed (e.g. separated by a reef, on either side of a point or island, etc.). The existence of sub-beds is due to the way beds were drawn on master bed charts in the early days of the fishery when several distinct polygons were sometimes labelled with the same bed code. Polygons with the same bed code were later individually identified by introducing sub-bed codes. Landings before 1997 were not geo-referenced and it is therefore not possible to determine which sub-bed early landings came from. Geo-referencing of some harvest events started in 1997 and since 2006, all harvest events have been geo-referenced and assigned to sub-beds.

The Geoduck fishery is now managed (i.e., quotas set by fishery managers) on a by-sub-bed basis. Biomass estimates for a bed are divided among its sub-beds proportionally to the area ratio of each sub-bed (area of sub-bed divided by area of bed). For example, for a bed composed of two sub-beds with 40% and 60% of the total bed area respectively, the biomass allocated to the sub-beds will be 40% and 60% of the estimated bed biomass, respectively.

Because early landings were only coded to the by-bed spatial scale, the stock index has, to date, been estimated at the by-bed spatial scale. Landings are involved in calculating current biomass (B_c) and, historically, unfished exploitable biomass (*B'*) and thus impact stock index estimate. In the current Geoduck assessment framework (Bureau et al. 2012), stock index is calculated as:

$$Stock\ Index_{Bed} = \frac{B_c}{B'} = \frac{B_c}{B_c+L_t} = \frac{B_S-L_{ps}}{B_S+L_{bs}} \qquad \text{Equation 29}$$

Where B_s is the biomass from the survey, L_t are total landings for the bed, L_{ps} are landings post-survey and L_{bs} are landings before the survey. Note that Equation 29 is based on the historical way to estimate *B'* and does not reflect some of the changes proposed in this document.

Equation 29 shows that there are two possible ways to estimate the stock index for surveyed beds, either directly from B_c or from B_s. However, for un-surveyed beds, the stock index can only be calculated from estimates of B_c due to the lack of survey data (B_s estimates not available for un-surveyed beds).

For surveyed beds, regardless of how *B'* is estimated, landings post-survey are subtracted from survey biomass (B_s) in the calculation of current biomass (B_c) used in stock index calculations. The spatial scale at which B_c is estimated may therefore impact stock index estimates for a sub-bed, regardless of how *B'* is estimated.

Calculating Stock Index at the by-bed spatial scale assumes that landings from a bed have been harvested proportionally to each sub-bed's area ratio. For example, for a bed composed of two sub-beds with 40% and 60% of the total bed area respectively, 40% and 60% of the landings would be assumed to have come from each sub-bed, respectively.

However, not all sub-beds within a bed are necessarily harvested proportionally to their area. For example, many beds are made up of one main (larger) sub-bed and a few to several smaller sub-beds. In these cases, harvest is sometimes concentrated on the main (larger) sub-bed with the smaller sub-beds receiving little to no harvest. In such cases, the assumption of proportional harvest would essentially dilute the harvest that happened on the main sub-bed to the smaller sub-beds which could result in a stock index estimate that does not truly reflect harvest that has occurred on the various sub-beds. It may therefore be more accurate to estimate the stock index on a by-sub-bed basis.

For un-surveyed beds, only estimates of current biomass are available because biomass on un-surveyed beds is extrapolated using current density from nearby surveyed beds. The stock index for un-surveyed beds could be estimated at the by-sub-bed spatial scale as:

$$I_{SubBed} = \frac{B_{c_{SubBed}}}{B'_{SubBed}} = \frac{B_{c_{SubBed}}}{B_{c_{SubBed}}+L_{t_{SubBed}}} = \frac{B_{c_{Bed}}a_{SubBed}}{B_{c_{Bed}}a_{SubBed}+L_{t_{SubBed}}} \qquad \text{Equation 30}$$

Where I_{SubBed} is the stock index for the sub-bed, $B_{c_{SubBed}}$ is the sub-bed current biomass, $L_{t_{SubBed}}$ are the total sub-bed landings, $B_{c_{Bed}}$ is the bed current biomass and a_{SubBed} is the area ratio of the sub-bed.

For surveyed beds, Equation 30 could also be used to estimate the stock index at the sub-bed scale. However, in Equation 30 the application of the area ratio occurs after estimation of the bed current biomass (B_c) so that landings post-survey are distributed between sub-beds proportionally to their area ratio. Applying the area ratio to the survey biomass (B_s) may be a more accurate method for surveyed beds so that sub-bed specific landings can be used in B_c estimations. Landings post-survey are used in the calculation of current biomass (B_c) for surveyed beds. Most post-survey landings have been geo-referenced and are thus assigned to sub-beds. Calculating B_c at the sub-bed spatial scale, by using sub-bed specific landings and sub-bed survey biomass, may therefore provide more accurate estimates of B_c on each sub-bed. For surveyed beds, the stock index could be calculated at the sub-bed spatial scale as follows:

$$I_{SubBed} = \frac{B_{c_{SubBed}}}{B'_{SubBed}} = \frac{B_{s_{SubBed}} - L_{ps_{SubBed}}}{B_{s_{SubBed}} + L_{bs_{SubBed}}} = \frac{B_{s_{Bed}} a_{SubBed} - L_{ps_{SubBed}}}{B_{s_{Bed}} a_{SubBed} + L_{bs_{SubBed}}} \quad \text{Equation 31}$$

Where I_{SubBed} is the Stock Index for the sub-bed, $B_{s_{SubBed}}$ is the sub-bed survey biomass, $L_{ps_{SubBed}}$ are the sub-bed landings post-survey, $L_{bs_{SubBed}}$ are the sub-bed landings before the survey, $B_{s_{Bed}}$ is the bed survey biomass and a_{SubBed} is the area ratio of the sub-bed. A change implied in Equation 31 is that sub-bed specific landings are subtracted from the sub-bed survey biomass estimate to yield sub-bed B_c (Equation 32), as opposed to the current method where bed-specific landings are subtracted from the bed survey estimate before the area ratio is applied (Equation 33). Using Equation 31 would thus also involve changing the spatial scale at which sub-bed B_c is estimated.

Method of estimating sub-bed B_c on surveyed beds when using Equation 31:

$$B_{c_{SubBed}} = B_{s_{Bed}} a_{SubBed} - L_{ps_{SubBed}} \quad \text{Equation 32}$$

Current method of estimating sub-bed B_c on surveyed beds:

$$B_{c_{SubBed}} = \left(B_{s_{Bed}} - L_{ps_{Bed}}\right) a_{SubBed} \quad \text{Equation 33}$$

For surveyed beds, Equation 31 is expected to provide more accurate estimates of sub-bed stock index because it does not assume that landings between sub-beds are proportional to area ratios. Sub-bed B_c is estimated using Equation 32, rather than Equation 33, so that landings are apportioned to sub-beds more accurately.

Harvest events for which the specific sub-bed they were harvested from is unknown are coded as sub-bed = 0 in the logbook database. If some landings post-survey on a bed are assigned to sub-bed 0 then landings post-survey for a given sub-bed can be estimated as:

$$L_{ps_{SubBed}} = L_{ps_0} a_n + L_{ps_n} \quad \text{Equation 34}$$

Where L_{ps_0} are the landings post-survey assigned to sub-bed 0, a_n is the area ratio of sub-bed *n* and L_{ps_n} are the landings post-survey known to have come from sub-bed *n*. A similar formula can be used to estimate sub-bed specific landings before a survey by substituting L_{ps} with L_{bs} in Equation 34.

The method of estimating B_c in Equation 31 to Equation 33 assumes that surplus production rates are zero. Because B_c is re-estimated yearly (to include the most up to date data), the implication of this assumption is that estimates of B_c may decrease more rapidly than the biomass is changing on a bed (if surplus production is taking place) between surveys. However, once a bed is re-surveyed, a new survey-based estimate of B_c will become available which will include the surplus production that occurred between surveys into the latest estimate. Including surplus production in the estimation of B_c between surveys would rely on the assumption that surplus production rate is constant over time (between surveys) and would likely also rely on regional or coast-wide surplus production rate estimates (assumption of constant surplus production rate within an area). Neither assumption is likely to be met. Not including surplus production in the estimation of B_c, between surveys, results in lower B_c estimates (and consequently lower stock index), therefore it is more precautionary and it does not rely on assumptions relating to surplus production rates. Whether estimation of B_c should be updated to include surplus production is a topic that may warrant further work but was outside the scope of this paper.

The method of estimating B_c in Equation 31 to Equation 33 divides a bed's survey biomass among sub-beds proportionally to each sub-bed's area ratio because survey density data cannot be analyzed at the sub-bed spatial scale due to the low number of surveyed transects on many sub-beds. Survey density data is analyzed at the "survey site" spatial scale, which can be a single bed if there is a sufficient number of transects, or a combinations of beds if beds are small and have too few transects to be analyzed individually. In other words, survey density is assumed to be the same on all sub-beds of a surveyed bed. Similarly, because mean Geoduck weight is estimated at the by-bed spatial scale, mean weight is assumed to be the same for all sub-beds of a given bed.

The established method of calculating current biomass at the by-bed spatial scale assumes that landings were spread among sub-beds proportionally to sub-beds' respective area ratios, irrespective of which sub-beds the landings actually came from. This could introduce uncertainties in the current biomass estimates on sub-beds. The advantage of estimating current biomass at the sub-bed spatial scale would be that only landings coded to sub-bed 0 would be divided proportionally among sub-beds while landings coded to non-zero sub-beds would be assigned appropriately to the correct sub-bed, thus providing more accurate estimate of removals from each sub-bed and reducing uncertainty. This may be particularly advantageous for relatively new beds, where few non geo-referenced landings exist, and for beds surveyed after 2005 as all post-survey landings for these will be geo-referenced. Because of issues with tracking landings history between sub-beds, the practice of creating sub-beds has been discontinued. All new beds discovered now get an individual bed code with a single sub-bed.

8.1 STOCK INDEX ESTIMATION METHODS COMPARISON BASED ON 2017-2018 GEODUCK BIOMASS ESTIMATES

Stock indices for all harvestable sub-beds were estimated on a by-bed spatial scale as part of the Geoduck biomass and stock index updates for the 2017-2018 fishing season. Stock indices for these sub-beds were also estimated at the sub-bed spatial scale using two methods and compared to the stock indices calculated at the bed level. The first method of estimating sub-bed stock indices was to apply Equation 30 to all sub-beds, surveyed or not. The second method of estimating sub-bed stock indices consisted of applying Equation 31 to surveyed beds and Equation 30 to un-surveyed beds.

