STOCK STATUS UPDATE AND HARVEST OPTIONS FOR THE GREEN SEA URCHIN (*STRONGYLOCENTROTUS DROEBACHIENSIS*) FISHERY IN BRITISH COLUMBIA, 2024-2027

CONTEXT

British Columbia's Green Sea Urchin (*Strongylocentrotus droebachiensis*) stock is assessed every three years using the assessment model developed by Perry et al. (2003). The last assessment was conducted in 2021 (DFO 2021a) and was used to inform the Pacific Region's Green Sea Urchin 2021-2024 Integrated Fishery Management Plan (IFMP) (DFO 2021b, 2022, 2023). The present assessment provides updated advice, based on the inclusion of new data, for the development of the next IFMP in 2024 and subsequent IFMPs until spring 2027.

Fisheries and Oceans Canada (DFO) Fisheries Management has requested advice for the Green Sea Urchin fishery in British Columbia (BC), by spring 2024, on the following:

1. Evaluate stock status of Green Sea Urchins in Northeast (Pacific Fisheries Management Areas - PFMAs: 11, 12, and 13) and Southeast Vancouver Island (PFMAs 14, 18, 19, and 20) using provisional reference points and density estimates derived from biological surveys within each management region.
2. Provide the ranges of sustainable harvest options for the commercial harvest regions (PFMAs 11, 12, 13, 14, 18, 19, and 20).
3. Analyze index site survey data (PFMAs 12 and 19) and present the recent trends in the local populations and population structure for Green Sea Urchins.
4. Examine and identify uncertainties in the data and methods.
5. Provide recommendations for additional research or stock assessment programs.

This assessment updates previously published time series data and provides new harvest options for the 2024-2025 to 2026-2027 Green Sea Urchin fishery. Methods remain largely unchanged since 2003 and a Bayesian biomass dynamic model continues to be used in the assessment of BC's Green Sea Urchin stock (Perry et al. 2003, 2006; Zhang and Perry 2005; Waddell et al. 2010; DFO 2015, 2016, 2018a, 2021a). This assessment updates the model results with the most recently available commercial catch (fishery-dependent) and biological dive survey (fishery-independent) information. Provisional reference points compliant with the DFO's Fishery Decision-Making Framework Incorporating the Precautionary Approach (DFO Precautionary Approach; DFO 2009) were established (DFO 2018a) and subsequently implemented in the fishery (DFO 2018b). Using these reference points, Green Sea Urchin stock status can be estimated in the regions of Northeast Vancouver Island (PFMAs 11, 12, and 13) and Southeast Vancouver Island (14, 18, 19, and 20); the two regions where the long-term index sites are located (PFMAs 12 and 19). This Science Response Report results from the May 23, 2024 regional peer review on Stock Status Update and Harvest Options for the Green Sea Urchin (*Strongylocentrotus droebachiensis*) Fishery in British Columbia, 2024-2027.

BACKGROUND

The Green Sea Urchin (Figure 1) is a benthic marine invertebrate with a wide geographic distribution, occurring in cool temperate circumpolar waters of the Atlantic and Pacific Oceans (Scheibling et al. 2020). In the Pacific region, they occur from northern Washington State, north through to the Aleutian Islands, Alaska, south through Kamchatka, Russia, and Hokkaido, Japan and west to the Korean Peninsula. Green Sea Urchins occur from the intertidal zone to depths of over 140 metres (Scheibling et al. 2020). Their preferred habitat is rocky, gravel, or shell substrates. Kelp and other marine algae are their principal food (Scheibling et al. 2020), and they are an important food source for sea stars, crabs, large fish, and Sea Otters (*Enhydra lutris*) (Estes and Duggins 1995; Scheibling et al. 2020).

Figure 1. A Green Sea Urchin (Strongylocentrotus droebachiensis) wearing an empty urchin test as camouflage. Photo courtesy of Pauline Ridings.

Green Sea Urchins have separate sexes and are broadcast spawners. Spawning is seasonal and varies by location, occurring from February to March in BC (Strathmann 1978). The larval period ranges from 7 to 22 weeks (Strathmann 1978). In southern BC, Green Sea Urchins reach sexual maturity at a Test Diameter (TD) of about 25 mm (Waddell et al. 2002) and the minimum legal harvest size is 55 mm TD. In Alaska, these TDs correspond to 2-3 year old and 4 year old urchins, respectively (Munk 1992). Growth is variable and is dependent on food supply and environmental conditions (Foreman and Lindstrom 1974; Scheibling et al. 2020).

Green Sea Urchins are the target of commercial, recreational, and traditional Food, Social, Ceremonial (FSC) fisheries. Recreational and FSC harvest landings are unknown. The commercial harvest in BC is hand-picked by SCUBA divers working from small vessels. Divers harvest when and where roe quality is best. The commercial fishery is managed with a minimum 55 mm TD size limit, license limitation, limited area openings, area quotas, and individual quotas. Details of the management of the fishery are provided in the most recent IFMP (DFO 2023).

BC's Green Sea Urchin commercial fishery currently takes place in two regions of the coast: Northeast Vancouver Island (NEVI), which includes PFMAs 11, 12, and 13, and Southeast Vancouver Island (SEVI), which includes PFMAs 14, 18, 19, and 20 (Figure 2). PFMA 14 was added to the SEVI because it is likely exposed to similar prevailing ocean currents and conditions as PFMAs 18, 19, and 20 (Dosser et al. 2021). The NEVI and SEVI regions are assessed separately. Most previous assessments included only PFMAs 12, 13, 18, and 19. PFMAs 11 and 20 were re-opened to commercial harvest in 2016 after being closed since 2006 due to low market demand, and were included in the 2018 assessment (DFO 2018a). PFMA 14 was opened to experimental harvest in 2021-22 fishing season and fishery-dependent data from PFMA 14 was added to the SEVI region as part of this 2024 assessment. Fishery-independent surveys are limited to PFMAs 12 and 19, which are now conducted on a three-year rotation. The first year of this new rotation was 2018 and 2020 for PFMAs 12 and 19, respectively; these surveys are not conducted during the same year. Biological trends of the population and its structure will be reported from areas 12 and 19 only.

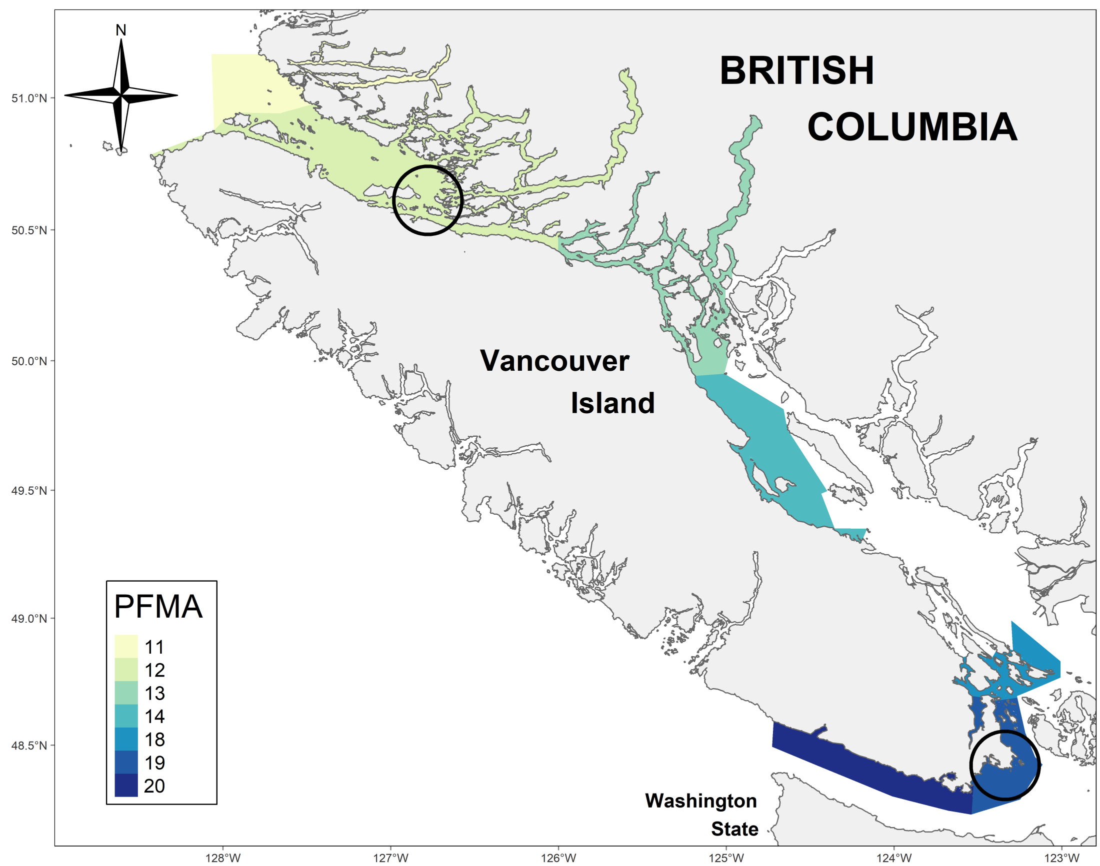

Figure 2. Map of southern British Columbia showing the seven Pacific Fisheries Management Areas (PFMAs 11, 12, 13, 14, 18, 19, and 20) assessed in the Green Sea Urchin stock status update. Black circles denote biological dive survey locations, i.e. fishery-independent data collection areas. PFMA 14 excludes sub-area 14-3.

