UPDATED REFERENCE POINTS AND HARVEST OPTIONS FOR THE GIANT RED SEA CUCUMBER (*APOSTICHOPUS CALIFORNICUS*) FISHERY IN BRITISH COLUMBIA USING DATA FROM EXPERIMENTAL FISHING AREAS

Giant Red Sea Cucumber (Apostichopus californicus). Photo credit – Pauline Ridings.

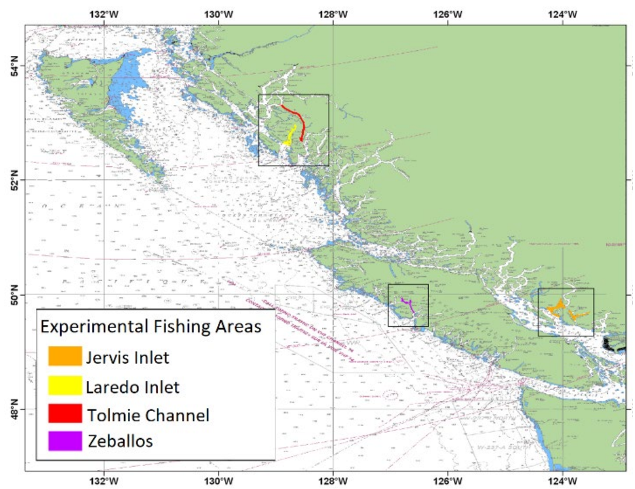


Figure 1. Location of Experimental Fishing Areas on the coast of British Columbia.

Context:

The Giant Red Sea Cucumber (Apostichopus californicus) fishery in British Columbia (BC) is managed using a rotational triennial harvest of ~10% of current biomass in some Quota Management Areas and an annual harvest of 2.2-4.2% in others. This adaptive management strategy is derived from analyses of harvest data, density survey data and experimental fishing area (EFA) data from 1998-2007.

Fisheries and Oceans Canada (DFO) Fisheries Management has requested that Science Branch provide updated estimates of harvest rates, Limit Reference Point (LRP) and Upper Stock Reference (USR) using the full 1998-2015 time series of Experimental Fishing Area (EFA) data. This report will accordingly support management of the commercial sea cucumber fishery by updating harvest advice and reference points, bringing it further into alignment with the Precautionary Approach Framework and the Fish Stocks Provisions in the revised Fisheries Act.

This Science Advisory Report is from the April 5-6, 2022 regional peer review of the Update to reference points and harvest advice for the commercial Sea Cucumber (Apostichopus californicus) Fishery in British Columbia. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

SUMMARY

- The Giant Red Sea Cucumber, *Apostichopus californicus*, is the subject of a commercial dive fishery (85 licences) in British Columbia, Canada (DFO 2022).
- Despite considerable research, the life history of this species is poorly understood, and many biological parameters cannot currently be estimated, preventing the use of typical fisheries models. As a result, four Experimental Fishing Areas (EFAs) were established in BC in 1998 to study the effects of harvest on sea cucumber densities.
- After 10 years, the EFA data were analyzed, a latent productivity model was developed, and recommendations were made regarding harvest rates and provisional reference points (Hand et al. 2009).
- The EFA project continued until 2015, generating another 8 years of data.
- The present document updates harvest advice based on the original latent productivity model (with some updates) and the full time series of EFA data, and also updates reference points.
- It is recommended to continue using 0.01 quantiles of the estimated sustainable harvest amounts as per Hand et al. (2009). Sustainable harvest amounts are provided in Table 1 for a variety of harvest strategies and post-harvest stock level objectives. For example, for a post-harvest stock level of 0.6 B_0 the sustainable annual harvest amount ranges from 2.0 - 8.0% of pre-harvest biomass (pre-harvest biomass is the biomass estimated from the most recent survey data). Harvest amounts for other post-harvest stock levels and harvest intervals are presented in Table 1. The upper ranges of the harvest amounts from the four EFAs may only be appropriate for areas with high productivity.
- The recommended coast wide Limit Reference Point is 0.029 sea cucumbers m^{-2} on sea cucumber habitat (spatial) and the Upper Stock Reference Point is 0.038 sea cucumbers m^{-2} on sea cucumber habitat (spatial). Reference points are expressed in spatial density units because this unit of measurement is independent of transect length and therefore more biologically meaningful and comparable among areas.
- The sea cucumber stock status will be assessed against the LRP and USR using a new coast wide multispecies benthic invertebrate survey that has been recently developed in a separate Canadian Science Advisory Secretariat (CSAS) process[1].
- It is recommended that future research consider the drivers of variable productivity, source/sink dynamics, Sea Otter (*Enhydra lutris*) impacts and whether coast wide reference points are appropriate. Future work comparing the recommended empirical reference points to B_{MSY}- or B_0-based reference points developed through data-rich methods could also be explored.