The number of sub-beds, amount of bed area and biomass that fall below the LRP (stock index < 0.4) were estimated using the bed-based and both sub-bed-based stock index estimation methods for each region of the BC coast (Table 13). The spatial scale at which the stock index was estimated, or method used for sub-bed-based estimates, had little impact overall on the number of sub-beds below the LRP in each region. For area and biomass, the spatial scale at which the stock index was estimated had relatively little impact, except in the Inside Waters where more area and biomass fell below the LRP when the stock index was estimated at the by-sub-bed spatial scale. For the first sub-bed-based method, the increases occurred because harvest was concentrated on a single sub-bed for each of two separate bed codes, the stock indices estimated at the by-bed spatial scale were above 0.4 but, for the more heavily harvested sub-beds, were below 0.4 when using the first sub-bed-based method. The second sub-bed-based method caused a further increase in the amount of bed area and biomass that fell below the LRP in the Inside Waters. The additional increases were due to two more sub-beds (one for each of two bed codes) falling below the LRP when using the second sub-bed-based method. These two sub-beds were only slightly above the LRP when using the first sub-bed-based method (< 0.415). These examples are a case in point illustrating inaccuracies associated with apportioning landings proportionally to area ratios between sub-beds, when estimating stock index on a by-bed basis, and why the move to estimating stock index to a by-sub-bed spatial scale was suggested.

The coast-wide number of sub-beds, amount of area and percent of biomass that fall within various categories of stock index values were estimated using the bed-based and both sub-bed-based methods (Table 14). Mean estimates of biomass for only the harvestable sub-beds were used, based on the Geoduck biomass estimates for the 2017-2018 fishing season. The number (and percent) of beds that fall within different categories of stock index were similar between the three stock index estimation methods. The amount (and percent) of bed area that was above or below a stock index value of 0.5 was similar between the three stock index estimation methods. However, estimating stock index at the by-sub-bed spatial scale resulted in slightly more bed area falling below the LRP, while at the same time more area had a stock index greater than 0.8. In terms of biomass, spatial scale at which the stock index was calculated had little impact overall. However slightly more biomass fell under the LRP when the stock index was calculated at the by-sub-bed spatial scale. The amount (and percent) of area and biomass that fall within various stock index values were similar to those reported in 2011 (Table 5 in DFO 2012). With regards to the number of beds, the 2012 report showed results on a by-bed basis while the current report shows results on a by-sub-bed basis; results are therefore not directly comparable.

The average of stock index, for all harvestable sub-beds and based on mean biomass estimates for the 2017-2018 Geoduck fishery, was 0.764 ± 0.003 when estimated using the bed-based method and 0.772 ± 0.003 for both sub-bed-based methods. For these calculations, *B'* was estimated using the existing method. By comparison, the average of bed stock index values in 2011 was 0.78 (DFO 2012). If one of the new options proposed for estimating *B*' is adopted, it is expected that average stock index values would increase.

The results presented in this section show that overall, on a coast-wide basis, estimating the stock index at the sub-bed vs. bed spatial scales has little effect on the number of beds, overall biomass and bed area available to be harvested. However, changing the spatial scale at which the stock index is estimated could have some impacts on biomass and area available to be harvested at small spatial scales, i.e., a few additional sub-beds closed to harvest. Since the Geoduck fishery is managed at the by-sub-bed spatial scale and data are now available to estimate the stock index on a by-sub-bed basis, it may be preferable to estimate the stock index at the by-sub-bed spatial scale to allow the best accuracy possible in stock tracking in the future.

9 DISCUSSION

The current method of estimating Geoduck unfished exploitable biomass (*B*') assumes that no surplus production occurs on a Geoduck bed after it is first harvested. The current methods used to estimate *B*' on surveyed and un-surveyed Geoduck beds were reviewed in Section 2. Unfished exploitable biomass on a Geoduck bed is one of the inputs to calculate a bed's stock index to determine if it is above or below 0.4, the Limit Reference Point (LRP) was defined as current biomass being equal to 40% of *B*'. Simulations presented in Section 3 showed that estimates of *B'*, and therefore of the stock index, are expected to be accurate when the assumption of no surplus production is met. However, the simulations showed that, when surplus production occurs , estimates of *B*' will increase after each survey, introducing a bias in *B*' estimates causing the stock index to decrease and not be reflective of actual current stock status on a Geoduck bed. In other words, the stock index will also be biased. The current method of estimating Geoduck *B*' may thus cause some beds to reach the LRP prematurely, if surplus production is occurring.

Whether the current method of estimating *B*' is adequate or not then depends on whether or not the assumption of no surplus production is valid. From a theoretical point, population growth and fishery models typically assume that surplus production occurs once a stock is fished down from equilibrium population levels (or carrying capacity). The assumption of no surplus production therefore contradicts many established population growth and fishery models. Also, data from Geoduck beds surveyed more than once suggested that surplus production has been occurring on harvested Geoduck beds in BC (Section 4). Data from re-surveyed harvested Geoduck tracts in Washington State have also shown recovery (surplus production) (Goodwin and Bradbury 2000, Orensanz et al. 2000, 2004). Neither theory nor empirical data support the assumption of no surplus production on Geoduck beds after the beginning of harvest. The assumption of no surplus production in the current way of estimating unfished exploitable biomass is therefore not likely to be met. Consequently, the current method of estimating *B*' is likely to produce biased estimates of *B*' which in turn produce biased stock index estimates. An alternative method of estimating unfished exploitable biomass on Geoduck beds for the BC Geoduck fishery is therefore desirable.

Several of new options for estimation of *B*' on surveyed beds were suggested in Section 5 and summarized in Table 10. The current method of estimating unfished exploitable biomass on surveyed Geoduck beds uses the latest survey data. The time period over which the assumption of no surplus production is applied is therefore longer than if data from the first survey was used (for re-surveyed beds). Using data from the first, instead of the latest, survey was therefore considered the first possible improvement to *B'* estimation. Further refinements using various methods of estimating surplus production were also suggested.

Evaluation of the performance of the various proposed *B*' estimation options, for beds where early estimates of *B*' were available, suggested that "Option 3A – unfished exploitable biomass = first survey biomass" was the most accurate and most precise option to estimate *B*'. Option 3B would have yielded the same results for the beds for which data was available. Options 3A and 3B offer advantages over the other proposed options. Option 3A does not rely on estimates of historical landings in the estimation of *B*', the uncertainty surrounding landings history is therefore eliminated from the *B*' estimation process. However, option 3A assumes that surplus production was equal to landings before the first survey, which assumes high surplus production rates in the 1980's when harvest rates were high and recruitment was low. This may lead to underestimates of B' for beds heavily harvested in the early years of the fishery. Option 3B may be a better option than option 3A since 3B assumes no surplus production before 1989. Option 3A and 3B use data from the first survey of each surveyed bed and therefore *B*' would be estimated in a consistent manner and under the same assumptions for all surveyed beds (regardless of how many times they have been surveyed). Option 3A and 3B do not rely on estimates of surplus production rates derived from survey data, uncertainty surrounding surplus production rates over time or between areas therefore would not affect *B*' calculations. Option 3A and 3B are easily implemented; although ease of implementation should not be the deciding factor in choosing which option to use, ease of implementation is an advantage.

The other options proposed for estimating *B*' on surveyed beds rely on more assumptions than option 3A and 3B. Options that include landings history in the estimation method assume that landings history is complete and accurate for each bed, which we know is not the case for some beds or for the early years of the fishery. Options that include estimates of surplus production rely on the assumption that surplus production is constant over time and between areas or that the surplus production rate before the first survey was equal to the surplus production rate between the first and last surveys. Options using survey-derived surplus production rates also assume that survey densities are estimated accurately. Uncertainty in density estimates therefore leads to uncertainty in survey-derived surplus production rates. Assumptions around surplus production are not likely to be met, based on our current understanding of Geoduck recruitment patterns.

Approximately 90% of Geoduck harvest in the last three three-year rotation periods has come from surveyed beds. Improvements to *B*' estimation methods for surveyed beds are therefore expected to have the most impact on the fishery.

Possible options for un-surveyed beds were presented in Section 6 and summarized in Table 12. If "Option 1 – no change" is chosen to estimate *B*' on un-surveyed beds, then un-surveyed beds will close once 60% of estimated *B*' on the bed has been harvested (Equation 10). The goal of the LRP in the BC Geoduck fishery is not to close a bed once 60% of the estimated unfished exploitable biomass has been harvested, rather, the goal of the LRP is to attempt to provide a safeguard that 40% of the estimated unfished exploitable biomass remains on a bed over time. Although, option 1 for un-surveyed beds is likely to be more precautionary than option 2, it provides no improvements; while with option 2, biomass estimation methods would be more consistent between surveyed and un-surveyed beds. Only 10 to 11% of Geoduck landings have come from un-surveyed beds in the last three rotations. The method used to estimate *B*' on un-surveyed beds is therefore unlikely to have a major impact on the fishery. Un-surveyed beds that are considered to be important to the fishery (e.g., beds that have a long harvest history, high landings or beds approaching the LRP) should be prioritized for surveying.

Regardless of which *B*' estimation option is chosen, the estimates of *B*' will not be fixed. Data used as inputs to Geoduck biomass calculations (bed area, mean weight and density) are updated yearly. Estimates of bed area are updated yearly, for a portion of the beds, based on new harvest, density survey and substrate mapping data. Updates to bed areas are generally considered to be improvements as more data becomes available for some beds. Mean weight and survey density estimates are updated yearly, for a portion of the beds, by adding the latest year of available data to the dataset. Consequently, the number of beds with bed-specific mean weight estimates and the number of surveyed beds increase yearly, thereby reducing the number of beds for which biomass is extrapolated which is expected to reduce uncertainty in the estimate of unfished exploitable biomass for those beds. From year to year, biomass is extrapolated for fewer and fewer beds as more bed-specific estimates of mean weight and density become available. Estimates of *B'* are therefore re-computed yearly, to ensure that the most up to date inputs are used for each bed, as part of the yearly current biomass and stock index calculations process. Estimates of *B'* will only change for beds where parameter estimates have changed because of new data. The goal of the new methods proposed was not to have fixed estimates of *B*' over time, rather, the goal was to develop methods that do not produce biased estimates of *B*' when surplus production occurs.