Stock Assessment and Harvest Options: Data Sources and Uses

Two sources of data are used in this assessment: (1) fishery-dependent data (i.e., commercial fishery data); and (2) fishery-independent data (i.e., standardized biological dive survey data). The Catch Per Unit Effort (CPUE; kg of urchins harvested per diver hour), total catch, and fishery-independent biomass (kg/m^2) data are used to model harvest options. The relationship between CPUE (log) and survey-derived biomass (log) is approximately linear, providing evidence that CPUE can be used as a biomass index (Zhang and Perry 2005).The density, biomass, and size distribution data collected during fishery-independent surveys are used to assess trends in the Green Sea Urchin populations within PFMAs 12 and 19. The fishery-independent density data are also used to assess stock status in the Northeast and Southeast Vancouver Island management regions. The data from both sources are presented, updated, and discussed in this assessment.

Fishery-Dependent Data

Catch and effort data were derived from harvest logbooks, validation logs and, prior to 1995, from sales slip data. Catch and effort data from the early years of the fishery (1987-1995) are uncertain because of the boom nature of the fishery, variable recording diligence, and different fishing strategies (Perry et al. 2003). Catch per unit effort (CPUE) is one of the main variables of fishery-dependent data used in the Bayesian model that estimates harvest options. In this case, CPUE is calculated by dividing the catch (landings) by the effort (diver hrs.) expended to collect or catch urchins. Effort in this fishery is the number of diver hours expended to collect the landed catch (Figures 3). If effort increases, but catch or landings remain stable this can lead to decreasing CPUE which can indicate that a stock is in decline. Effort in this fishery has remained relatively stable since fishery management reforms in 1995 (Figures 3), but as mentioned there are significant uncertainties in the pre-1995 effort data. To address uncertainties associated with the CPUE data, the Bayesian model used to generate harvest options for this fishery incorporates larger uncertainties in catch and effort data for the developing years of the fishery, as well as random variability in CPUE. Median CPUE values with associated standard errors were chosen to represent CPUE trends because medians are more robust to outliers in effort data than means (Perry and Waddell 1998).

Perry et al. (2002) described three periods in the history of the fishery: the developing period (1987 to 1990), the crisis period (1991 to 1993), and the rebuilding period (1994 to 2002) (Figures 3, 4, 5; DFO (2018a)). Landings below the Total Allowable Catch (TAC) for fishing seasons 2004-2005 to 2011-2012 (Figure 5) were due to low market demand and are not considered to be reflective of stock status. Markets have improved recently and the TAC was almost fully achieved in the 2020-21, 2021-22, and 2022-23 seasons (Figure 5). Although a slight decline in median CPUE has been observed since the 2012-13 season, overall, median CPUE in recent years has been higher relative to the onset of the fishery. Trends in median CPUE between the two fishing regions were similar from 2015 to 2021, but appear to diverge in the 2021-22 and 2022-23 seasons (Figure 4). This divergence is likely due to slight increases in effort in SEVI resulting from the addition of TAC to parts of PFMA 14 since 2021. Since the 2021-22 season, effort and the resulting CPUE increased slightly in both regions (Figures 3, 4) but were within the post-1995 range. These slight increases in CPUE likely reflect the overall increases in TAC in the fishery since the 2021-22 season.

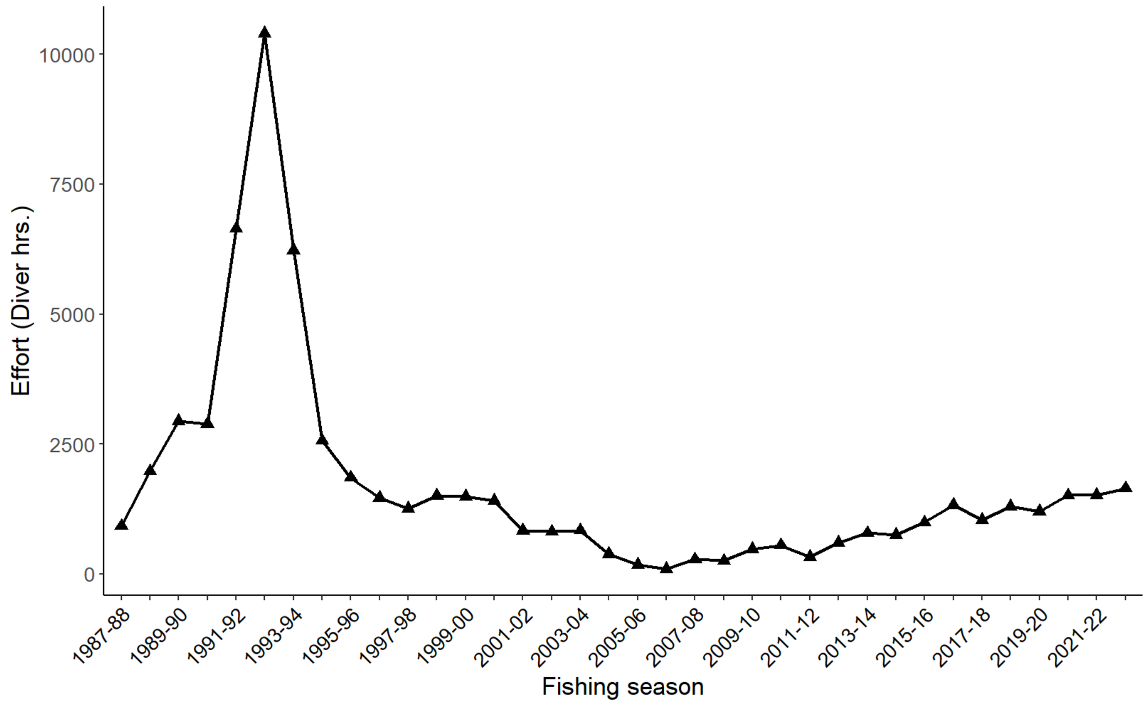

Figure 3. Total effort (diver hours) for Green Sea Urchin harvesting in PFMAs 11, 12, 13, 14, 18, 19, and 20 combined by commercial fishing season from the 1987-88 to the 2022-23 fishing seasons.

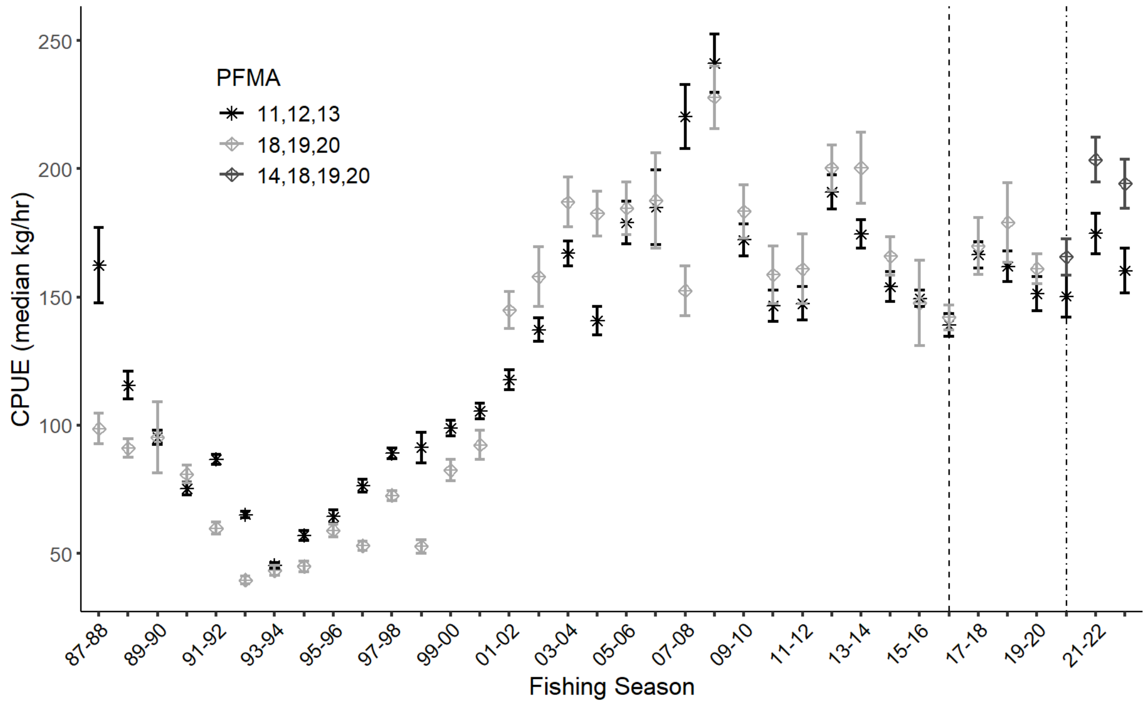

Figure 4. Median catch per unit effort (CPUE) (kg/hr) ± 1 standard error for PFMAs 11, 12, and 13 and 14, 18, 19, and 20 by commercial fishing seasons from the 1987-1988 fishing season to the 2022-2023 fishing season. In some cases, the standard errors are small and appear within the markers. See legend at top left for symbol descriptions. The dashed line represents the addition of PFMAs 11 and 20 to the NEVI and SEVI assessment, respectively. The dot dashed line represents the addition of PFMA 14 to the SEVI assessment.