[1] Lochead, J., Schwarz, C.J., Rooper, C., and Bureau, D. Recommendations on the design of a multispecies benthic marine invertebrate dive survey program for stock monitoring in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. In prep.

BACKGROUND

The Giant Red Sea Cucumber, *Apostichopus californicus* (formerly *Parastichopus*) (Stimpson 1857), is a valued marine resource.

Although there are 47 species of sea cucumbers (Class Holothuroidea) in BC waters (Lambert 1997; Lambert and Boutillier 2011), *A. californicus* is the only one subject to a commercial fishery. Its history of commercial exploitation dates to 1971, when landings were first recorded, however its use as a traditional food by coastal First Nations dates back countless generations (Stephenson et al. 1995). The commercial fishery is a limited entry fishery with 85 licence eligibilities and is summarized in the Integrated Fisheries Management Plan (IFMP) (DFO 2022). The fishery commences in October and is scheduled for 8 weeks, and sea cucumbers are hand-picked while SCUBA diving. The commercial fishery operates under a Total Allowable Catch (TAC), with Individual Quotas (IQ) and Area Quotas. All commercial landings are tracked using a coast wide Dockside Monitoring Program (DMP). Other management measures in place for the fishery include area licensing and a precautionary harvest strategy. The commercial fishery takes place along portions of the British Columbia coast in units called Quota Management Areas (QMA) which are comprised of Areas and Subareas, as described in the Pacific Fishery Management Area Regulations. The fishery is currently managed using a rotational triennial harvest of ~10% of current biomass in some Quota Management Areas and an annual harvest of 2.2-4.2% in others.

In 1995, the first stock assessment and quota options paper for the *A. californicus* fishery was produced (Phillips and Boutillier 1998), and the process highlighted a number of knowledge gaps and data deficiencies. This led to an alignment with Perry et al.'s (1999) recommended framework for managing new and developing invertebrate fisheries. The framework for emerging invertebrate fisheries involves a phased approach, wherein Phase 0 collects existing information, Phase 1 collects new information, and Phase 2 involves fishing for commerce (Perry et al. 1999). At the beginning of Phase 1 in 1998, commercial harvest was restricted to only 25% of the coast while additional information was collected. Phase 1 lasted 10 years, with the data from fisheries-dependent and -independent research, such as harvest data, surveys, EFAs and biological sampling, culminating in the development of a latent productivity model and fishery recommendations (Hand et al. 2009). The *A. californicus* commercial fishery then entered Phase 2 in 2008. Since that time, large portions of the coast have been re-opened following targeted opening surveys. Once the re-opening process is complete it is expected that less than 60% of the coast will be open to commercial harvest.

This advisory report was produced at the request of DFO Resource Management, with the overall goals of updating the model, comparing model outputs using the 1998-2007 subset and the full 1998-2015 EFA dataset, and updating estimates of sustainable harvests, the Limit Reference Point and to identify a range for the Upper Stock Reference, as defined by DFO's Precautionary Approach (PA) policy (DFO 2009) and defined in the Terms of Reference (TOR). Instead of a range for the USR a novel technique was developed. The upper 99% CI on the minimum population density averaged across EFAs – which came out as a point estimate.