When the current Geoduck assessment framework was developed, no harvest data was available at the by-sub-bed spatial scale. Calculations of current biomass, unfished exploitable biomass and stock index were therefore implemented at the by-bed spatial scale, the finest spatial scale possible at the time. With a shift to managing the fishery on a by-sub-bed level in the mid 2000's, harvest data became available at the by-sub-bed spatial scale. The finer spatial scale of landings data now available thus makes it possible to estimate current biomass and stock index at the by-sub-bed spatial scale. Switching the spatial scale, from by-bed to by-sub-bed, for calculations of current biomass and stock index could increase accuracy of sub-bed biomass and stock index estimates and thereby reduce uncertainty, make the best use of currently available data and allow for more accurate stock tracking in the future. The by-sub-bed stock index methods evaluated had little overall effect on the number of beds, area and biomass below the LRP, at regional and coast wide spatial scales. However, differences are expected at smaller spatial scales (e.g., the GMA scale).

10 FUTURE CONCERNS

Sea Otters (*Enhydra lutris*) are predators on Geoducks. Sea Otter populations are established on the WCVI and Central Coast of BC and their range is expanding (Nichol et al. 2015). As the abundance and range of Sea Otters increase, their impact on Geoducks stocks is likely to also increase. Under the current Geoduck stock assessment model, predation by Sea Otters is likely to lead to the closure of several beds on the coast (as the stock index is likely to fall below 0.4 once beds affected by Sea Otters get re-surveyed) and have a negative impact on the fishery.

Preliminary data from WCVI suggest that Geoduck beds can exist and sustain harvest in Sea Otter occupied areas. The presence of Sea Otters in an area may lead to a phase-shift in Geoduck abundance. One of the problems with a LRP based on estimates of *B'* is to decide when in time the virgin state was, since biomass and carrying capacity in the absence of a fishery can fluctuate over time (e.g. before – after Sea Otters).

After Sea Otters become established in an area, it could be argued that Geoduck *B'* should be updated to reflect the new phase in Geoduck abundance. This would be relatively easy to achieve by surveying an area after Sea Otters have become established and could provide new LRP estimates for those beds. However, research is needed to determine what, if any, may be an acceptable harvest rate for Geoduck populations in regions where Sea Otters are established. This topic was outside the scope of the current paper.

The virtual absence of the sunflower star (*Pycnopodia helianthoides*) and many other species of sea stars in BC in recent years (D. Bureau, pers. obs.), after an epidemic of sea star wasting disease (Hewson et al. 2014), may reduce predation pressure and improve survival of Geoducks for some years and thus increase productivity, until populations of sea stars recover. How long sea star populations will take to recover is unknown.

Other environmental factors may affect Geoduck productivity. Geoduck growth rates in BC are positively correlated with warmer sea surface temperature (Black et al. 2009). No studies on the possible effects of ocean acidification on Geoducks have been published (see review by Haigh et al. 2015). However, ocean acidification has been shown to reduce survival, calcification, growth and development of molluscs (Kroeker et al. 2013, Parker et al. 2013). Ocean acidification has also been shown to negatively affect fertilization, embryonic and larval development and settlement for a variety of mollusc species (Parker et al. 2013). Haigh et al. (2015) concluded that the effects of ocean acidification on shelled molluscs will be negative, that the effects will occur at various life-history stages and they anticipated that the negative effects would also affect Geoducks.

11 RECOMMENDATIONS

1. For surveyed Geoduck beds, estimate unfished exploitable biomass (*B*') using "Option 3B – Unfished exploitable biomass = biomass from first survey + landings before 1989".
2. For un-surveyed Geoduck beds, estimate unfished exploitable biomass (*B*') using "Option 2 – Use regional estimates of unfished exploitable density to estimate unfished exploitable biomass on un-surveyed beds".
3. Keep updating estimates of Geoduck unfished exploitable biomass (*B*') when estimates of Geoduck current biomass are updated so that the most up to date inputs (bed area, mean Geoduck weight and density) are used.
4. For un-surveyed Geoduck beds, estimate stock index on a by-sub-bed spatial scale using Equation 30.

5. For surveyed Geoduck beds, estimate stock index on a by-sub-bed spatial scale using Equation 31. This implies estimating current biomass (B_c) at the by-sub-bed scale using Equation 32.

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Table 1: Simulated values of unfished exploitable density (D') on a Geoduck bed surveyed every 10 years under the assumption of no surplus production. Values of current density (Dc) are estimated as Dc the previous year minus density removed in the year of interest (white cells), until a bed is re-surveyed (green cells) and a survey-based estimate of Dc becomes available. Yearly landings density are specified as 2% of Dc the previous year. Estimated D' equals Dc plus cumulative removals. Under this assumption, survey density decreases between surveys by an amount equal to the density removed by the fishery and the current method of estimating the Stock Index yields the correct value (equal to value calculated using true D'). Estimated D' remains constant over time. Illustrated in Figure 2 A. Density values represent relative densities and are dimensionless. Stock index is a dimensionless ratio.

	Estimated	Landings Density		Estimated	Stock Index		
Year	D_c	Year	Cumulative	D'	Current Method	Using True D'	Comments
1990	1.000	0.000	0.000	1.000	1.000	1.000	True D'
1991	0.980	0.020	0.020	1.000	0.980	0.980	First year fished
1992	0.960	0.020	0.040	1.000	0.960	0.960	-
1993	0.941	0.019	0.059	1.000	0.941	0.941	-
1994	0.922	0.019	0.078	1.000	0.922	0.922	-
1995	0.904	0.018	0.096	1.000	0.904	0.904	-
1996	0.886	0.018	0.114	1.000	0.886	0.886	-
1997	0.868	0.018	0.132	1.000	0.868	0.868	-
1998	0.851	0.017	0.149	1.000	0.851	0.851	-
1999	0.834	0.017	0.166	1.000	0.834	0.834	-
2000	0.817	0.017	0.183	1.000	0.817	0.817	Survey D_c = 0.817
2001	0.801	0.016	0.199	1.000	0.801	0.801	-
2002	0.785	0.016	0.215	1.000	0.785	0.785	-
2003	0.769	0.016	0.231	1.000	0.769	0.769	-
2004	0.754	0.015	0.246	1.000	0.754	0.754	-
2005	0.739	0.015	0.261	1.000	0.739	0.739	-
2006	0.724	0.015	0.276	1.000	0.724	0.724	-
2007	0.709	0.014	0.291	1.000	0.709	0.709	-
2008	0.695	0.014	0.305	1.000	0.695	0.695	-
2009	0.681	0.014	0.319	1.000	0.681	0.681	-
2010	0.668	0.014	0.332	1.000	0.668	0.668	Survey D_c = 0.668

Table 2: Simulated values of estimated unfished exploitable density (D') on a Geoduck bed surveyed every 10 years under the assumption of surplus production lower than fishery removals. Values of current density (Dc) are estimated as Dc the previous year minus density removed in the year of interest (white cells), until a bed is re-surveyed (green cells) and a survey-based estimate of Dc becomes available. Yearly landings density are specified as 2% of Dc the previous year. Estimated D' equals Dc plus cumulative removals. Under this assumption, survey density between surveys decreases by a smaller amount than the density removed by the fishery. The estimate of D' increases after each survey and the current method of estimating the Stock Index yields values that are below those calculated using true D'. Illustrated in Figure 2 B. Density values represent relative densities and are dimensionless. Stock index is a dimensionless ratio.

	Estimated	Landings Density		Estimated	Stock Index		
Year	D_c	Year	Cumulative	D'	Current Method	Using True D'	Comments
1990	1.000	0.000	0.000	1.000	1.000	1.000	True D'
1991	0.980	0.020	0.020	1.000	0.980	0.980	First year fished
1992	0.960	0.020	0.040	1.000	0.960	0.960	-
1993	0.941	0.019	0.059	1.000	0.941	0.941	-
1994	0.922	0.019	0.078	1.000	0.922	0.922	-
1995	0.904	0.018	0.096	1.000	0.904	0.904	-
1996	0.886	0.018	0.114	1.000	0.886	0.886	-
1997	0.868	0.018	0.132	1.000	0.868	0.868	-
1998	0.851	0.017	0.149	1.000	0.851	0.851	-
1999	0.834	0.017	0.166	1.000	0.834	0.834	-
2000	0.900	0.017	0.183	1.083	0.831	0.900	Survey D_c = 0.900
2001	0.882	0.018	0.201	1.083	0.814	0.882	-
2002	0.864	0.018	0.219	1.083	0.798	0.864	-
2003	0.847	0.017	0.236	1.083	0.782	0.847	-
2004	0.830	0.017	0.253	1.083	0.767	0.830	-
2005	0.814	0.017	0.269	1.083	0.751	0.814	-
2006	0.797	0.016	0.286	1.083	0.736	0.797	-
2007	0.781	0.016	0.302	1.083	0.721	0.781	-
2008	0.766	0.016	0.317	1.083	0.707	0.766	-
2009	0.750	0.015	0.333	1.083	0.693	0.750	-
2010	0.850	0.015	0.348	1.198	0.710	0.850	Survey D_c = 0.850

Table 3: Simulated values of estimated unfished exploitable density (D') on a Geoduck bed surveyed every 10 years under the assumption of surplus production equal to fishery removals. Values of current density (Dc) are estimated as Dc the previous year minus density removed in the year of interest (white cells), until a bed is re-surveyed (green cells) and a survey-based estimate of Dc becomes available. Yearly landings density are specified as 2% of Dc the previous year. Estimated D' equals Dc plus cumulative removals. Under this assumption, survey density remains the same each time the bed is surveyed. The estimate of D' increases after each survey and the current method of estimating the Stock Index yields values that are below those calculated using true D'. Illustrated in Figure 2 C. Density values represent relative densities and are dimensionless. Stock index is a dimensionless ratio.