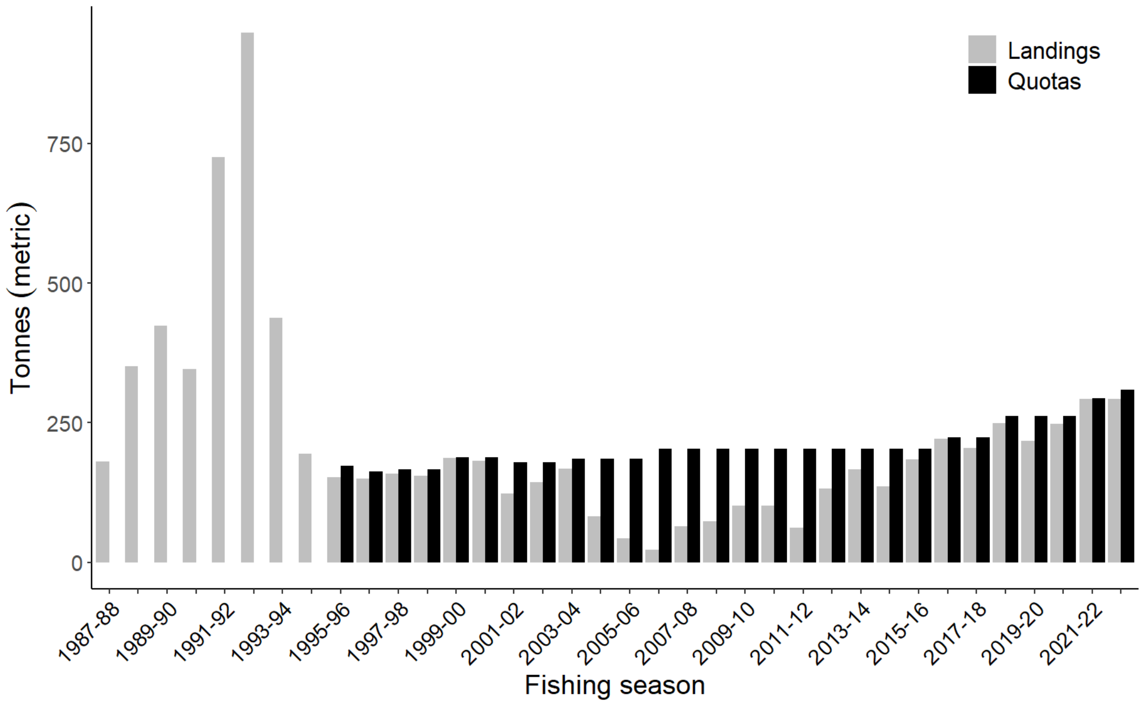

Figure 5. Total landings (catch) of Green Sea Urchins (from sales slip data up to 1994, then from harvest and validations logs) and quota (Total Allowable Catch: TAC, from inception of individual quotas and dockside validation in 1995 onwards) in metric tonnes for commercial fishing seasons 1987-1988 to 2022-2023, in PFMAs 11, 12, 13, 14, 18, 19, and 20.

Fishery-Independent Data

Fishery-independent dive surveys have been conducted jointly by the Department of Fisheries and Oceans Canada (DFO) and the Pacific Urchin Harvesters Association (PUHA)[1]. In recent years, divers from the Sc'ianew (Beecher Bay) First Nation have also participated in PFMA 19 surveys. The main objective of the surveys is to monitor Green Sea Urchin populations in the areas of BC's coast that are open to commercial harvest. See DFO (2015) and Waddell et al. (2010) for detailed descriptions of the survey protocol.

Surveys in PFMA 12, NEVI have been conducted since 1995 and contain the longest data series in this assessment (Waddell et al. 1997, 2002; Waddell and Perry 2005, 2006, 2007, 2012) (Figure 2). The survey area in Haro Strait, in PFMA 19 on Southeast Vancouver Island has been surveyed since 2008 (Waddell 2017) (Figure 2). Since the last stock status update (DFO 2021a), one fishery-independent survey was done within each management region, i. e. PFMA 12 (September 2021) and PFMA 19 (February/March 2023).

Mean densities and their associated confidence bounds were historically estimated from survey data using the Green Sea Urchin Analysis Program (GUAP) (Lochead et al. 2015). Since 2021, the GUAP program has been translated into the R statistical programming language (Meghan Burton, Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, BC) and fishery-independent estimates from 2021 onwards were derived from this translation. Analyses were

[1]In 2015, the West Coat Green Sea Urchin Association dissolved and members joined the Pacific Urchin Harvesters Association (PUHA).

conducted in the R version 4.3.1 (Schauberger and Walker 2022; R Core Team 2023; Ripley and Lapsley 2023; Wickham et al. 2023; Wickham and Henry 2023).

The individual weights of measured urchins were estimated from an allometric relationship that was developed from data collected from the northeast and southeast regions of Vancouver Island during surveys from 1996 to 2010 (Lochead et al. 2015). From 2002 to 2010, biological samples were collected during the surveys and provided length-weight data. For these years, parameter values were estimated separately for each survey using data from biological samples taken that year (Waddell and Perry 2005, 2006, 2007, 2012). Biological sampling was discontinued in 2011, after which all available length-weight data were pooled to estimate the allometric parameters for surveys where no length-weight data were collected. The sample size of the pooled data was 3706, from 69 survey/index site/year combinations conducted in areas open to commercial harvest (PFMAs 12, 18, and 19). The corresponding mean weight-at-length was estimated using the equation for the mean of a lognormal distribution (Gelman et al. 2004):

$$\overline{W} = exp\left(-6.866 + 2.728 * log(TD) + \frac{0.160^2}{2}\right)$$

or,

$$\overline{W} = 0.001042 * TD^{2.728} * 1.013$$

For each transect, the mean weight and proportion of legal- (Test Diameter; TD $\geq$ 55mm) and sublegal-sized (TD $<$ 55mm) urchins were estimated from TD measurements recorded in the measured quadrats (see survey protocol, DFO (2015); Waddell et al. (2010)). These means were then applied to urchins from the other non-measured (count) quadrats. Based on this analysis, the density and biomass could be estimated for both legal- and sublegal-sized urchins, for each transect.

As described in Lochead et al. (2015), the ratio estimator (Cochran 1977) was applied to abundance estimates from individual transects to generate estimates of mean population and biomass density, and bootstrapping (Efron and Tibshirani 1993) was used to generate confidence bounds on the estimated mean densities.

ANALYSIS AND RESPONSE

Stock Assessment and Status: PFMAs 12 and 19

PFMA 12

PFMA 12 was surveyed annually or biennially from 1995 to 2018 and as of 2018 it is being surveyed on a triennial basis. Since the initial three surveys in 1995, 1996, and 1997, legal- and sublegal-sized urchin biomass and densities within PFMA 12 have increased by approximately a factor of three up to 2008. Since 2008, they have remained relatively stable (Figure 6). Legal-sized density ranged from 0.9 $\pm$ 0.2 to 1.4 $\pm$ 0.3 urchins/m^2 (mean $\pm$ SE) in 1995 through 1997, increasing to between 3.5 $\pm$ 0.5 urchins/m^2 and 4.2 $\pm$ 0.7 urchins/m^2 in 2012 to 2021. Since 2008, legal-sized densities have remained above 3.2 urchins/m^2 . Sublegal-sized population density ranged from 1.1 $\pm$ 0.3 urchins/m^2 to 2.1 $\pm$ 0.5 urchins/m^2 in 1995 through 1997, and then increased in 2012 to 2021 when they ranged from 6.0 $\pm$ 1.1 urchins/m^2 to 9.2 $\pm$ 1.2 urchins/m^2. In general, sublegal-sized densities have varied more than legal-sized densities since 2008, while legal-sized biomass has varied more than sub-legal biomass. Since 2010, sub-legal-sized densities appear to be increasing in comparison to legal-sized densities (Fig. 6b).

Legal-sized biomass ranged from 93.6 $\pm$ 18.1 g/m^2 (mean $\pm$ SE) to 116.8 $\pm$ 35.7 g/m^2 in 1995 through 1997, and increased to a range of 149.7 $\pm$ 36.5 g/m^2 and 482.0 $\pm$ 144.1 g/m^2 in 2012 through 2021. Sublegal-sized biomass ranged from 43.3 $\pm$ 11.1 g/m^2 to 70.1 $\pm$ 19.0 g/m^2 in 1995 through 1997 and increased to a range of 216.0 $\pm$ 50.2 g/m^2 and 291.8 $\pm$ 42.5 from 2016 to 2021. In general, immature-sized biomass and densities have varied more than legal and sublegal-sized urchins since 1995. With the exception of 2018, immature-size densities and biomass of Green Sea Urchins have been increasing since 2010 (Figure 6).

The estimated mean TD was relatively stable at about 50.4 mm from 2006 to 2012, decreased slightly to 46.6 in 2014 and 2016, and increased again in 2018 to 56.8 mm TD. In 2021, the mean estimated TD was 54.9 $\pm$ 0.7 mm (mean $\pm$ SE) (Figure 6).

Transects in PFMA 12 are separated into three sub-locations: Stubbs Island (n=4), Plumper Islands (n=4), and Stephenson Islets (n=10). Stubbs and Plumper Islands are in a research closure, and therefore the four transects within each of those sub-locations act as unfished controls, whereas the ten transects at Stephenson Islets are within an area where commercial harvest is permitted. Up to 2021, there were no clear trends between densities at fished versus unfished sites (Figure 7), suggesting factors other than fishing may be affecting biomass trends in the survey area. However, it appears that the biomass of sublegal urchins has been increasing at a higher rate at the Stephenson Islets than other sub-locations since 2016.