Biology

A. californicus is the largest species of sea cucumber in BC and is distributed from the intertidal to ~250 m depth (Lambert and Boutillier 2011). Numerous life history knowledge gaps complicate the assessment and management of this species. Notably, there is no practical method to age *A. californicus.* Furthermore, *A. californicus* is a soft-bodied organism that can change body dimensions by absorbing or expelling water and contracting muscles in the body wall. This species also reabsorbs and regenerates viscera and changes body wall thickness seasonally (Fankboner and Cameron 1985). Spatial and temporal variation in size and growth make this species difficult to size consistently and preclude the use of size-based proxies for age. Adults are relatively sedentary, moving less than 4 m day^{-1}, although some sources suggest that they undertake seasonal depth migrations (Lambert 1997; Hand and Rogers 1999). A long larval duration (51 to 125 days) (Strathman 1978; Cameron and Fankboner 1989) likely plays a more important role in genetic mixing and dispersal, but source/sink dynamics are largely unknown (Xuereb et al. 2018). Finally, juveniles are rarely observed during surveys (Bazinet et al. *In press*), suggesting an unknown ontogenetic shift in crypsis or habitat. All of these features limit the collection of typical fisheries biology parameters and the inclusion of life-history data in fisheries models.

ANALYSIS

Methods

The Model

The Bayesian latent productivity model used to inform this advice is an update of the one used in Hand et al. (2009) and Hajas et al. (2011). In the model, productivity is a function of current biomass. Productivity, or more precisely “latent productivity”, is the rate at which biomass increases in the absence of harvests. A pervasive (Ricker 1975; Hilborn and Walters 1992) and simplifying assumption is that productivity can be determined from the current stock level, i.e., pre-harvest biomass.

Harvest data from the EFAs were represented as a series of instantaneous harvest events in the model. The more traditional approach is to approximate harvest as a continuous process, however that approach was not used in these analyses because in the case of the EFAs and BC’s sea cucumber fishery in general, harvest at any location occurs during very brief period. Productivity is therefore approximated as a process that stops momentarily prior to harvest and resumes immediately after.

The model was ported to a more modern platform, some of the numeric methods were updated and some minor errors were corrected. Overall, running the new model had only minor changes to the productivity values.

Reference Points

A common limit reference point, especially useful for data poor stocks, is the lowest historical estimated stock-level from which recovery has been observed (Marentette et al. 2021). The most common measure of stock-level for this type of reference point is biomass ($B_{recover}$). Density (D) is an alternate indicator of abundance that is measured directly from surveys and is especially important for successful reproduction of broadcast spawning marine invertebrates (Uthicke et al. 2009; Read et al. 2012). $D_{recover}$ can therefore be defined as the lowest density observed in the EFA time series, from which recovery was observed. For selecting the LRP, recovery was defined as when the 95% confidence intervals of a subsequent density in the timeline was within the range of the first survey estimate (i.e. the proxy for the unfished density) and was above, and not overlapping, the 95% confidence intervals of the lowest density in the timeline.

Once the lowest mean density observed in each EFA time series had been identified, survey data from later years were reviewed to determine whether densities recovered from these minima on any subsequent surveys. Minima that met the definition of recovery were averaged to determine a coast wide LRP.