	Estimated	Landings Density		Estimated	Stock Index		
Year	D_c	Year	Cumulative	D'	Current Method	Using True D'	Comments
1990	1.000	0.000	0.000	1.000	1.000	1.000	True D'
1991	0.980	0.020	0.020	1.000	0.980	0.980	First year fished
1992	0.960	0.020	0.040	1.000	0.960	0.960	-
1993	0.941	0.019	0.059	1.000	0.941	0.941	-
1994	0.922	0.019	0.078	1.000	0.922	0.922	-
1995	0.904	0.018	0.096	1.000	0.904	0.904	-
1996	0.886	0.018	0.114	1.000	0.886	0.886	-
1997	0.868	0.018	0.132	1.000	0.868	0.868	-
1998	0.851	0.017	0.149	1.000	0.851	0.851	-
1999	0.834	0.017	0.166	1.000	0.834	0.834	-
2000	1.000	0.017	0.183	1.183	0.845	1.000	Survey D_c = 1
2001	0.980	0.020	0.203	1.183	0.828	0.980	-
2002	0.960	0.020	0.223	1.183	0.812	0.960	-
2003	0.941	0.019	0.242	1.183	0.796	0.941	-
2004	0.922	0.019	0.261	1.183	0.780	0.922	-
2005	0.904	0.018	0.279	1.183	0.764	0.904	-
2006	0.886	0.018	0.297	1.183	0.749	0.886	-
2007	0.868	0.018	0.315	1.183	0.734	0.868	-
2008	0.851	0.017	0.332	1.183	0.719	0.851	-
2009	0.834	0.017	0.349	1.183	0.705	0.834	-
2010	1.000	0.017	0.366	1.366	0.732	1.000	Survey D_c = 1

Table 4: Long range simulated values of estimated unfished exploitable density (D') on a Geoduck bed surveyed every 10 years under the assumption of surplus production equal to fishery removals. Current density every 10 years are survey estimates. Estimated D' equals current density plus cumulative density removed. Under this assumption, survey density remains the same each time the bed is surveyed. The estimated D' increases after each survey and the current method of estimating the Stock Index yields values that are below those calculated using true D'. Stock index based on true D' = current density. The Limit Reference Density (LRD), the density that must be maintained in the bed over time for the bed to stay open, increases over time. Illustrated in Figure 3 A. Density values represent relative densities and are dimensionless. Stock index is a dimensionless ratio.

Year	Current Density	Cumulative Density Removed*	Estimated *D'*	Stock Index	LRD** = 0.4 X *D'*	Comments
1980	1.00	0.00	1.00	1.00	0.40	True *D'*
1990	1.00	0.20	1.20	0.83	0.48	-
2000	1.00	0.40	1.40	0.71	0.56	-
2010	1.00	0.60	1.60	0.63	0.64	-
2020	1.00	0.80	1.80	0.56	0.72	-
2030	1.00	1.00	2.00	0.50	0.80	-
2040	1.00	1.20	2.20	0.45	0.88	-
2050	1.00	1.40	2.40	0.42	0.96	-
2055	1.00	1.50	2.50	0.40	1.00	LRD = True *D'*
2060	1.00	1.60	2.60	0.38	1.04	-
2070	1.00	1.80	2.80	0.36	1.12	-
2080	1.00	2.00	3.00	0.33	1.20	-

*: Assuming harvest rate of 2% from latest survey per year.

**: Limit Reference Density: Relative density below which bed will fall below LRP

Table 5: Long range simulated values of estimated unfished exploitable density (D') on a Geoduck bed surveyed every 10 years under the assumption of surplus production below fishery removals. Current density every 10 years are survey estimates. Estimated D' equals current density plus cumulative density removed. Under this assumption, survey density decreases over time but less than fishery removals. The estimated D' increases after each survey and the current method of estimating the Stock Index yields values that are below those calculated using true D'. Stock index based on true D' = current density. The Limit Reference Density (LRD), the density that must be maintained in the bed over time for the bed to stay open, increases over time. Illustrated in Figure 3 B. Density values represent relative densities and are dimensionless. Stock index is a dimensionless ratio.

Year	Current Density	Cumulative Density Removed*	Estimated *D′*	Stock Index	LRD** = 0.4 X *D′*	Comments
1980	1.00	0.00	1.00	1.00	0.40	True *D′*
1990	0.95	0.20	1.15	0.83	0.46	-
2000	0.90	0.39	1.29	0.70	0.52	-
2010	0.85	0.57	1.42	0.60	0.57	-
2020	0.80	0.74	1.54	0.52	0.62	-
2030	0.75	0.90	1.65	0.45	0.66	-
2040	0.70	1.05	1.75	0.40	0.70	LRP reached
2050	0.65	1.19	1.84	0.35	0.74	-
2060	0.60	1.32	1.92	0.31	0.77	-
2070	0.55	1.44	1.99	0.28	0.80	-
2080	0.50	1.55	2.05	0.24	0.82	-

*: Assuming harvest rate of 2% biomass from latest survey per year.

**: Limit Reference Density: Relative density below which bed will fall below LRP

Table 6: Simulated values of estimated unfished exploitable density (D') on a Geoduck bed surveyed every 10 years under the assumption of net mortality between the 1990 and 2000 surveys and increase in density between 2000 and 2010 surveys. Values of current density (D_c) are estimated as D_c the previous year minus density removed in the year of interest (white cells), until a bed is re-surveyed (green cells) and a survey-based estimate of D_c becomes available. Yearly landings density are specified as 2% of D_c the previous year. Estimated D' equals D_c plus cumulative removals. Under this assumption, density on second survey is less than density on first survey minus fishery removals. The estimate of D' decreases after the second survey and the current method of estimating the Stock Index yields values that are above those calculated using true D'. Illustrated in Figure 2 D. Density values represent relative densities and are dimensionless. Stock index is a dimensionless ratio.

	Estimated	Landings Density		Estimated	Stock Index		
Year	D_c	Year	Cumulative	*D'*	Current Method	Using True *D'*	Comments
1990	1.000	0.000	0.000	1.000	1.000	1.000	True *D'*
1991	0.980	0.020	0.020	1.000	0.980	0.980	First year fished
1992	0.960	0.020	0.040	1.000	0.960	0.960	-
1993	0.941	0.019	0.059	1.000	0.941	0.941	-
1994	0.922	0.019	0.078	1.000	0.922	0.922	-
1995	0.904	0.018	0.096	1.000	0.904	0.904	-
1996	0.886	0.018	0.114	1.000	0.886	0.886	-
1997	0.868	0.018	0.132	1.000	0.868	0.868	-
1998	0.851	0.017	0.149	1.000	0.851	0.851	-
1999	0.834	0.017	0.166	1.000	0.834	0.834	-
2000	0.390	0.017	0.183	0.573	0.681	0.390	Survey D_c = 0.390
2001	0.382	0.008	0.191	0.573	0.667	0.382	-
2002	0.375	0.008	0.198	0.573	0.654	0.375	-
2003	0.367	0.007	0.206	0.573	0.641	0.367	-
2004	0.360	0.007	0.213	0.573	0.628	0.360	-
2005	0.353	0.007	0.220	0.573	0.615	0.353	-
2006	0.345	0.007	0.227	0.573	0.603	0.345	-
2007	0.339	0.007	0.234	0.573	0.591	0.339	-
2008	0.332	0.007	0.241	0.573	0.579	0.332	-
2009	0.325	0.007	0.248	0.573	0.568	0.325	-
2010	0.700	0.007	0.254	0.954	0.734	0.700	Survey D_c = 0.700

Table 7: Regional and overall average estimates of (A) first and last survey densities, number of years, rate of density change, and percent yearly relative density difference between surveys and (B) yearly density removed by harvest, B' ratio, stock index estimated using B' from first and last survey and yearly surplus production rate between surveys. Results are from first and last surveys of Geoduck beds surveyed more than once, excluding beds in Sea Otter occupied areas. The B' ratio was estimated as B' estimated from the last survey to B' estimated from the first survey; where B' was calculated using Equation 2. Stock indices used biomass from the last survey as the estimate of current biomass and B' estimates based on the first and last surveys.

A		Average Survey Density (Geoducks/m^2)				# of Years Between Surveys		Yearly Density Difference Between Surveys (Geod/m^2/Year)		Percent Yearly Relative Density Difference (%/year)	
		First Survey		Last Survey							
Management Region	Number of Beds	Average	SE	Average	SE	Average	SE	Average	SE	Average	SE
Inside Waters	32	0.67	0.09	0.80	0.12	11.0	0.9	0.012	0.006	2.89	1.15
WCVI	31	0.91	0.15	1.11	0.12	10.3	0.9	0.030	0.014	8.68	2.54
Central Coast	28	2.65	0.40	2.11	0.42	15.4	0.5	-0.038	0.010	-1.64	0.35
Prince Rupert	77	2.37	0.19	2.92	0.24	12.8	0.3	0.050	0.012	2.83	0.82
Haida Gwaii	53	1.68	0.16	1.78	0.17	10.2	0.5	0.017	0.010	3.03	1.14
Overall	221	1.79	0.11	1.98	0.12	11.9	0.3	0.023	0.000	3.14	0.58

B	Yearly Density Harvested (Geod/m^2/Year)		*B'* Ratio *B'* Last / *B'* First		Average Stock Index Based on *B'* from				Yearly Surplus Production Density (Geoducks/m^2/year)		Percent Yearly Surplus Production Density (%/year)	
					First Survey		Last Survey					
Management Region	Average	SE	Average	SE	Average	SE	Average	SE	Average	SE	Average	SE
Inside Waters	0.004	0.001	1.169	0.069	0.696	0.068	0.581	0.031	0.016	0.007	3.68	1.25
WCVI	0.006	0.001	1.306	0.082	0.815	0.096	0.591	0.032	0.036	0.013	9.29	2.51
Central Coast	0.021	0.004	0.942	0.062	0.672	0.060	0.701	0.043	-0.017	0.011	-0.69	0.43
Prince Rupert	0.017	0.001	1.347	0.063	1.124	0.066	0.806	0.019	0.067	0.012	3.74	0.83
Haida Gwaii	0.027	0.006	1.317	0.086	1.017	0.087	0.755	0.018	0.045	0.012	4.93	1.18
Overall	0.017	0.002	1.256	0.036	0.936	0.038	0.718	0.013	0.039	0.006	4.23	0.59

Table 8: Estimates of surplus production density, for first and second survey intervals, for Geoduck beds surveyed three times. Geoduck beds in Sea Otter occupied areas were excluded. Density removed between surveys estimated as landings between surveys divided by bed area and Geoduck mean weight.