PFMA 19

Surveys were conducted in PFMA 19 annually or biannually from 2008 to 2016, and then in 2020 and 2023 (Figure 8). Similar to PFMA 12, these surveys will continue on a triennial basis that started in 2020. Densities for legal-sized urchins decreased from 2.4 $\pm$ 0.6 urchins/m^2 (mean $\pm$ SE) in 2008 to 0.9 $\pm$ 0.3 urchins/m^2 in 2009 and then ranged between 1.7 $\pm$ 0.3 and 3.0 $\pm$ 0.6 urchins/m^2 from 2012 through 2016. In 2023, legal density was 5.7 $\pm$ 0.9 urchins/m^2. The density of sublegal-sized urchins increased from 0.5 $\pm$ 0.0 urchins/m^2 in 2009 to a peak of 7.7 $\pm$ 2.6 urchins/m^2 in 2023. Since 2010, densities have been greater than 0.8 $\pm$ 0.0 urchins/m^2. In 2023, sublegal density was 7.7 $\pm$ 2.6 urchins/m^2.

The biomass of legal-sized urchins followed a similar trend, it dropped from 260.8 $\pm$ 89.6 g/m^2 (mean $\pm$ SE) in 2008 to 109.1 $\pm$ 50.6 g/m^2 in 2009, but since 2010 has steadily increased and remained greater than 137.0 $\pm$ 50.1 g/m^2, peaking at 542.1 $\pm$ 77.2 g/m^2 in 2023 (Figure 8). Sublegal-sized biomass densities followed a similar trend, with a sixteen fold increase from 14.0 $\pm$ 3.4 g/m^2 in 2009 to a peak of 224.5 $\pm$ 73.1 g/m^2 in 2023, but some variability did occur as it decreased to 34.6 $\pm$ 7.9 g/m^2 in 2016 (Figure 8).

The mean TD was 59 mm in 2008 and 2009 but decreased to 53, 54, and 53 mm in 2012, 2014, and 2016, respectively. Most recently, the mean TD was 50 mm in 2023 (Figure 8). The mean TD of GSU in PFMA 19 has remained within a range of 50 to 60 mm since 2008. The precision (standard errors) associated with these estimates was highly variable across time. Survey results suggest that the legal-sized GSU population was increasing concurrently and that the population structure in PFMA 19 was bimodal with both small (20-40 mm TD) and large (> 50 mm TD) individuals being well represented in the population. All indicators accordingly show that the decrease in mean TD in 2023 was not reflective of changes due to fishing pressure, but rather due to changes in the overall population related to decreases in predation pressure (i. e., decline of the main predator, the Sunflower star (Burt et al. 2018)).

A reliable method to age Green Sea Urchins has not yet been developed. The growth-band ageing method used in other echinoids is unreliable in this species (Russell and Meredith 2000). Therefore, population structure continues to be inferred by examining size distributions. Size frequency distributions for all years in PFMAs 12 and 19 show a broad range of test diameters, suggesting a wide range of age classes are likely represented (Figures 9 and 10). In most years, the distribution of size classes is bimodal with one small peak under 25 mm TD and another larger peak that ranges from 40 to 70 mm TD.

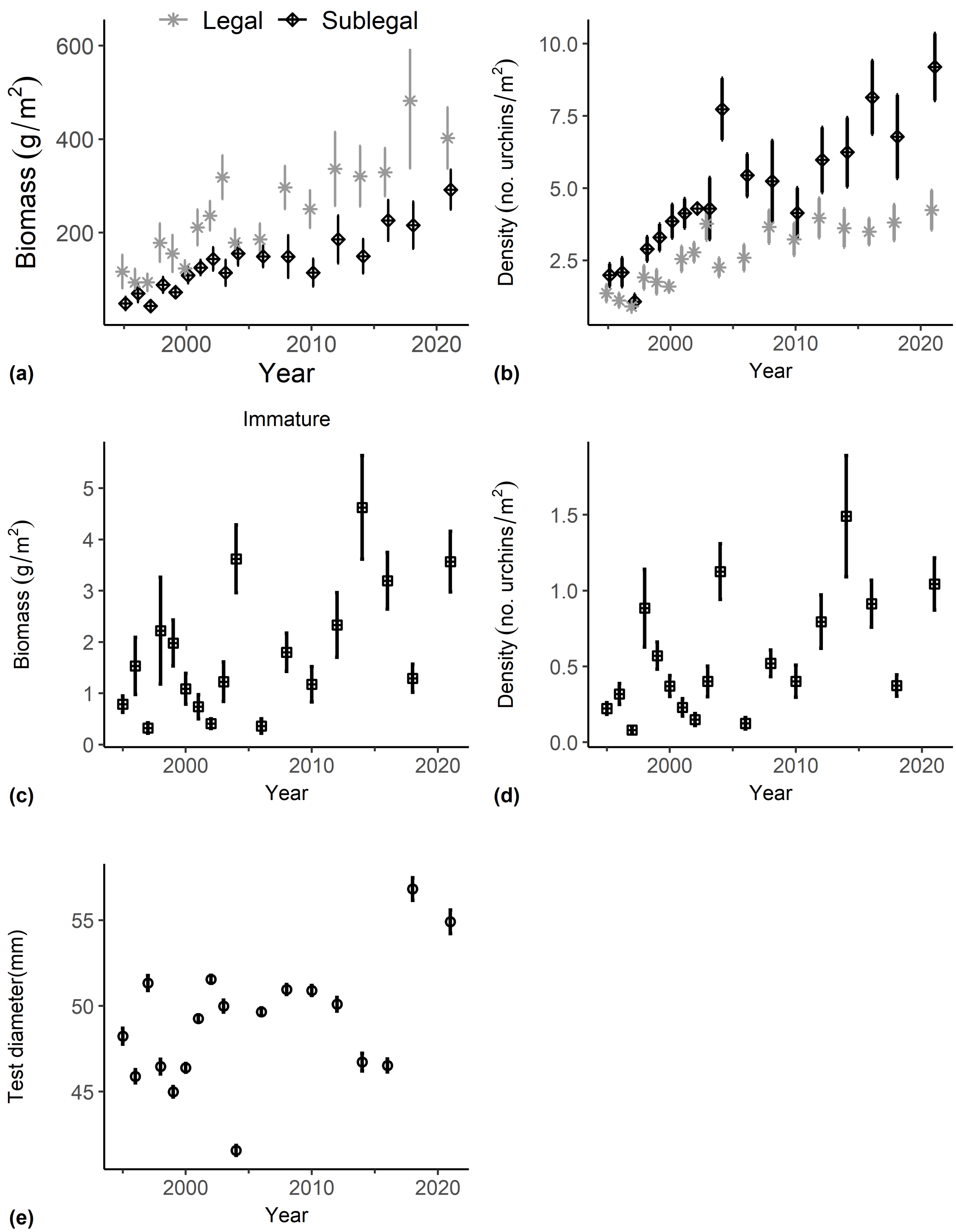

Figure 6. The estimated mean (± 1 standard error) of legal (≥ 55 TD mm) and sublegal (<55 TD mm) sized (a) biomass (g/m^2) and (b) density (no. urchins/m^2), as well as immature (<25 TD mm) (c) biomass and (d) density, and (e) test diameters of Green Sea Urchins in PFMA 12 from fall, fishery-independent dive surveys. In some cases, the standard errors are small and appear within the markers. Note that points are offset in (a) and (b) to improve legibility.