Results

Harvest Advice

Maximum sustainable harvests are presented for various harvest strategies, combining harvest intervals of 1 to 5 years with different minimum equilibrium stock level thresholds (minimum observed, 0.50 B_0, 0.60 B_0, and 0.80 B_0) and estimates of either pre-harvest (i.e., current) or virgin biomass. Combinations of all these strategies are presented in tabular format in the Research Document[2] to be considered and implemented at the fishery managers' discretion Since virgin biomass can be difficult to estimate and given that the minimum stock level thresholds (based on the lower range of data) are less conservative than those used previously in Hand et al. (2009), it is recommended that maximum sustainable harvests are based on pre-harvest levels required to maintain a minimum stock level of 0.60 B_0. Considering the uncertainty in data, models, and the environment, it is recommended that the 0.01 quantiles be considered for setting harvest rates (Table 1). This yields a recommended harvest rate of 2.0 to 8.0% of pre-harvest biomass in an annual fishery or 5.7 to 18.8% of pre-harvest biomass in a triennial fishery. Given that the range represents variability across EFAs, the higher percentages would only be suitable for productive areas and therefore should be employed with caution. Further precaution is incorporated in the assessment system by continuing to use the lower 90% confidence interval of estimated mean density to estimate biomass and for implementing reference points.

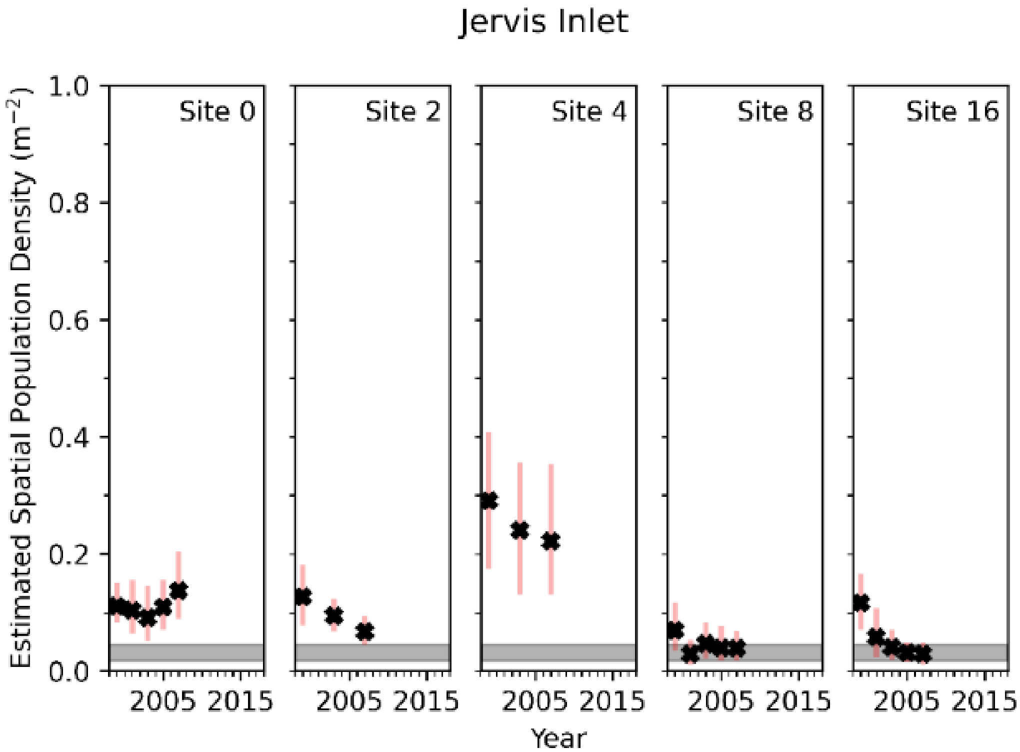
Table 1. The 0.01 quantiles on sustaining harvest amounts as a fraction of pre-harvest (i.e., current) biomass for combinations of harvest intervals and equilibrium post-harvest stock levels (reference points from Hand et al. 2009), using the full dataset (1998-2015).