			First Survey		Second Survey		Third Survey		Time Between Surveys (years)		Density Removed Between Surveys (Geoducks/m^2)		Surplus Production Rate (Geoducks/m^2/Year)	
Stat Area	Sub Area	Bed	Year	Density (Geod./m^2)	Year	Density (Geod./m^2)	Year	Density (Geod./m^2)	Int. 1	Int. 2	Interval 1	Interval 2	Interval 1	Interval 2
2	18	4	1996	1.70	1999	3.15	2010	2.98	3	11	0.04	0.46	0.495	0.027
2	31	1	1996	1.16	1999	1.89	2012	0.66	3	13	0.03	0.19	0.253	-0.080
2	31	3	1996	2.83	1999	4.02	2011	3.84	3	12	0.02	0.41	0.404	0.020
5	20	1	1995	4.07	2006	5.36	2015	6.18	11	9	0.35	0.31	0.149	0.125
5	20	5	1995	2.35	2006	2.56	2015	3.19	11	9	0.19	0.18	0.036	0.089
7	31	8	1993	0.79	2011	0.18	2014	0.24	18	3	0.13	0.00	-0.027	0.021
7	31	9	1993	0.79	2011	0.34	2014	0.24	18	3	0.19	0.00	-0.015	-0.032
12	6	1	1994	0.20	2011	0.13	2013	0.23	17	2	0.02	0.00	-0.003	0.050
13	15	1	1992	0.45	2002	0.41	2013	0.27	10	11	0.04	0.06	0.000	-0.007
13	15	2	1992	0.11	2002	0.23	2013	0.33	10	11	0.02	0.01	0.015	0.009
13	15	11	1992	0.21	2002	0.30	2013	0.23	10	11	0.01	0.05	0.010	-0.002
14	10	1	1993	0.25	1998	0.33	2007	0.22	5	9	0.02	0.02	0.020	-0.010
23	6	11	2002	1.00	2011	0.80	2013	1.24	9	2	0.06	0.00	-0.016	0.220
23	10	1	2000	0.84	2010	0.51	2012	1.01	10	2	0.06	0.01	-0.028	0.256
24	6	26	1995	1.59	2006	1.20	2015	1.29	11	9	0.22	0.14	-0.014	0.025
24	6	27	1995	1.11	2004	1.03	2015	1.21	9	11	0.06	0.12	-0.003	0.027
24	7	2	1995	2.50	2006	1.72	2015	1.29	11	9	0.21	0.15	-0.052	-0.030
			Average:	1.29		1.42		1.45	9.9	8.1	0.10	0.12	0.072	0.042
			SE:	0.27		0.37		0.40	1.1	1.0	0.02	0.04	0.039	0.021

Table 9: Number of years fished, number of years since first fished, yearly and total density removed for un-surveyed Geoduck beds.

Management Region	Number of Beds	Number of Years Fished Average	SE	Number of Years Since First Fished* Average	SE	Yearly Density Removed** (Geoducks/m^2/Year) Average	SE	Density Removed All Years (Geoducks/m^2) Average	SE
Inside Waters	236	4.1	0.2	27.0	0.6	0.006	0.001	0.159	0.015
WCVI	285	4.1	0.2	24.4	0.5	0.014	0.001	0.343	0.029
Central Coast	412	2.8	0.1	14.6	0.3	0.020	0.001	0.292	0.016
Prince Rupert	219	2.5	0.1	13.9	0.5	0.015	0.001	0.211	0.032
Haida Gwaii	213	2.8	0.1	16.1	0.5	0.017	0.002	0.253	0.033
Overall	1365	3.3	0.1	18.9	0.3	0.015	0.001	0.261	0.011

*: Calculated as 2017 - Year First Fished

**: Calculated as Density Removed divided by Number of Years since First Fished

Table 10: Summary of proposed options to estimate unfished exploitable biomass (B') on surveyed Geoduck beds.

Option	Description	Equations	Assumptions	Applicability	Advantages	Disadvantages
Current	*B′* = Current biomass + Landings	2 and 6	No surplus production Landings history complete and accurate	All surveyed beds	-	Estimates *B′* from latest survey Surplus production before last survey included in *B′* estimate Biased estimates of *B′* and stock index when surplus production occurs
Option 1	*B′* = First survey biomass + Landings before first survey	15	No surplus production before first survey Landings history complete and accurate	All surveyed beds	Consistent method to estimate *B′* for all surveyed beds Assumes no surplus production over a shorter period than current method Simple to implement	Surplus production before first survey included in *B′* estimate Biased estimates of *B′* and stock index when surplus production occurs before first survey
Option 2	*B′* = First survey biomass + Landings before first survey - Surplus production before first survey					
2A	- Using fixed surplus production rate from literature	17	Surplus production constant over time Surplus production constant coast-wide Landings history complete and accurate	All surveyed beds	Consistent method to estimate *B′* for all surveyed beds Simple to implement	Uses a single surplus production rate for the entire coast Potential regional differences in surplus production ignored
2B	- Estimating surplus production from survey data	18 and 19	Surplus production rate before first survey = surplus production rate between first and last surveys Surplus production rates are accurate and constant Landings history complete and accurate	Only beds surveyed more than once	Bed-specific estimates of surplus production rates	Applicable to few beds Other method required for beds surveyed only once
2C	- Using fixed regional surplus production rates from survey data	20	Surplus production rate before first survey = surplus production rate between first and last surveys Surplus production constant within a region Surplus production rates are accurate and constant Landings history complete and accurate	All surveyed beds	Consistent method to estimate *B′* for all surveyed beds Regional differences in surplus production rates considered	Complex to implement Many assumptions
2D	- Using age frequency distributions to estimate *D′*	21	Age frequency distribution of sample is representative of the population Landings history complete and accurate	Only beds with age data	Proportion of Geoducks recruited since start of fishery can be estimated	Applicable to very few beds Most complex to implement
Option 3A	*B′* = First survey biomass	22	Surplus production before first survey = landings before first survey	All surveyed beds	Consistent method to estimate *B′* for all surveyed beds No assumptions about landings history No assumptions about surplus production after first survey Simple to implement Fewest assumptions	Likely to provide the lowest *B′* estimates and consequently higher stock indices, may be less precautionary May understimate *B′* for beds heavily harvested in early years of the fishery
Option 3B	*B*' = First survey biomass + pre-1989 landings	23	No surplus production before 1989 Surplus production from 1989 to first survey = landings from 1989 to first survey	All surveyed beds	Consistent method to estimate *B′* for all surveyed beds Reasonable assumptions No assumptions about surplus production after first survey Simple to implement	Relies on pre-1989 landings data
Option 4	Hybrid approach based on data available	24	Vary between beds, based on what data is available for each bed	All surveyed beds	Makes use of best data available for each bed *B′* not allowed to fall below biomass from first survey	*B′* not estimated with a single consistent method Varying assumptions behind *B′* estimates for different beds More complex to implement

Table 11A: Comparison of alternative unfished exploitable biomass (B’) estimation options 1, 2A and 2C for beds where an early estimate of unfished exploitable biomass was available. First survey biomass estimate used as early B’ estimate for beds surveyed before first harvest. For beds surveyed a year or two after first harvest, early B’ was estimated as the sum of survey biomass and landings before survey since the assumption of no surplus production should be valid over one to two year time span. The second survey was considered as the “first post-harvest survey” and used when estimating B’ for each option. B’ ratio is the ratio of the estimate of B’ from each option to the early B’ estimate. These results mimic beds first surveyed years after first harvest. Continued next page for options 3A, 4A and 4C.

							Alternative Virgin Biomass Estimation Options for Surveyed Geoduck Beds					
			Year Surveyed		Early *B'*[1]	Number of Years Between	Option 1 - First[2] Survey + Landings		Option 2A - First[2] Survey + Landings - C[4] Surplus Prod		Option 2C - First[2] Survey + Landings - R[4] Surplus Prod	
Stat Area	Sub Area	Bed	First	Last	(t)	Surveys	*B'* Est (t)	*B'* Ratio[3]	*B'* Est (t)	*B'* Ratio[3]	*B'* Est (t)	*B'* Ratio[3]
2	42	1	2001	2008	27.7	7	60.5	2.181	58.5	2.110	51.6	1.861
2	42	4	2001	2008	13.1	7	14.0	1.071	13.7	1.048	12.7	0.967
2	42	6	2001	2008	29.0	7	47.0	1.621	43.6	1.503	31.7	1.095
2	42	7	2001	2008	13.0	7	18.5	1.425	17.1	1.319	12.3	0.950
2	42	8	2001	2008	6.0	7	11.0	1.817	10.3	1.704	7.9	1.311
2	42	9	2001	2008	103.9	7	105.3	1.013	101.3	0.975	87.6	0.842
2	42	10	2001	2008	2.1	7	3.8	1.831	3.7	1.803	3.5	1.704
2	42	12	2001	2008	10.9	7	11.2	1.033	10.9	1.000	9.6	0.887
5	13	1	1997	2012	167.9	15	146.6	0.873	137.4	0.818	85.0	0.506
5	13	3	1997	2012	23.6	15	40.1	1.700	34.9	1.480	5.4	0.229
5	13	4	1997	2012	371.7	15	320.8	0.863	299.9	0.807	180.9	0.487
5	13	6	1997	2012	514.1	15	377.5	0.734	348.4	0.678	182.7	0.355
5	13	8	1997	2012	119.2	15	182.8	1.534	177.8	1.492	149.4	1.254
5	13	9	1997	2012	71.1	15	110.7	1.557	107.7	1.514	90.6	1.274
5	13	10	1997	2012	27.4	15	28.7	1.047	22.1	0.807	-15.2	-0.557
5	13	14	1997	2012	160.9	15	169.9	1.056	163.1	1.014	124.5	0.774
5	13	15	1997	2012	260.6	15	296.9	1.139	282.2	1.083	198.5	0.762
5	13	16	1997	2012	60.4	15	89.0	1.474	86.5	1.433	72.3	1.197
5	13	17	1997	2012	37.2	15	51.3	1.380	49.8	1.338	40.8	1.097
5	13	20	1997	2012	33.3	15	38.0	1.141	36.1	1.085	25.6	0.770
6	9	32	1996	2007	70.8	11	39.3	0.555	35.2	0.497	11.7	0.166
6	13	48	1995	2007	26.9	12	30.4	1.129	26.9	1.001	7.3	0.273
6	13	49	1995	2007	34.6	12	34.4	0.992	28.8	0.831	-3.0	-0.086
6	13	51	1995	2007	26.6	12	26.9	1.013	22.6	0.852	-1.7	-0.066
6	13	52	1995	2007	60.0	12	79.0	1.316	71.3	1.188	27.6	0.459
6	16	25	1994	2008	145.1	14	101.6	0.700	95.9	0.661	101.6	0.700
6	16	26	1994	2008	2.9	14	3.7	1.258	3.5	1.188	3.7	1.258
6	18	2	1994	2013	242.3	19	253.0	1.044	241.8	0.998	253.0	1.044
6	18	3	1994	2013	279.6	19	449.2	1.607	425.1	1.521	449.2	1.607
6	18	5	1994	2008	145.0	14	110.6	0.763	105.5	0.727	110.6	0.763
6	18	11	1994	2008	80.0	14	60.6	0.757	57.7	0.721	60.6	0.757
7	31	11	1993	2008	86.3	15	63.7	0.739	52.5	0.608	63.7	0.739
106	2	1	1998	2014	32.0	16	44.6	1.395	40.9	1.278	19.6	0.613
106	2	2	1998	2014	544.7	16	872.0	1.601	853.0	1.566	745.1	1.368
106	2	3	1998	2014	1861.5	16	1,845.1	0.991	1,785.6	0.959	1,447.1	0.777
106	2	6	1998	2014	878.3	16	817.4	0.931	803.7	0.915	725.7	0.826
106	2	14	1998	2014	210.6	16	187.2	0.889	179.9	0.854	138.2	0.656
106	2	15	1998	2014	444.8	16	637.7	1.434	622.2	1.399	534.0	1.201
106	2	17	1998	2014	20.0	16	6.1	0.303	3.7	0.187	-9.4	-0.473
					Average:	13.2		1.177		1.102		0.778
					SE:	0.6		0.063		0.063		0.086