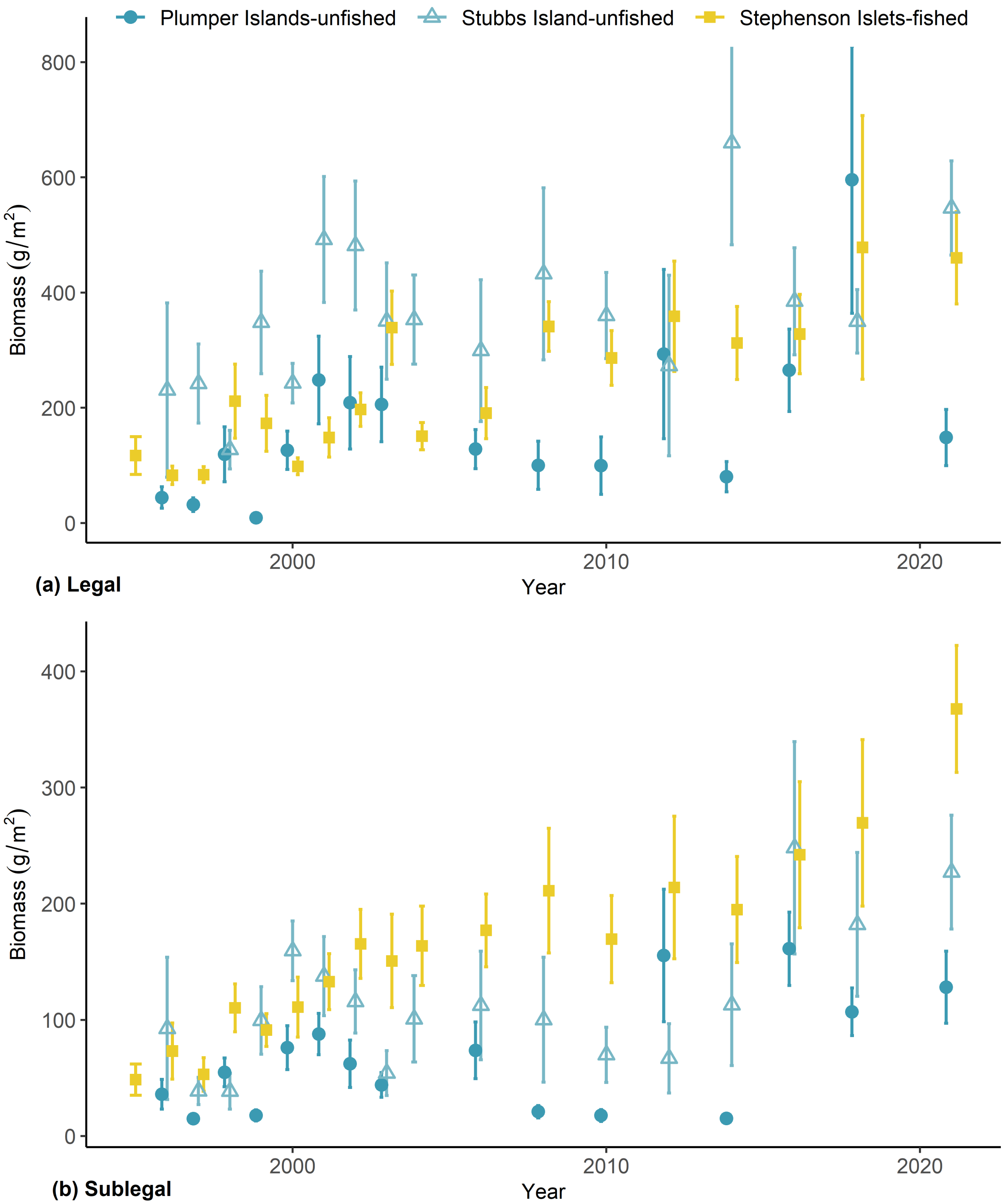

Figure 7. The estimated mean biomass (g/m^2; $\pm$ 1 standard error) of, (a), legal- ($\geq$ 55 TD mm) and (b) sublegal-sized (<55 TD mm) Green Sea Urchins in three PFMA 12 sub-locations during fall, fishery-independent dive surveys. Only one transect was completed at Plumper Island in 2004 so data are not shown. Note that points are offset to improve legibility.

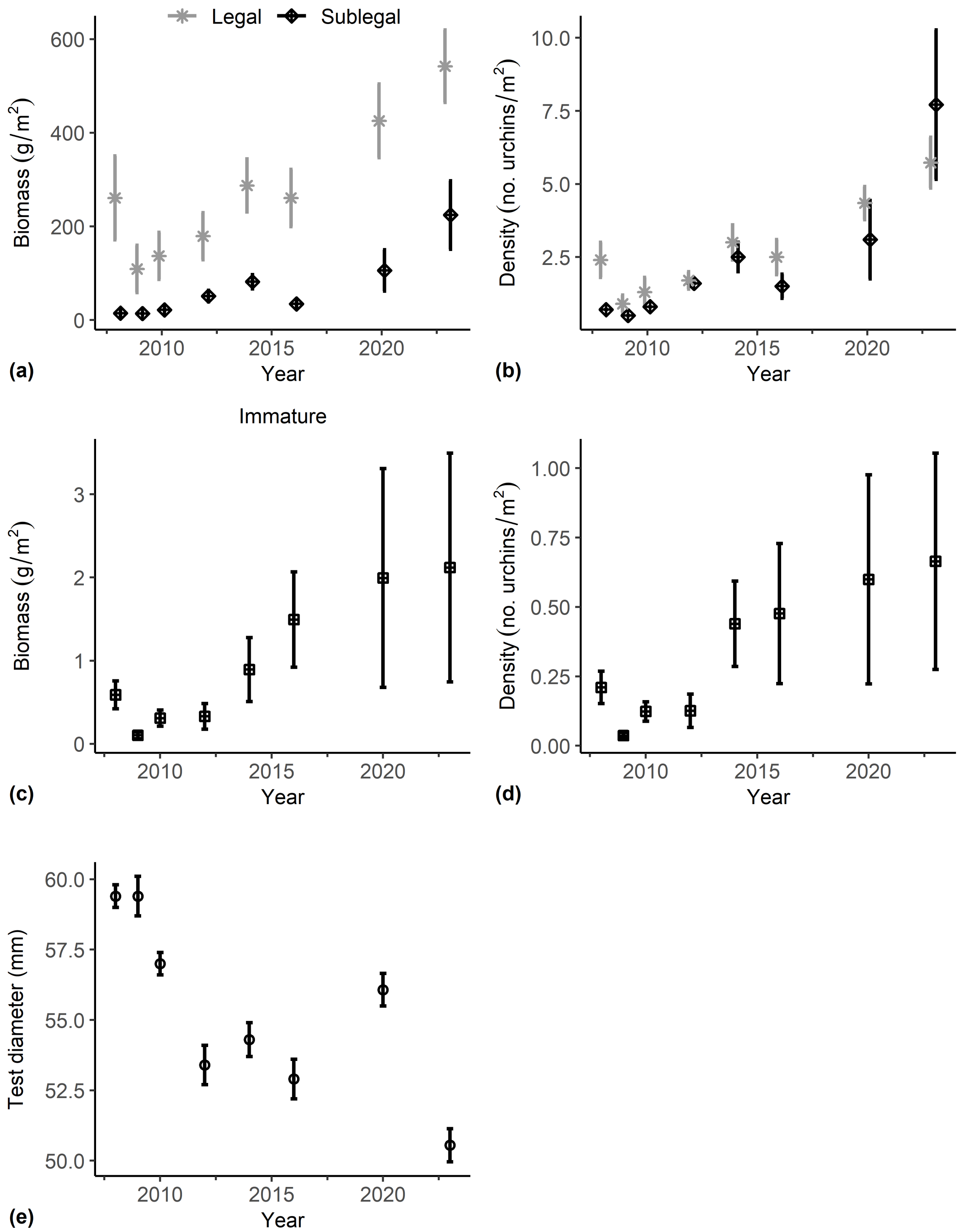

Figure 8. The estimated mean (± 1 standard error) of legal (≥ 55 TD mm) and sublegal (<55 TD mm) sized (a) biomass (g/m²) and (b) density (no. urchins/m²), as well as immature (<25 TD mm) (c) biomass, (d) density, and (e) test diameter of Green Sea Urchins in PFMA 19 from spring, fishery-independent dive surveys. In some cases, the standard errors are small and appear within the markers. Note that points are offset in (a) and (b) to improve legibility.

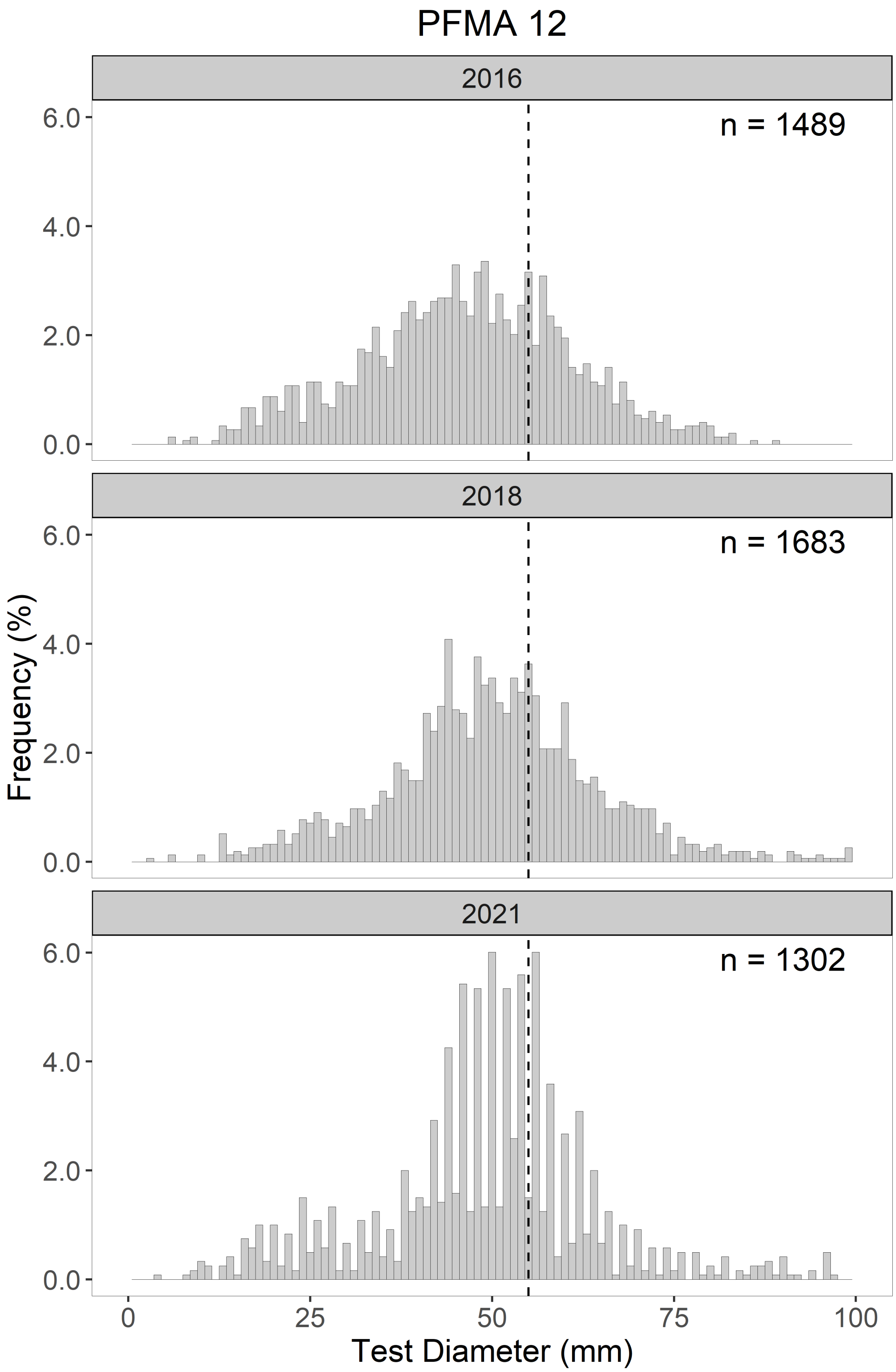

Figure 9. Size frequency distributions of Green Sea Urchin measured during the fishery-independent dive surveys in PFMA 12 from 2016, 2018, and 2021 (test diameter in mm). The dashed lines denote the minimum legal commercial harvest size of 55 TD mm; n = the number of urchins measured in each respective year.