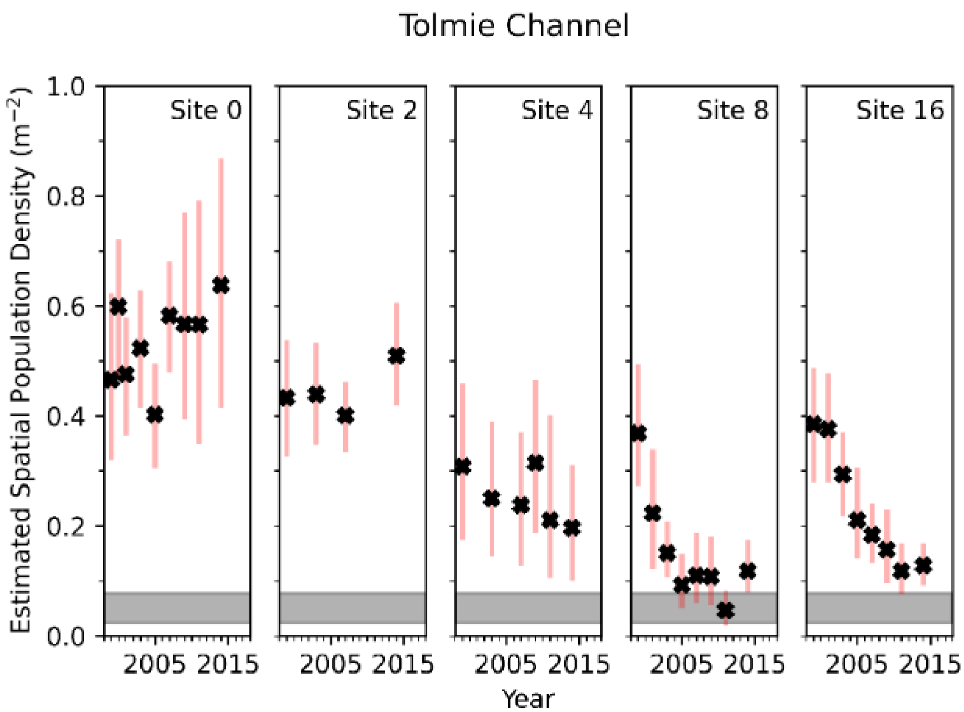
Post-Harvest Target Stock Level (Fraction of Virgin Biomass)	Harvest Interval (years)	EFA			
		Jervis Inlet	Laredo Inlet	Tolmie Channel	Zeballos
0.5	1	0.111	0.066	0.064	0.029
0.5	2	0.191	0.123	0.117	0.055
0.5	3	0.251	0.172	0.162	0.079
0.5	4	0.298	0.214	0.200	0.102
0.5	5	0.335	0.251	0.232	0.123
0.6	1	0.080	0.051	0.044	0.020
0.6	2	0.140	0.096	0.083	0.039
0.6	3	0.188	0.135	0.115	0.057
0.6	4	0.226	0.168	0.144	0.074
0.6	5	0.256	0.197	0.169	0.090
0.8	1	0.034	0.024	0.018	0.008
0.8	2	0.062	0.046	0.033	0.016
0.8	3	0.084	0.064	0.048	0.024
0.8	4	0.103	0.081	0.061	0.031
0.8	5	0.119	0.095	0.072	0.038

[2] Table 2, 4-7 in Hajas, W., Hansen, S.C., and Lochead, J. 2022. Updated Reference Points and Harvest Options for the Giant Red Sea Cucumber (*Apostichopus californicus*) Fishery in British Columbia using data from Experimental Fishing Areas. CSAP Working Paper 2017INV01.