1: Estimated form first survey of the bed where first survey provided early *B'*.
2: "First Survey" refers to the second actual survey, which was considered as the first post-harvest survey.
3: Ratio of *B'* estimated from the option to early *B'*.
4: C = Coast wide fixed surplus production rate of 0.01 Geoducks/m^2/year; R = Regional fixed surplus production rates from re-surveyed beds.

Table 11B: Comparison of alternative unfished exploitable biomass (B') estimation options 3A, 4A and 4C for beds where an early estimate of unfished exploitable biomass was available. First survey biomass estimate used as early B' estimate for beds surveyed before first harvest. For beds surveyed a year or two after first harvest, early B' was estimated as the sum of survey biomass and landings before survey since the assumption of no surplus production should be valid over one to two year time span. The second survey was considered as the "first post-harvest survey" and used when estimating B' for each option. B' ratio is the ratio of the estimate of B' from each option to the early B' estimate. These results mimic beds first surveyed years after first harvest.

						Number	Alternative Virgin Biomass Estimation Options for Surveyed Geoduck Beds					
			Year		Early	of Years	Option 3A		Option 4A - Hybrid		Option 4C - Hybrid	
Stat	Sub		Surveyed		*B'*[1]	Between	First[2] Survey		Fixed C[4] SP Rate		Fixed R[4] SP Rate	
Area	Area	Bed	First	Last	(t)	Surveys	*B'* Est (t)	*B'* Ratio[3]	*B'* Est (t)	*B'* Ratio[3]	*B'* Est (t)	*B'* Ratio[3]
2	42	1	2001	2008	27.7	7	49.3	1.778	58.5	2.110	51.6	1.861
2	42	4	2001	2008	13.1	7	8.5	0.652	13.7	1.048	12.7	0.967
2	42	6	2001	2008	29.0	7	38.8	1.337	43.6	1.503	38.8	1.337
2	42	7	2001	2008	13.0	7	15.6	1.206	17.1	1.319	15.6	1.206
2	42	8	2001	2008	6.0	7	7.8	1.285	10.3	1.704	7.9	1.311
2	42	9	2001	2008	103.9	7	83.3	0.802	101.3	0.975	87.6	0.842
2	42	10	2001	2008	2.1	7	1.6	0.796	3.7	1.803	3.5	1.704
2	42	12	2001	2008	10.9	7	9.9	0.913	10.9	1.000	9.9	0.913
5	13	1	1997	2012	167.9	15	123.5	0.736	137.4	0.818	123.5	0.736
5	13	3	1997	2012	23.6	15	32.0	1.357	34.9	1.480	32.0	1.357
5	13	4	1997	2012	371.7	15	233.4	0.628	299.9	0.807	233.4	0.628
5	13	6	1997	2012	514.1	15	311.7	0.606	348.4	0.678	311.7	0.606
5	13	8	1997	2012	119.2	15	174.5	1.465	177.8	1.492	174.5	1.465
5	13	9	1997	2012	71.1	15	95.0	1.335	107.7	1.514	95.0	1.335
5	13	10	1997	2012	27.4	15	21.4	0.782	22.1	0.807	21.4	0.782
5	13	14	1997	2012	160.9	15	160.1	0.995	163.1	1.014	160.1	0.995
5	13	15	1997	2012	260.6	15	246.6	0.946	282.2	1.083	246.6	0.946
5	13	16	1997	2012	60.4	15	87.3	1.446	87.3	1.446	87.3	1.446
5	13	17	1997	2012	37.2	15	49.7	1.337	49.8	1.338	49.7	1.337
5	13	20	1997	2012	33.3	15	33.1	0.994	36.1	1.085	33.1	0.994
6	9	32	1996	2007	70.8	11	36.4	0.514	36.4	0.514	36.4	0.514
6	13	48	1995	2007	26.9	12	28.0	1.042	28.0	1.042	28.0	1.042
6	13	49	1995	2007	34.6	12	32.2	0.929	32.2	0.929	32.2	0.929
6	13	51	1995	2007	26.6	12	24.7	0.929	24.7	0.929	24.7	0.929
6	13	52	1995	2007	60.0	12	62.5	1.042	71.3	1.188	62.5	1.042
6	16	25	1994	2008	145.1	14	92.5	0.637	95.9	0.661	101.6	0.700
6	16	26	1994	2008	2.9	14	3.3	1.129	3.5	1.188	3.7	1.258
6	18	2	1994	2013	242.3	19	223.5	0.922	241.8	0.998	253.0	1.044
6	18	3	1994	2013	279.6	19	400.4	1.432	425.1	1.521	449.2	1.607
6	18	5	1994	2008	145.0	14	109.4	0.755	109.4	0.755	110.6	0.763
6	18	11	1994	2008	80.0	14	60.4	0.755	60.4	0.755	60.6	0.757
7	31	11	1993	2008	86.3	15	57.1	0.662	57.1	0.662	63.7	0.739
106	2	1	1998	2014	32.0	16	33.3	1.043	40.9	1.278	33.3	1.043
106	2	2	1998	2014	544.7	16	843.9	1.549	853.0	1.566	843.9	1.549
106	2	3	1998	2014	1861.5	16	1,762.4	0.947	1,785.6	0.959	1,762.4	0.947
106	2	6	1998	2014	878.3	16	778.6	0.886	803.7	0.915	778.6	0.886
106	2	14	1998	2014	210.6	16	185.4	0.881	185.4	0.881	185.4	0.881
106	2	15	1998	2014	444.8	16	592.7	1.333	622.2	1.399	592.7	1.333
106	2	17	1998	2014	20.0	16	2.1	0.105	3.7	0.187	2.1	0.105
					Average:	13.2		0.997		1.112		1.047
					SE:	0.6		0.054		0.062		0.057

1: Estimated form first survey of the bed where first survey provided early *B'*.
2: "First Survey" refers to the second actual survey, which was considered as the first post-harvest survey.
3: Ratio of *B'* estimated from the option to early *B'*.
4: C = Coast wide fixed surplus production rate of 0.01 Geoducks/m^2/year; R = Regional fixed surplus production rates from re-surveyed beds.

Table 12: Summary of proposed options to estimate unfished exploitable biomass (B’) on un-surveyed Geoduck beds.

Option	Description	Equations	Assumptions	Applicability	Advantages	Disadvantages
Current / Option 1	*B′* = Current biomass + Landings	2	No surplus production Landings history complete and accurate	All un-surveyed beds	Likely more precautionary than Option 2	Beds close once harvest = 60% *B′* No improvement for most beds
Option 2	*B′* = Regional *D′* x Bed area x Mean weight	28	Depend on *B′* estimation option selected for surveyed beds Average *D′* on surveyed beds in a region reflect *D′* on un-surveyed beds	All un-surveyed beds	More consistent with method recommended for surveyed beds *B′* not affected by landings	Likely less precautionary than Option 1

Table 13: Comparison of the number of Geoduck sub-beds (A), area of sub-beds (B) and biomass (C) below the Limit Reference Point (stock index < 0.4) based on calculations of stock index at the bed and sub-bed spatial scales; for harvestable sub-beds, based on 2017-2018 mean biomass estimates. Sub-bed stock index estimated using two methods, SI1 used Equation 30 for all beds while SI2 used Equation 31 for surveyed beds and Equation 30 for un-surveyed beds.

A	Number of Sub-Beds						
Management Region	Total	with Bed SI < 0.4 #	with Bed SI < 0.4 %	with Sub-Bed SI1 < 0.4 #	with Sub-Bed SI1 < 0.4 %	with Sub-Bed SI2 < 0.4 #	with Sub-Bed SI2 < 0.4 %
Inside Waters	697	74	10.6	69	9.9	71	10.2
WCVI	458	28	6.1	36	7.9	35	7.6
Central Coast	993	36	3.6	35	3.5	36	3.6
Prince Rupert	1,057	36	3.4	27	2.6	28	2.6
Haida Gwaii	781	15	1.9	20	2.6	25	3.2
Total	3,986	189	4.7	187	4.7	195	4.9

B	Area of Sub-Beds (Ha)						
Management Region	Total	with Bed SI < 0.4 Area	with Bed SI < 0.4 %	with Sub-Bed SI1 < 0.4 Area	with Sub-Bed SI1 < 0.4 %	with Sub-Bed SI2 < 0.4 Area	with Sub-Bed SI2 < 0.4 %
Inside Waters	7,965	607.4	7.6	997.7	12.5	1148.1	14.4
WCVI	3,375	385.5	11.4	392.2	11.6	390.5	11.6
Central Coast	1,543	74.3	4.8	71.6	4.6	72.5	4.7
Prince Rupert	2,568	60.5	2.4	44.2	1.7	45.9	1.8
Haida Gwaii	2,384	16.7	0.7	21.2	0.9	26.8	1.1
Total	17,834	1,144.4	6.4	1,526.9	8.6	1,683.9	9.4

C	Sub-Bed Biomass (Metric Tons)						
Management Region	Total	with Bed SI < 0.4 Biomass	with Bed SI < 0.4 %	with Sub-Bed SI1 < 0.4 Biomass	with Sub-Bed SI1 < 0.4 %	with Sub-Bed SI2 < 0.4 Biomass	with Sub-Bed SI2 < 0.4 %
Inside Waters	24,395	1,255	5.1	2,004	8.2	2,224	9.1
WCVI	30,124	1,584	5.3	1,627	5.4	1,617	5.4
Central Coast	29,352	466	1.6	414	1.4	419	1.4
Prince Rupert	76,726	375	0.5	303	0.4	318	0.4
Haida Gwaii	33,676	84	0.2	99	0.3	126	0.4
Total	194,274	3,763	1.9	4,448	2.3	4,703	2.4

Table 14: Number of sub-beds, bed area and percent of biomass that fall within various stock index ranges, for stock index calculations done at the bed and sub-bed spatial scales. Results based on mean biomass estimates for the 2017-2018 Geoduck harvest season and for harvestable sub-beds only. Sub-bed stock index was estimated using two methods, SI1 used Equation 30 for all beds while SI2 used Equation 31 for surveyed beds and Equation 30 for un-surveyed beds.