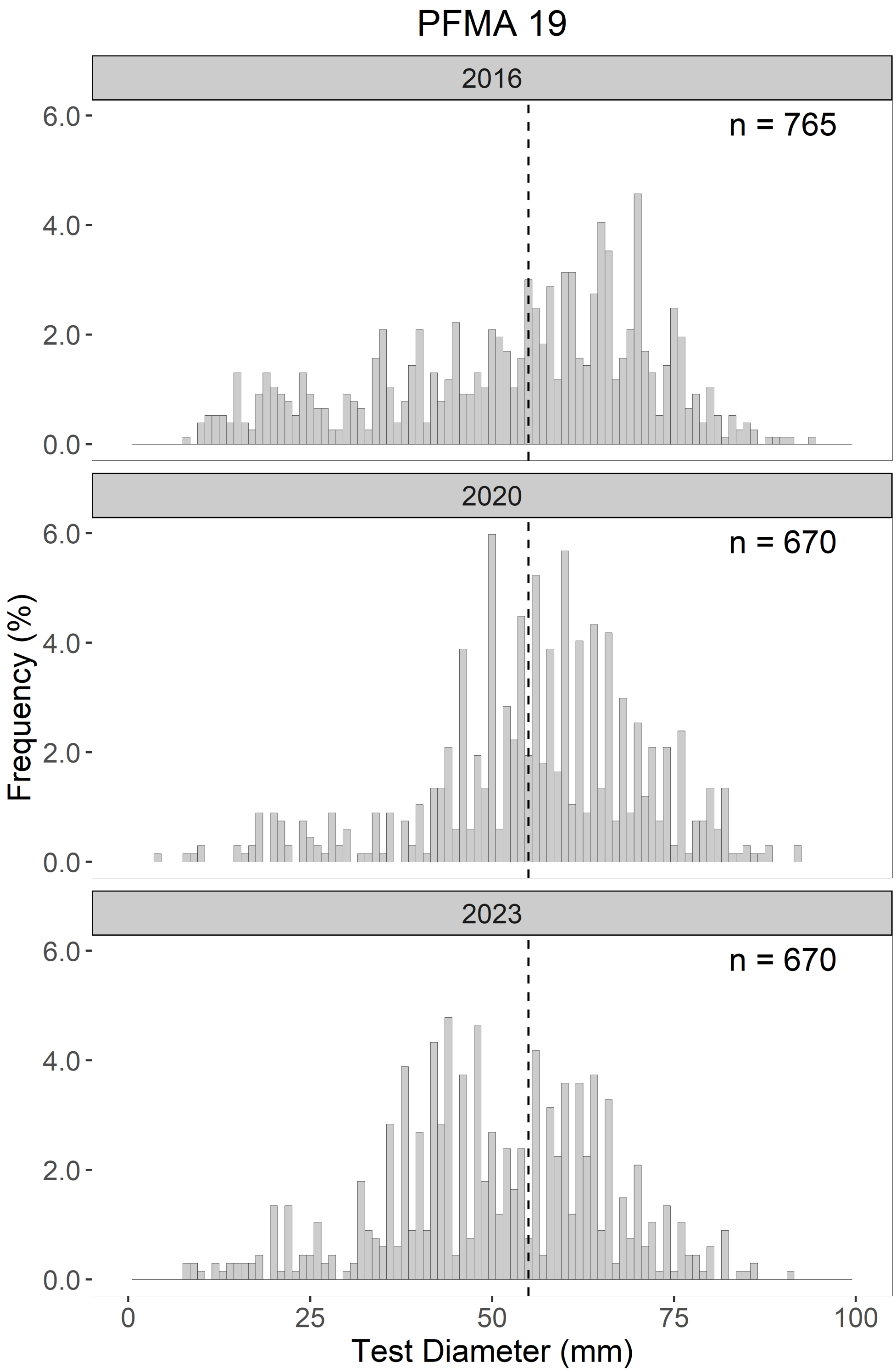

Figure 10. Size frequency distributions of Green Sea Urchin measured during fishery-independent surveys in PFMA 19 from 2016, 2020, and 2023 (test diameter in mm). The dashed lines denote the minimum legal commercial harvest size of 55 TD mm; n = the number of urchins measured in each respective year.

Harvest Options

This assessment updates previously published time series data and provides new harvest options for the 2024-2025 to 2026-2027 Green Sea Urchin fishery by implementing the Bayesian biomass dynamic model used in the assessment of BC's Green Sea Urchin stock since 2003 (DFO 2021a). The model incorporates both fishery-dependent and fishery-independent data with separate analyses for Northeast Vancouver Island (NEVI) and Southeast Vancouver Island (SEVI), producing maximum sustainable yield (MSY) posterior probability distributions for each region. The allocation of harvest options to each PFMA within a region is based on the proportion of total historic landings from each PFMA from the 1995-1996 to 2022-23 fishing seasons (Table 1).

This assessment takes into account the fishery expansion back into historically fished PFMAs in both regions (PFMA 11 in Northeast Vancouver Island and PFMA 20 in Southeast Vancouver Island) and the recent re-opening of PFMA 14 in the 2020-21 fishing season. Fishery-independent survey data from PFMA 12 along with total catch and CPUE data from PFMAs 11, 12, and 13 were included as inputs to the model for Northeast Vancouver Island. Similarly, fishery-independent survey data from PFMA 19 along with total catch and CPUE data from PFMAs 14, 18, 19, and 20 were included as inputs to the model for Southeast Vancouver Island. Catch and CPUE data from PFMAs 11 (NEVI) and 20 (SEVI) have been included in the assessment of the stock since 2018 (DFO 2018a), while catch and CPUE data from PFMA 14 (2022-21 - 2022-23) were included in the SEVI model in the current assessment. In assessments prior to 2018, models only included catch and CPUE data from PFMAs 12 and 13 for Northeast Vancouver Island and PFMAs 18 and 19 for Southeast Vancouver Island (Figure 4). See DFO (2015) and Waddell et al. (2010) for more detailed descriptions of model inputs.

The median MSY estimates (median of the estimated posterior probability distribution for MSY) for each region are uncertain and could be any MSY as represented by the posterior probability distributions from the Bayesian model. The harvest options represent various reductions from the estimated median of the MSY posterior probability distribution, along with the probabilities of harvest options exceeding the true MSY (Table 1).

The median MSY for Northeast Vancouver Island was estimated at 321 metric tonnes (t) in the current stock status update, compared to 302 t, 310 t, and 308 t in 2016, 2018, and 2021, respectively (DFO 2021a). The median MSY for Southeast Vancouver Island was estimated at 103 t in the current stock status update, whereas in 2016, 2018, and 2021 estimates were 76 t, 95 t, and 98 t, respectively (DFO 2021a). The 1995-1996 to 2022-2023 fishing seasons in PFMAs 11, 14, and 20 were only harvested for 7, 2, and 15 out of 28 seasons, respectively, and landings were relatively low, therefore harvest options were relatively small.

From the 2006-2007 through 2015-2016 fishing seasons, the Green Sea Urchin commercial fishery quotas were constant at 177.3 t in Northeast Vancouver Island (NEVI) and 25.5 t in Southeast Vancouver Island (SEVI). The regional quotas were increased in the 2018-2021 IFMP (DFO 2018b) to a total fishery quota of 262.3 t (i. e. SEVI and NEVI combined). Since 2021, the fishery has been managed with an annual IFMP and the total quota was increased to 293.4 t, 308.9 t, and 320.1 t in the 2021-22, 2022-23, and 2023-24 fishing seasons, respectively. For example, If a quota of 334.9 t (738,425 lbs) is used (264.2 t/582,425 lbs for NEVI and 70.76 t/156,00 lbs for SEVI), the predicted probability that the quota exceeds the true MSY is 19.29% for Northeast Vancouver Island and 9.8% for Southeast Vancouver Island.

Table 1. Harvest options in metric tonnes as percentages of the estimated median Maximum Sustainable Yield (MSY), the percent probability that the option may be greater than or equal to the true MSY, and allocation of the total harvest to each of the two management regions and open Pacific Fisheries Management Areas: (A) Northeast Vancouver Island (PFMAs 11, 12, and 13) and (B) Southeast Vancouver Island (PFMAs 14, 18, 19, and 20).

A. Northeast Vancouver Island

	Harvest Options (tonnes)				
Percentage of median MSY	PFMAs 11, 12, & 13	PFMA 11	PFMA 12	PFMA 13	% Probability Harvest Option ≥ true MSY
100	321.4	1.0	193.2	127.2	50
90	289.3	0.9	173.9	114.5	31.6
80	257.1	0.8	154.5	101.7	16.1
70	225.0	0.7	135.2	89.0	5.7
60	192.8	0.6	115.9	76.3	1.4
50	160.7	0.5	96.6	63.6	0.3
40	128.6	0.4	77.3	50.9	0.1
30	96.4	0.3	58.0	38.2	0
20	64.3	0.2	38.6	25.4	<0.001
10	32.1	0.1	19.3	12.7	<0.001

B. Southeast Vancouver Island

	Harvest Options (tonnes)					
Percentage of median MSY	PFMAs 14, 18, 19, & 20	PFMA 14	PFMA 18	PFMA 19	PFMA 20	% Probability Harvest Option ≥ true MSY
100	102.9	2.2	25.7	56.3	18.7	50
90	92.6	2.0	23.1	50.7	16.8	34.2
80	82.3	1.8	20.5	45.0	14.9	20.1
70	72.0	1.6	18.0	39.4	13.1	10.6
60	61.7	1.3	15.4	33.8	11.2	5.2
50	51.4	1.1	12.8	28.2	9.3	2.4
40	41.1	0.9	10.3	22.5	7.5	0.9
30	30.9	0.7	7.7	16.9	5.6	0.1
20	20.6	0.4	5.1	11.3	3.7	<0.001
10	10.3	0.2	2.6	5.6	1.9	<0.001

Sources of Uncertainty

There are uncertainties that are generally related to the data and the simplifying assumptions necessary to develop mathematical and statistical models that are used to analyze the data.