Reference Points

Sea cucumbers in British Columbia are considered one coast wide stock with many management subunits (Quota Management Areas) and will accordingly be subject to one LRP. In the 18-year EFA time series, the sea cucumber population at several sites and several EFAs was observed persisting at low densities, occasionally even increasing from low levels under continued fishing pressure (Figure 2). For example, increases from low densities were observed at Tolmie Channel (Site 8) and Zeballos (Sites 4, 8, and 16). Densities at Laredo Inlet were generally low (the median ranges from 0.40 to 4.73 sea cucumbers m^{-1} or 0.009 to 0.140 sea cucumbers m^{-2}) throughout the time series. In fact, the lowest estimated population density in any of the EFAs over the time series was observed at Site 8 in Laredo Inlet in 2005: 0.40 sea cucumbers m^{-1} or 0.009 m^{-2} (95% CI: 0.12 to 0.83 m^{-1} and 0.003 to 0.018 m^{-2}). Statistically significant recovery from this low density to within the range of the first survey estimate occurred by 2015 when the median density reached 2.05 sea cucumbers m^{-1} or 0.050 m^{-2} (95% CIs: 1.02 to 3.420 m^{-1}; 0.024 to 0.083 m^{-2}), despite an additional harvest event in 2007 (Figure 2). The second lowest population density that showed statistically significant recovery back to within the range of the first survey estimate was observed at Site 8 in Zeballos, where densities dropped to a minimum of 0.900 sea cucumbers m^{-1} or 0.020 m^{-2} (95% CIs: 0.430 to 1.400m^{-1}; 0.010 to 0.040 m^{-2}) in 2008 and recovered to 3.430 sea cucumbers m^{-1} or 0.090 m^{-2} (2.310 to 4.860 m^{-1}; 0.060 to 0.130 m^{-2}) in 2010. The upper 99% CI of the minima are 0.920 m^{-1} or 0.019 m^{-2} at Laredo Inlet and 1.490 m^{-1} or 0.039 m^{-2} at Zeballos. Using the upper limit of the 99% CI provides a high degree of confidence of being above the true minima. There was significant debate in the meeting about the selection of the reference points using only data from Laredo Inlet or also incorporating data from Zeballos. It is recommended that the mean of the upper 99% CI of the minimum spatial estimates from Laredo Inlet and Zeballos is used as the LRP for sea cucumbers, i.e. 0.029 sea cucumbers m^{-2}, as this incorporates additional spatial variability and is more conservative. This value equates to 1.20 sea cucumbers m^{-1} (linear), a value provided here for comparison with previously reported values; however, as noted, it is recommended that the reference points be expressed in units of spatial density because it is independent of transect length and therefore more biologically meaningful and comparable among areas.


Jervis Inlet
Site 0
Site 2
Site 4
Site 8
Site 16
Estimated Spatial Population Density (m^{-2})
1.0
0.8
0.6
0.4
0.2
0.0
2005 2015
Year


Tolmie Channel
Site 0
Site 2
Site 4
Site 8
Site 16
Estimated Spatial Population Density (m^{-2})
1.0
0.8
0.6
0.4
0.2
0.0
2005 2015
Year