	Sub-Beds		Area of Sub-Beds		Biomass
Stock Index Range	Number	%	Hectares	%	%
All Sub-Beds	3,986	100.0	17,834	100.0	100.0
Bed Stock Index					
≥ 0.8	2,096	52.6	4,945	27.7	53.6
≥ 0.5 to <0.8	1,474	37.0	8,885	49.8	39.1
≥ 0.4 to <0.5	227	5.7	2,860	16.0	5.3
<0.4 (below LRP)	189	4.7	1,144	6.4	1.9
Sub-Bed Stock Index 1 (Equation 30 for all sub-beds)					
≥ 0.8	2,153	54.0	5,485	30.8	53.6
≥ 0.5 to <0.8	1,415	35.5	8,263	46.3	38.7
≥ 0.4 to <0.5	231	5.8	2,559	14.3	5.3
<0.4 (below LRP)	187	4.7	1,527	8.6	2.3
Sub-Bed Stock Index 2 (Equation 30 (un-surveyed) & 31 (surveyed))					
≥ 0.8	2,158	54.1	5,486	30.8	53.6
≥ 0.5 to <0.8	1,415	35.5	8,242	46.2	38.8
≥ 0.4 to <0.5	218	5.5	2,423	13.6	5.2
<0.4 (below LRP)	195	4.9	1,684	9.4	2.4

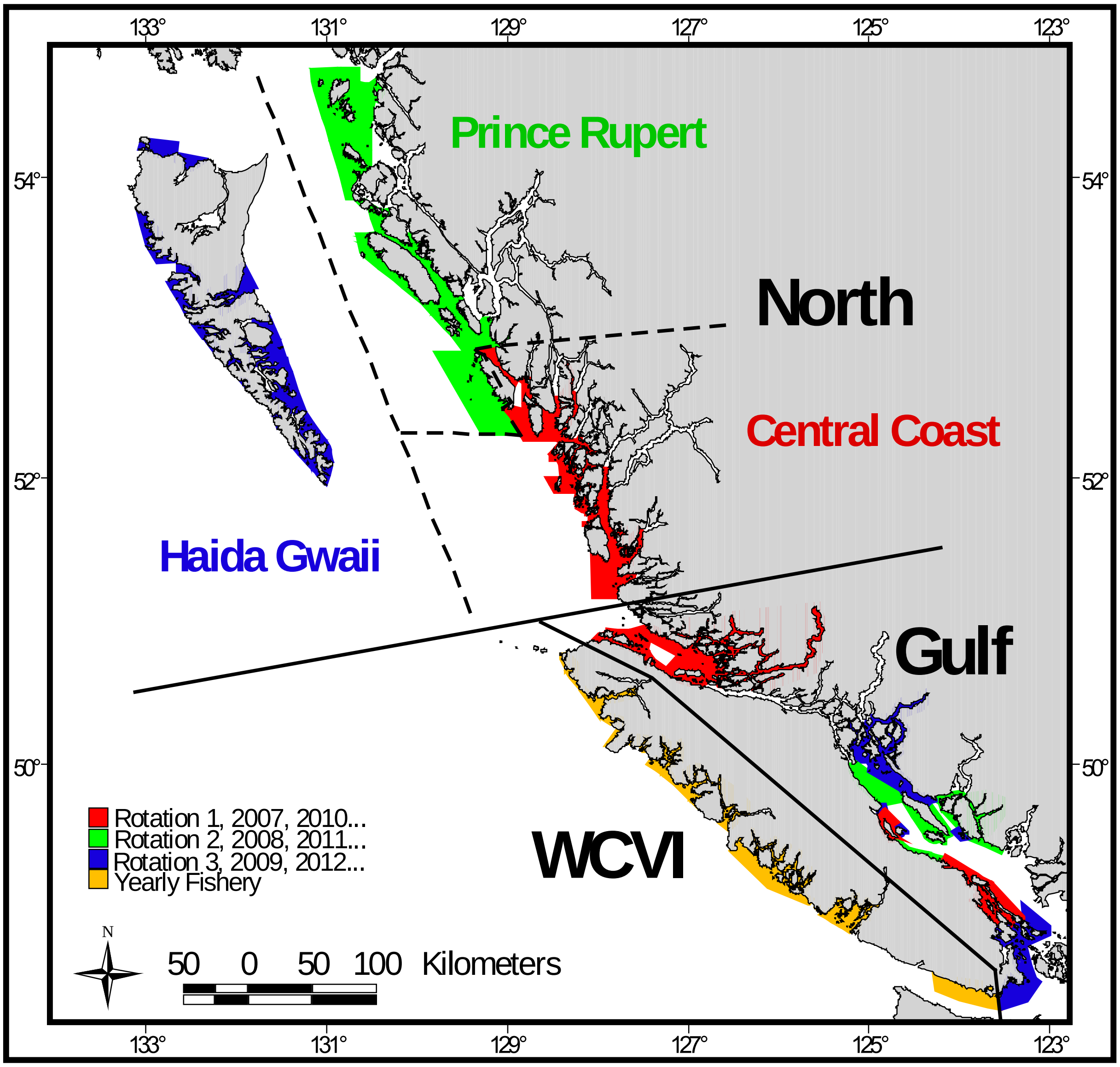


Figure 1: Map of British Columbia showing the location of the five geographical regions for the Geoduck fishery. WCVI = West Coast of Vancouver Island. Gulf = Inside Waters.

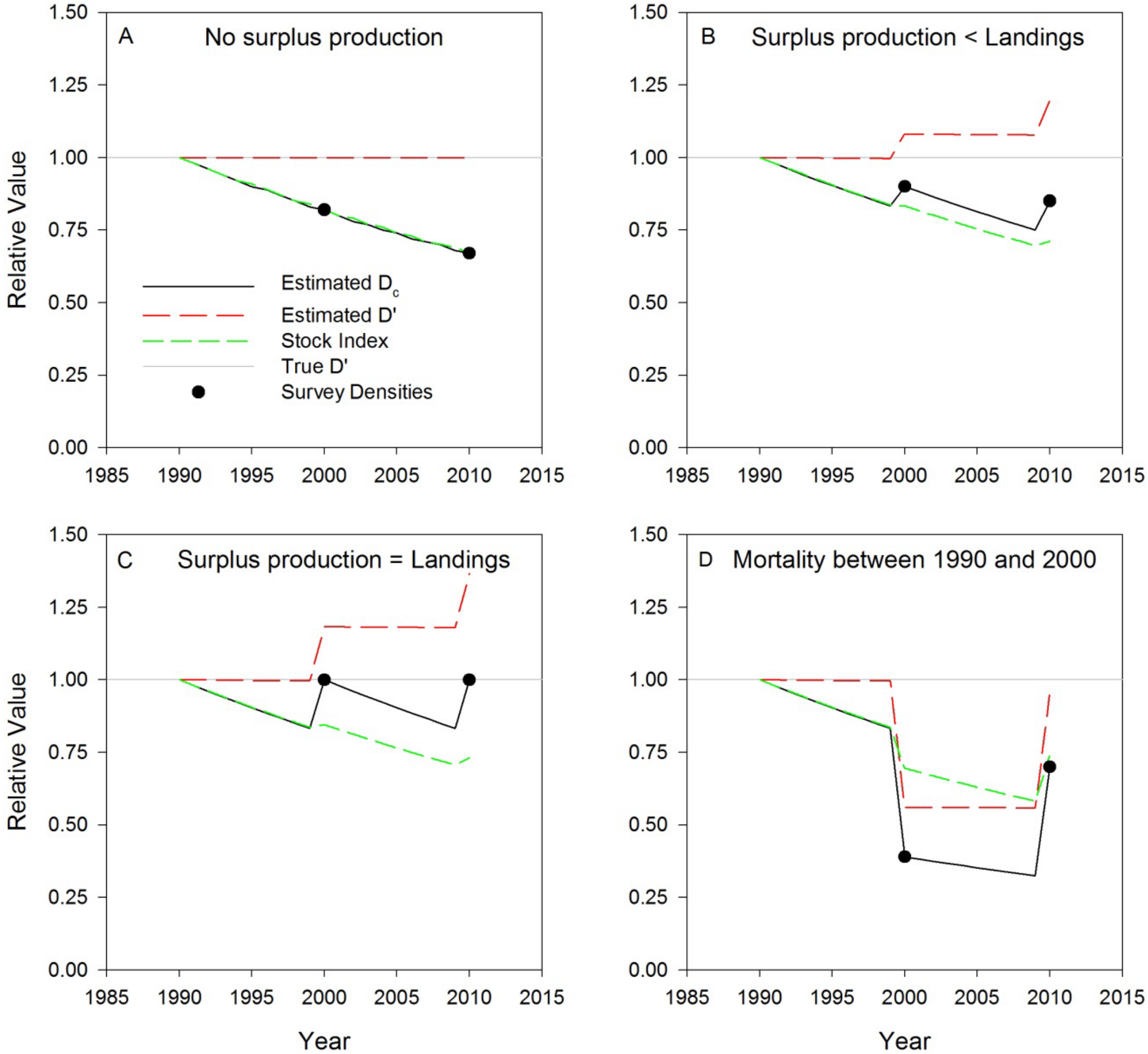
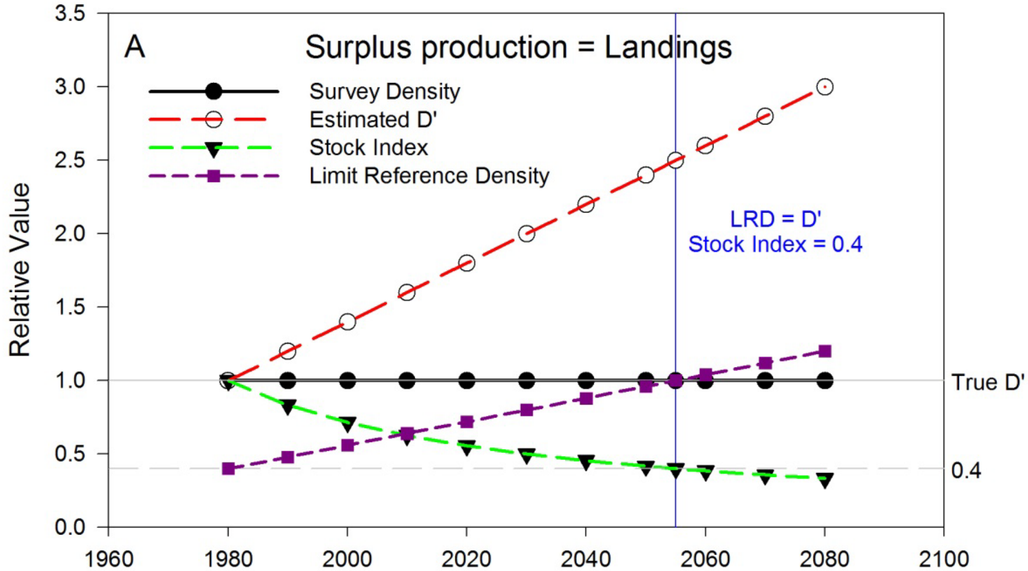