The uncertainties surrounding the data used in this assessment involve both the fishery-dependent and fishery-independent data. There are two main uncertainties involved in the fishery-dependent data. One is the accuracy of the catch and effort data derived from fish slips before the fishery management reforms in 1995. The second uncertainty revolves around the effort data. Effort is defined as the number of diver hours spent harvesting the landed (or caught) urchins and may not include the time spent on discards or searching for market quality roe. The main uncertainty in the fishery-dependent data is whether the data from the biological surveys (i. e. index sites within a PFMA) accurately reflect Green Sea Urchin population trends in each management region (NEVI and SEVI) as a whole. This uncertainty also extends to the potential impacts of dynamic ecosystem effects caused by climate change and Sea Otter predation.

In addition to data-related uncertainties, there are model-related uncertainties. As with virtually all quantitative analyses, model error contributes to uncertainty. The estimation of MSY is based on a productivity model that carries inherent uncertainties. The production model combines growth, reproduction, and mortality into one production function, ignoring interactions and temporal effects on these processes. This model represents a simplified approximation of the population dynamics, lacking some realism when compared to more complex fisheries models, such as age-structured models. For instance, the model assumes that surplus production (amount of increase in biomass of the stock) in any given year is related to the biomass in the previous year, without considering a time lag for larvae or juveniles to grow before contributing to the harvestable biomass (~2-4 years; Munk (1992)), and also implies a closed population. Therefore, MSY estimates need to be treated with some caution. Further, the allometric relationship between test diameter and weight used in the model was based on data that was collected between 2002 and 2012, and it is unknown whether it accurately represents current day Green Sea Urchin populations. Given the numerous uncertainties of this model, various harvest options were provided with associated probability that an adopted harvest option would be larger than the true MSY.

An additional uncertainty relates to the way estimates of MSY are allocated among PFMAs within each region. The allocation among PFMAs within a region is based on the proportion that each PFMA contributed to landings from 1995-96 to 2022-23. This method carries a risk that a potential historic over- or under-exploitation may be perpetuated, or that some PFMAs may become more or less exploited than intended, if the Green Sea Urchin distributions and abundance change among areas over time.

Stock Status and the Precautionary Approach

In 2018, provisional Upper Stock Reference (USR) and Limit Reference points (LRP) were recommended for BCs Green Sea Urchin populations within the Northeast and Southeast Vancouver Island management regions (DFO 2018a). The provisional LRP and USR were developed using fishery-independent data from two fished and highly productive management regions (PFMAs 12 and 19). At this time, whether they are appropriate for GSU along the entire BC coast is unknown.

Briefly, the intention is to keep the stock status above the LRP and out of the critical zone, aiming to maintain the stock above the USR and in the healthy zone (DFO 2009). For further details, see DFO's Fishery and Decision-Making Framework Incorporating the Precautionary Approach.

The USR and LRP for BCs Green Sea Urchin stock are as follows:

USR = 0.9 legal-sized urchins/m^2 on sea urchin habitat

LPR = 0.5*USR = 0.45 legal-size urchins/m^2 on sea urchin habitat

Both of these stock reference points were implemented in the 2021-22, 2022-23, and 2023-24 Integrated Fishery Management Plans (IFMP; DFO (2023)).

The estimated mean density of legal-sized urchins in 2021 was 4.2 urchins/m^2 in PFMA 12 and 5.7 urchins/m^2 on sea urchin habitat in PFMA 19 in 2023. This places the Green Sea Urchin stock in the Healthy Zone in both management regions. A full assessment (i.e., review of the assessment model) should occur if estimated mean density of legal-sized urchins within Northeast (PFMAs 11, 12, and 13) or Southeast (PMFAs 14, 18, 19, and 20) Vancouver Island falls below the USR for a period of six consecutive years (two advice periods) or falls below the LRP, which ever comes first.

The GSU population in BC is likely composed of one genetic stock, similar to Red Sea Urchins and Geoducks (Miller et al. 2006), but genetic studies have not been done to confirm this hypothesis. Due to the limited area where fishery-independent surveys are conducted, a coast wide assessment of stock status has not been possible. Future work will investigate means to expand the assessment and alternative approaches to assess the stock.

CONCLUSIONS

Based on the survey derived estimated mean density of legal-sized Green Sea Urchins on sea urchin habitat within PFMAs 12 and 19, the current evaluation of the Green Sea Urchin stock relative to the USR and LRP, places both the Northeast and Southeast Vancouver Island management regions in the Healthy Zone. Further, these estimates indicate that the legal and sub-legal populations of Green Sea Urchins within these regions have been increasing since 2015. The increase in density and biomass seen in these populations of urchins was most likely caused by climactic events, which resulted in the mass mortality of an important urchin predator, the Sunflower Seastar (*Pycnopodia helianthoides*; (Burt et al. 2018)). Whether Green Sea Urchin populations will continue to increase is unknown at this time and will require more data to determine if this is a long-term trend.

FUTURE DIRECTIONS

The Green Sea Urchin assessment will benefit from continued work to fill knowledge gaps and incorporate new information into future assessments and management procedures. Priorities for the Pacific Region's Green Sea Urchin program are consistent with DFO Science's initiative of Strategic Stock Assessment Planning and include: 1) bringing the fishery fully into compliance with the Precautionary Approach and DFO's Sustainable Fisheries Framework in the Fish Stocks Provisions of the revised Fisheries Act; 2) adopting multispecies approaches to include ecosystem interactions and maximize efficiencies; and 3) taking into account the biology of the species and environmental conditions affecting the stock.

DFO Science's Stock Assessment and Research Division is currently pursuing three areas of research related to Green Sea Urchins and the above priorities: robust management procedures, population and genomic connectivity, and coastwide stock monitoring. Green Sea Urchin is one of the case studies in a project developing a closed-loop simulation framework capable of testing invertebrate management procedures under a range of uncertainties. This framework could be used to better understand how robust the current management and assessment are to changing ecosystem conditions and could assist with the application of reference points. Similarly, Green Sea Urchin is one of the case studies in a related project investigating the population and genomic connectivity of several benthic marine invertebrates. The latter study will investigate the connectivity and structure of Green Sea Urchin populations under different environmental conditions (e. g., heat waves). Lastly, recommendations on the design of a coastwide multispecies survey, based on 6 years of pilot data, were recently peer-reviewed and published (Lochead et al. 2023). Recommendations were implemented and the multispecies benthic invertebrate dive survey (MSBIDS) time series was initiated in northern BC in 2023. MSBIDS will next be carried out in southern BC in the fall of 2024. This coastwide data collection may assist in the development and application of coastwide reference points, and may provide an opportunity to update the allometric test diameter-weight relationship of BC's Green Sea Urchin population.

Sea Otter range expansion and climate change are two important factors that are expected to impact the ecosystem dynamics of rocky subtidal systems in BC in the future. Sea Otters have been observed in the NEVI Green Sea Urchin management region and may quickly (2-5 years; (Curtis and Leus 2022)) impact the Green Sea Urchin population in that region. Monitoring changes in Green Sea Urchin abundance in NEVI due to Sea Otter predation may require more frequent fishery-independent biological surveys than are presently undertaken (i.e. present 3-year rotation). How Sea Otter predation and climate change effects such as increasing ocean temperature and ocean acidification will interact to impact Green Sea Urchin populations and ecosystem dynamics like kelp growth represents a critical knowledge gap. However, ongoing research may elucidate some of the changes to urchin populations due to climate change effects.

LIST OF MEETING PARTICIPANTS

Name	Affiliation
Christine Hansen	DFO Science, Pacific Region
Lyanne Curtis	DFO Science, Pacific Region (lead)
Meghan Burton	DFO Science, Pacific Region
Erin Wylie	DFO Fisheries Management, Pacific Region
Roger Kanno	DFO Fisheries Management, Pacific Region
Amy Ganton	DFO Fisheries Management, Pacific Region
Kyle Krumsick	DFO Science, Pacific Region (reviewer)

SOURCES OF INFORMATION

Burt, J.M., Tinker, M.T., Okamoto, D.K., Demes, K.W., Holmes, K., and Salomon, A.K. 2018. Sudden collapse of a mesopredator reveals its complementary role in mediating rocky reef regime shifts. Proc. R. Soc. B. 285: 20180553.

Cochran, W.G. 1977. Sampling techniques. Chapman & Hall, New York, New York.

Curtis, L.J.F., and Leus, D. 2022. Experimental harvest of Red Sea Urchins, *Mesocentrotus franciscanus* [A. Agassiz, 1863], and trends in Red, Green (*Strongylocentrus droebachiensis*; [Des Moulins, 1837]), and Purple (*S. purpuratus*; [Stimpson, 1857]) Sea Urchin populations within the Tofino Research area (1994-2012)]. Can. Manuscr. Rep. Fish. Aquat. Sci. 324: xi + 57 p.