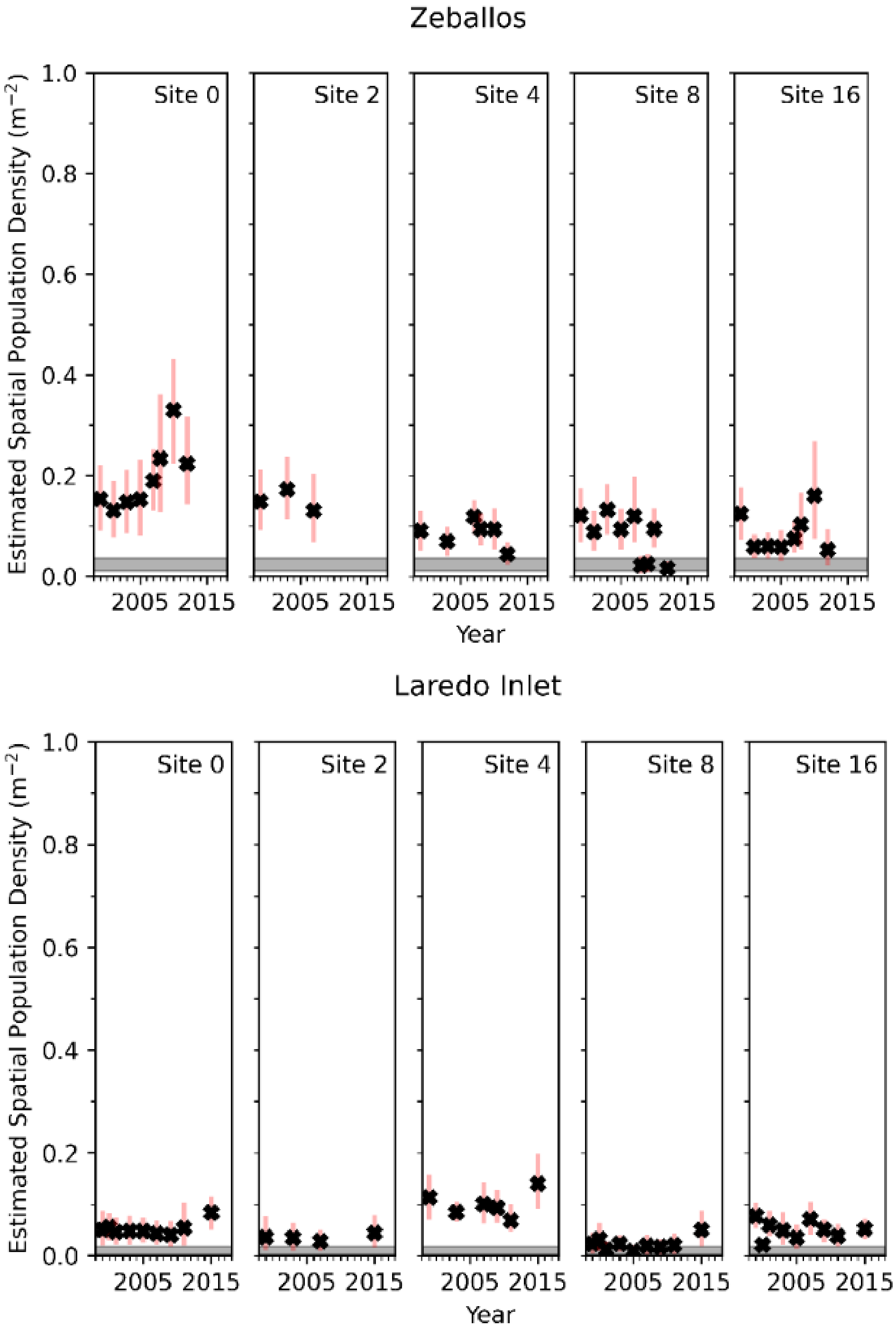


Figure 2. Estimated spatial population densities by EFA, site and year. Pink lines show the 95% confidence bounds on estimated mean spatial population density (m-2), x's show medians, and grey bars show estimated 95% confidence intervals (CI) for the minimum density from each EFA (excluding final density estimates). Zoom into the figure to see the small densities in better detail.

The EFAs show considerable differences in latent productivity and density. In order to incorporate some of this spatial variability into the reference points, it is recommended to set the USR equal to the upper 99% CI on the minimum population density averaged across all four

EFAs. Note that these minima exclude the final survey year, to ensure that stocks persisted following the observed minima. The recommended minima-derived USR is accordingly 0.038 sea cucumbers m^{-2} (spatial). In linear units this value is 1.95 sea cucumbers m^{-1} (linear), and as stated above, it is recommended that the USR be expressed in units of spatial density as the linear value is only relevant to this dataset and cannot be applied to other datasets.

Sources of Uncertainty

Model Uncertainty

As predominantly occurs with mathematical models, the model used to describe the biological system within the EFAs is an approximation of the actual system. Most significantly, the model assumes the system is stationary; the joint distribution of the parameter values does not change with time. Implicitly, this assumption means that changes to the stock levels are entirely attributable to harvest, productivity and random year effects. There is no allowance for declines in stock levels that are not related to the commercial fishery, such as climate change or predation.