Figure 2: Simulations of estimated Geoduck current density (D_c), unfished exploitable density (D') and stock index, using various surplus production scenarios, over a 20 year period using the current method of estimating D'. Actual unfished exploitable density set to 1.0 in 1990, and beds surveyed in 2000 and 2010. D_c decreases between surveys because of harvest (harvest rate set at 2% of D_c). A- Surplus production = 0, assumption under the current model. B- If some surplus production occurs between surveys, estimate D' increases after each survey and discrepancies between estimated stock index (green line) and true stock index (black line) appear. C- Surplus production = landings, or, survey density constant over time, produces similar results to B but with greater increase in D' and greater discrepancies between true and estimated stock index (black and green lines respectively). D- If net mortality occurs between 1990 and 2000, then D' after the 2000 survey is under-estimated and stock index over-estimated.



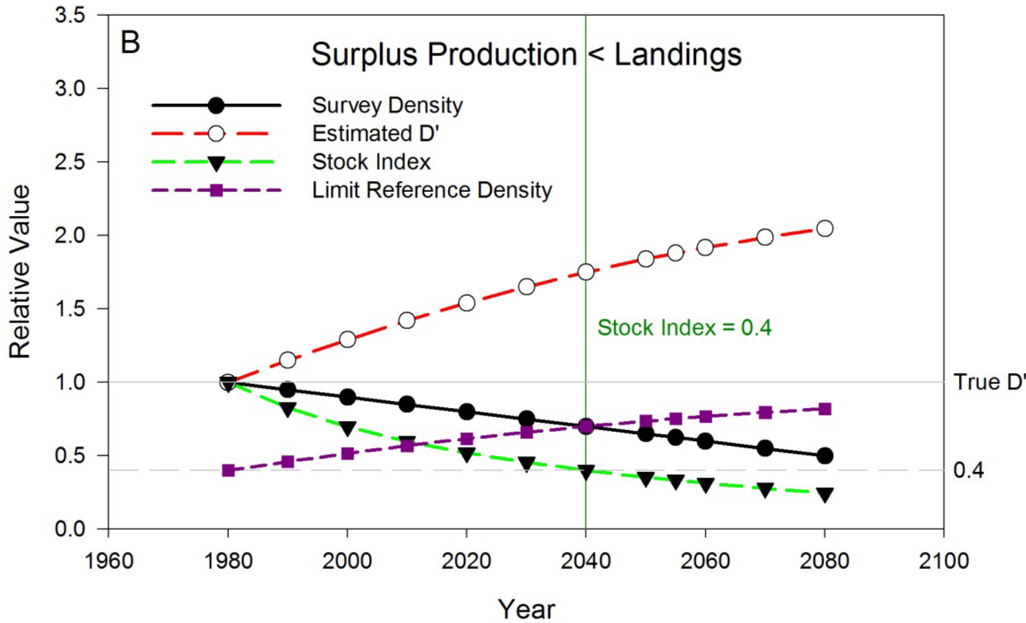


Figure 3: Long range simulations of estimated Geoduck survey density, unfished exploitable density (D'), stock index and limit reference density (LRD), using two surplus production scenarios and the current method of estimating D'. Actual unfished exploitable density set to 1.0 in 1990, and beds surveyed every 10 years thereafter. Harvest set at 2% of latest survey estimate. Black line also represents true stock index. A- If surplus production = landings, survey density remains constant over time, D' and LRD increase over time so that after 75 years, stock index = 0.4 and LRD = 1.0. B- If surplus production is less than landings, the LRP is reached sooner (stock index = 0.4) because survey density decreases, but LRD increases slower.

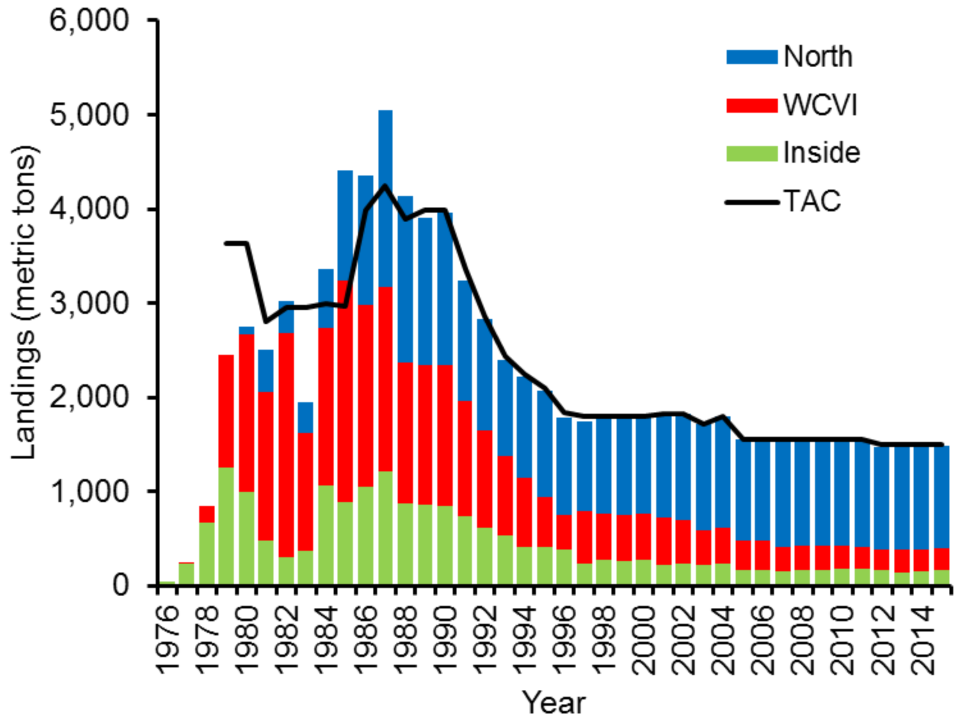


Figure 4: Landings history of the BC Geoduck fishery, in metric tons, by region. TAC = Total Allowalable Catch, WCVI = West Coast of Vancouver Island.

14 APPENDIX 1: LIST AND DEFINITION OF VARIABLES AND THEIR UNITS

List of variables, their definitions and units; sorted alphabetically.

Variable	Definition	Units
A	Area of a Geoduck bed or sub bed	m^2
a_n	Area ratio of sub-bed number *n*	
a_{SubBed}	Area ratio of a sub-bed, equal to area of sub-bed divided by total area of the bed	
B'	Unfished exploitable biomass estimate for a Geoduck bed or sub-bed	kg
B_c	Current biomass estimate for a Geoduck bed or sub-bed	kg
B_s	Survey-based estimate of biomass for a Geoduck bed or sub-bed	kg
B_{s1}	Biomass estimate from first survey or a Geoduck bed	kg
B_{sl}	Biomass estimate from last survey or a Geoduck bed	kg
D'	Unfished exploitable density estimate for a Geoduck bed or sub-bed	Geoducks/m^2
$\overline{D_{P_R}}$	Average surplus production density per year for region R	Geoducks/m^2/year
D_r	Density of Geoducks removed by harvest before a survey	Geoducks/m^2
$\overline{D'_R}$	Average regional unfished exploitable Geoduck density for region *R*	Geoducks/m^2
D_{rb}	Density of Geoducks removed by harvest between surveys	Geoducks/m^2
D_s	Survey density estimate for a Geoduck bed	Geoducks/m^2
D_{s1}	Density estimate from first survey of a Geoduck bed	Geoducks/m^2
D_{s2}	Density estimate from second survey of a Geoduck bed	Geoducks/m^2
I_{SubBed}	Stock Index for a Geoduck sub-bed, ratio of sub-bed B_c to B'	
L_{b1989}	Landings on a geoduck bed before 1989	kg
L_{bs}	Landings before a survey for a Geoduck bed or sub-bed	kg
L_{bs1}	Landings before the first survey of a Geoduck bed	kg
L_j	Landings between first and last survey of a Geoduck bed, during time interval *j*	kg
L_{ps}	Landings post-survey for a Geoduck bed or sub-bed	kg
L_{ps_0}	Landings post-survey assigned to sub-bed number 0	kg
L_{ps_n}	Landings post-survey assigned to sub-bed number *n*	kg
L_{rb}	Landings between surveys for a Geoduck bed	kg
L_t	Total historical landings for a Geoduck bed or sub-bed	kg
$P_{h1\text{-}s1}$	Surplus production estimate between first year harvested and first year surveyed	kg
p_r	Proportion of Geoducks that have recruited to a bed since start of harvest (estimated from biological sample data)	
r	Generic term referring to surplus production rate in hybrid Option 4	kg/year
R_j	Average yearly surplus production rate, during time interval *j* (bed-specific)	kg/year
T_j	Time between first and last survey of a Geoduck bed, during time interval *j*	years
T_1	Time between first survey and first year of harvest	years
W	Mean weight of Geoducks for a bed or sub-bed	kg
Y_{h1}	Year a Geoduck bed was first harvested	
Y_{s1}	Year a Geoduck bed was first surveyed	