DFO. 2009. A fishery decision-making framework incorporating the Precautionary Approach. (Accessed March 3, 2021).

DFO. 2015. Stock status update and quota options for the Green Sea Urchin (*Strongylocentrotus droebachiensis*) fishery in British Columbia, 2013-2016. DFO Can. Sci. Advis. Sec. Sci. Resp. 2014/052.

DFO. 2016. Stock status update and harvest options for the Green Sea Urchin (*Strongylocentrotus droebachiensis*) fishery in British Columbia, 2016-2019. DFO Can. Sci. Advis. Sec. Sci. Resp. 2016/031.

DFO. 2018a. Stock status update and harvest options for the Green Sea Urchin (*Strongylocentrotus droebachiensis*) fishery in British Columbia, 2018-2021. DFO Can. Sci. Advis. Sec. Sci. Resp. 2018/054.

DFO. 2018b. Pacific Region Integrated Fisheries Management Plan, Green Sea Urchin, September 1, 2018 to August 31, 2021.

DFO. 2021a. Stock status update and harvest options for the Green Sea Urchin (*Strongylocentrotus droebachiensis*) fishery in British Columbia, 2021-2024. DFO Can. Sci. Advis. Sec. Sci. Resp. 2021/036.

DFO. 2021b. Pacific Region Integrated Fisheries Management Plan, Green Sea Urchin, September 1, 2021 to August 31, 2022.

DFO. 2022. Pacific Region Integrated Fisheries Management Plan, Green Sea Urchin, September 1, 2022 to August 31, 2023.

DFO. 2023. Pacific Region Integrated Fisheries Management Plan, Green Sea Urchin, September 1, 2023 to August 31, 2024. 2023/24.

Dosser, H.V., Waterman, S., Jackson, J.M., Hannah, C.G., Evans, W., and Hunt, B.P.V. 2021. Stark physical and biogeochemical differences and implications for ecosystem stressors in the northeast pacific coastal ocean. J. Geophysical Res. 11:126.

Efron, B., and Tibshirani, R.J. 1993. An introduction to the bootstrap. Chapman & Hall, New York, New York.

Estes, J.A., and Duggins, D.O. 1995. Sea Otters and kelp forests in Alaska: generality and variation in a community ecological paradigm. Ecol. Monogr. 65(1): 75–100.

Foreman, R.E., and Lindstrom, S.C. 1974. Urchin survey report. Rep. Fish. Res. Bd., Pacific Biol. Stn.: 1–59.

Gelman, A., Carlin, J.B., Stern, H.S., and Rubin, D.B. 2004. Bayesian data analysis (Vol. 2). Chapman & Hall/CRC, Boca Raton, FL, USA.

Lochead, J., Hajas, W., and Leus, D. 2015. Calculation of mean abundance in the Red Urchin Analysis Program and Green Urchin Analysis Program. Can. Manuscr. Rep. Fish. Aquat. Sci. 3065: vi + 41 p.

Miller, K.M., Supernault, K.J., Li, S., and Withler, R.E. 2006. Population structure in two marine invertebrate species (*Panopea abrupta* and *Strongylocentrotus franciscanus*) targeted for aquaculture and enhancement in British Columbia. J. Shellfish Res. 25: 33–42.

Munk, J.E. 1992. Reproduction and growth of Green Urchins *Strongylocentrotus droebachiensis* (Müller) near Kodiak, Alaska. J. Shellfish Res. 11: 245–254.

Perry, R.I., and Waddell, B.J. 1998. Stock assessment and quota recommendations for 1996/97 for the Green Sea Urchin fishery in British Columbia. *In* Invertebrate working papers reviewed by the Pacific Stock Assessment Review Committee (PSARC) in 1996. *Edited by* G. E. Gillespie and L. C. Walthers. Can. Tech. Rep. Fish. Aquat. Sci. 2221. pp. 261–308.

Perry, R.I., Zhang, Z., and Harbo, R. 2002. Development of the Green Sea Urchin (*Strongylocentrotus droebachiensis*) fishery in British Columbia, Canada – back from the brink using a precautionary framework. Fish. Res. 55: 253–266.

Perry, R.I., Zhang, Z., and Waddell, B. 2006. Stock assessment and quota options for the Green Sea Urchin (*Strongylocentrotus droebachiensis*) fishery in British Columbia, 2006-2009. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2005/064.

Perry, R.I., Zhang, Z., and Waddell, B.J. 2003. Assessment of Green Sea Urchin (*Strongylocentrotus droebachiensis*) stocks in British Columbia, 2003. DFO Can. Sci. Advis. Sec. Res. Doc. 2003/082. 55 p.

R Core Team. 2023. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ripley, B., and Lapsley, M. 2023. RODBC: ODBC database access. R package version 1.3-23.

Russell, M.P., and Meredith, R.W. 2000. Natural growth lines in echinoid ossicles are not reliable indicators of age: A test using *Strongylocentrotus droebachiensis*. Invertebr. Biol. 119: 410–420.

Schauberger, P., and Walker, A. 2022. Openxlsx: Read, write and edit xlsx files. R package version 4.2.5.1.

Scheibling, R.E., Feehan, C.J., and Hatcher, B.G. 2020. Chapter 31 - *Strongylocentrotus droebachiensis*. *In* Lawrence JM (ed) Developments in Aquaculture and Fisheries Science, Book 43. Elsevier.

Strathmann, R. 1978. Length of pelagic period in echinoderms with feeding larve from the north pacific. J. Exp. Mar. Biol. Ecol. 34: 23–27.

Waddell, B. 2017. Survey results of Green Sea Urchin (*Strongylocentrotus droebachiensis*) populations in Haro Strait, British Columbia, March 2008, March and August 2009, and March 2010. Can. Tech. Rep. Fish. Aquat. Sci. 3208: viii + 69 p.

Waddell, B.J., Crossley, C.M., Tzotzos, D.P., Perry, R.I., and Kensall, D. 2002. Survey results of Green Sea Urchin (*Strongylocentrotus droebachiensis*) populations in Queen Charlotte Strait, British Columbia, November 1996 and February, 1997. Can. Tech. Rep. Fish. Aquat. Sci. 2419.

Waddell, B.J., and Perry, R.I. 2005. Survey results of Green Sea Urchin (*Strongylocentrotus droebachiensis*) populations in Queen Charlotte Strait, British Columbia, November 1998, 1999, 2000, 2001 and October 2002. Can. Tech. Rep. Fish. Aquat. Sci. 2591.

Waddell, B.J., and Perry, R.I. 2006. Survey results of Green Sea Urchin (*Strongylocentrotus droebachiensis*) populations in Queen Charlotte Strait, British Columbia, October 2003 and November, 2004. Can. Tech. Rep. Fish. Aquat. Sci. 2633.

Waddell, B.J., and Perry, R.I. 2007. Survey results of Green Sea Urchin (*Strongylocentrotus droebachiensis*) populations in Queen Charlotte Strait, British Columbia, October 2006. Can. Tech. Rep. Fish. Aquat. Sci. 2742.

Waddell, B.J., and Perry, R.I. 2012. Survey results of Green Sea Urchin (*Strongylocentrotus droebachiensis*) populations in Queen Charlotte Strait, British Columbia, October 2008 and November, 2010. Can. Tech. Rep. Fish. Aquat. Sci. 3000.

Waddell, B.J., Perry, R.I., Scharf, G., and Ross, G. 1997. Surveys on Green Sea Urchin (*Strongylocentrotus droebachiensis*) populations in Queen Charlotte Strait, British Columbia, October 1995 and March 1996. Can. Tech. Rep. Fish. Aquat. Sci. 2419.

Waddell, B., Zhang, Z., and Perry, R.I. 2010. Stock assessment and quota options for the Green Sea Urchin, *Strongylocentrotus droebachiensis*, fishery in British Columbia, 2010-2013. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/027. vi + 36 p.

Wickham, H., François, R., Henry, L., Müller, K., and Vaughan, D. 2023. Dplyr: A grammar of data manipulation. R package version 1.1.4.

Wickham, H., and Henry, L. 2023. Purrr: Functional programming tools. R package version 1.0.2. R package version 0.3.5.

Zhang, Z., and Perry, R.I. 2005. Use of state-space modeling with a Bayesian approach to estimate target reference points for Green Sea Urchin (*Strongylocentrotus droebachiensis*) stocks in the Queen Charlotte Strait regions, British Columbia, Canada. Fish. Res. 74: 253–264.

THIS REPORT IS AVAILABLE FROM THE:

Center for Science Advice (CSA)
Pacific Region
Fisheries and Oceans Canada
3190 Hammond Bay Rd.
Nanaimo, BC V9T 6N7

E-Mail: DFO.PacificCSA-CASPacifique.MPO@dfo-mpo.gc.ca
Internet address: www.dfo-mpo.gc.ca/csas-sccs/

ISSN 1919-3769
ISBN 978-0-660-75121-4 Cat. No. Fs70-7/2025-004E-PDF

Correct Citation for this Publication:

DFO. 2025. Stock Status Update and Harvest Options for the Green Sea Urchin (*Strongylocentrotus droebachiensis*) fishery in British Columbia, 2024-2027. DFO Can. Sci. Advis. Sec. Sci. Resp. 2025/004.

Aussi disponible en français :

*MPO. 2025. Évaluation des stocks et options de quota pour la pêche à l'oursin vert (*Strongylocentrotus droebachiensis*) en Colombie-Britannique, 2024-2027. Secr. can. des avis sci. du MPO. Rép. des Sci. 2025/004.*