Climate Change

Although more research is required to better understand the effects of ocean acidification, the existing evidence shows that there are potential negative direct and indirect effects to echinoderms (Haigh et al. 2015). There are no known studies on ocean acidification effects for the Giant Red Sea Cucumber, however a study on a reef-dwelling sea cucumber species (*Holothuria* sp.) found impaired sperm motility at low pH values (Morita et al. 2010). Declines in sea cucumbers could have a detrimental effect on the nutrient cycling function they provide to ecosystems, however ecosystem-level effects remain unknown. Climate change impacts could be introduced to the model through further research.

$D_{RECOVER}$ Reference Point

The use of $D_{recover}$, the lowest historical density from which recovery has been observed, or its derivations as a limit reference point comes with some uncertainty. Foremost, the assumption of recovery in the future depends on the prevailing conditions at the time. If the future drivers of productivity (e.g., recruitment success, natural mortality) are as good as, or better than, the past drivers of productivity, then it is reasonable to expect a similar recovery. However, if productivity decreases, then recovery becomes more uncertain. It is reasonable to expect a site to recover from $D_{recover}$ if recruitment has not been altered or impaired (i.e., if it is an isolated incident and other areas are unaffected), however it remains unknown what would happen if multiple areas were simultaneously driven to $D_{recover}$ levels. Here, the lowest density from which recovery was observed occurred in the Laredo Channel EFA. The LRP is more conservatively derived from an average of two EFAs with the lowest overall densities (Laredo Channel and Zeballos), while still subject to ongoing fishing pressure (Laredo Channel only), and at a point in time when predation by *Pycnopodia* sea stars would also have been occurring (i.e., before the onset of sea star wasting disease, which occurred in 2014-2015 on the central and north coast of BC).

Sea Otters

Ecosystem considerations include potential Sea Otter (*Enhydra lutris)* impacts on invertebrates. Although Sea Otters demonstrate strong prey preferences and tend to target high energy food sources such as sea urchins when they first arrive in an area, once these prey items become depleted, Sea Otters target other species including sea cucumbers (Ostfeld 1982).

CONCLUSIONS AND ADVICE

- It is recommended to continue using 0.01 quantiles of the maximum sustaining harvest amounts in keeping with strategies from Hand et al. (2009). Estimated sustainable harvest amounts are provided in Table 1 for a variety of harvest strategies and post-harvest stock level objectives. The upper ranges of the harvest amounts from the four EFAs may only be appropriate for areas with high productivity.
- It is recommended to use the 0.01 quantiles of the maximum sustainable harvest amounts that are based on pre-harvest (i.e., current) biomass, and are projected to maintain a minimum stock level of 0.60 B_0 or 0.80 B_0.
- Set the coast wide Limit Reference Point of 0.029 sea cucumbers m^{-2} on sea cucumber habitat (spatial) and the Upper Stock Reference Point at 0.038 sea cucumbers m^{-2} on sea cucumber habitat (spatial). Reference points are expressed in spatial density units because this unit of measurement is independent of transect length and therefore more biologically meaningful and comparable among areas.
- It is recommended that an independent scientific survey be used to assess the sea cucumber stock status against the LRP and USR. A coast wide multispecies benthic invertebrate survey is under development in a separate CSAS process.
- Future research could seek to address the drivers of productivity, source/sink dynamics, Sea Otter impacts and whether coast wide reference points are appropriate for this species. Future work comparing the empirical reference points recommended here to more data-rich B_{MSY}- or B_0-based reference points could also be explored as more information becomes available.

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SOURCES OF INFORMATION

This Science Advisory Report is from the April 5-6, 2022 regional peer review on the Update to reference points and harvest advice for the commercial Sea Cucumber (*Apostichopus californicus*) Fishery in British Columbia. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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