Status of the California sea cucumber (*Parastichopus californicus*) and red sea urchin (*Mesocentrotus franciscanus*) commercial dive fisheries in the San Juan Islands, Washington State, USA

Henry S. Carson*, Michael Ulrich, Dayv Lowry, Robert E. Pacunski, Robert Sizemore

Washington Department of Fish and Wildlife, Fish Management Division, 1111 Washington St. SE, Olympia, WA 98501, USA

ABSTRACT

The San Juan Archipelago is the most intensely fished region of Washington State for echinoderms. Commercial dive fisheries for both the California sea cucumber (*Parastichopus californicus*) and red sea urchin (*Mesocentrotus franciscanus*) were characterized by high levels of harvest in the late 1980s and early 1990s. Here we evaluate stock performance of both species under the current fishery management regime using biomass estimates from a remotely-operated vehicle survey, time series of relative abundance from SCUBA index station surveys, and harvester log book data. We also report habitat associations of both species with depth and seafloor substrate composition. The fully-utilized quota for *Parastichopus* represents an 11.4% annual harvest rate on the current harvestable biomass estimate, and signs that this rate is unsustainable include: low density in shallow waters, a relative abundance that has remained depressed, and a continuous decline in catch-per-unit-effort (CPUE). Abundant *Parastichopus* below harvestable depths may not be of sufficient density to act as a consistent reservoir to replenish the shallows with recruits. The partially-utilized quota for *Mesocentrotus* represents a 3.9% annual harvest rate on the current biomass estimate, relative abundance has increased from a recent low, and there is no trend in CPUE. Numerous similarities between the two fisheries with regard to fleet composition and harvest history, coupled with diverging stock status, suggest that the sea cucumber fishery may be slower to recover from over-exploitation. Despite the challenges of co-managing the fisheries among several stakeholder groups, agreement has been reached to improve the long term viability of the *Parastichopus* fishery using reduced harvest quotas and a closure during peak spawning months, and to continue to closely monitor the *Mesocentrotus* fishery.

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1. Introduction

Echinoderm fisheries in Washington State have followed a classic pattern of exploitation experienced worldwide (reviewed in Anderson et al., 2011). Washington fisheries began with a discovery and market development phase, followed by unregulated exploitation leading to concerns of depletion, resulting in a modern era of limited-entry permits and comparatively low harvest quotas. Commercial harvest of the California sea cucumber (*Parastichopus californicus* or *Apostichopus californicus*) began in 1971 and peaked during the years between 1988 and 1994 with a maximum

of 4.1 million pounds landed and a US$4.6 million ex-vessel value in 1991 (Washington Department of Fish and Wildlife [WDFW] unpubl. data). The state fishery for red sea urchins (*Mesocentrotus franciscanus*, see Kober and Bernardi 2013 for reclassification from *Strongylocentrotus*) also began in 1971 and peaked during the years between 1986 and 1992. Maximum landings for red urchin, 8.9 million pounds, occurred in 1988 but maximum ex-vessel value occurred in 1991 at US$3.3 million (WDFW unpublished data).

Subsequent to these exploitation peaks, management of both species changed significantly. First, the 1994 Rafeedie court decision reaffirmed the rights of 15 Puget Sound American Indian tribes to harvest shellfish in their usual and accustomed harvest areas, resulting in harvest quotas for all species divided equally between state and tribal harvesters (United States v. Washington, 873 F. Supp. 1422 W.D. Wash. 1994). Second, a moratorium was placed on issuance of new state commercial harvest licenses in 1989, and an industry-driven license buy-back program was instituted in 2000,

* Corresponding author. Fax: +1 360 902 2943.
E-mail addresses: henry.carson@dfw.wa.gov (H.S. Carson),
michael.ulrich@dfw.wa.gov (M. Ulrich), dayv.lowry@dfw.wa.gov (D. Lowry),
robert.pacunski@dfw.wa.gov (R.E. Pacunski), robert.sizemore@dfw.wa.gov
(R. Sizemore).

eventually reducing the non-tribal fleet from 49 to 25 sea cucumber licenses and from 42 to 23 sea urchin licenses. Third, fishery-wide harvest quotas were instituted at levels well below the preceding maximum harvest levels.

The quotas and regulations were initially developed using a variety of methods including a drop-camera survey for both species (Bradbury et al., 1998) and catch-at-size analysis models for red sea urchins (Lai and Bradbury 1998). For *Parastichopus,* the San Juan Islands harvest management area (Fig. 1) annual quota has been near 675,000 pounds since 1998. The fishery management unit is "split-drained pounds," the weight of the animal after it has been cut and drained of water and viscera, which is the way the vast majority of the product is landed. Less than 1% of harvest is landed whole-live (WDFW unpubl. data). The annual quota for *Mesocentrotus* from the islands has been near 350,000 pounds (whole weight) since 1998, and has been accompanied by minimum (83 mm) and maximum (127 mm) test diameter restrictions.

These quotas have remained static for over 15 years not because of any evidence of their continued sustainability but, conversely, due to a lack of information about the status of the resources. Anecdotal evidence from harvesters suggests that *Parastichopus* populations have not recovered from historic intensive harvest, and may be in continued decline. Harvesters often return to some of the same locations year after year, and therefore are well-positioned to note abundance over time. Both tribal and non-tribal fishers report lower densities than past decades, and note areas that are "fished out" and have not recovered. Declining densities of *Mesocentrotus* in an adjacent harvest management district in the Strait of Juan de Fuca led to a precautionary fishery closure there in 2004. Therefore, an updated stock assessment is needed for both species, as is a synopsis of other supporting information on fishery status to reassess the current management strategy.

Parastichopus is a difficult species to manage because little is known about its life history relative to many other harvested species (Perry et al., 1999). Cameron and Fankboner (1986, 1989) describe the species' reproductive biology and development, but most other studies focus on abundance or habitat utilization (e.g. Cripps and Campbell, 2000), or are based on aquaculture/caging (e.g. Hannah et al., 2012). Attempts to fit the animals with tags or other markings that persist longer than a few months have been unsuccessful (e.g., Cieciel et al., 2009; Kirshenbaum et al., 2006), which makes it difficult to make *in situ* estimates of growth, natural mortality, or longevity. Measurements made over shorter time scales are confounded by the animals' ability to expand and contract in length and diameter, expel or retain large amounts of water, and reabsorb the viscera seasonally. It would be difficult to enforce fishery management techniques such as minimum or maximum sizes, or harvest of only males, due to sea cucumbers' plasticity and lack of obvious sexual dimorphism. The main population assessment information currently available to managers comes from absolute or relative abundance, harvest weight, and fishery-dependent metrics such as catch-per-unit-effort (CPUE).

More is known about the life history of *Mesocentrotus* because their hard tests alleviate many of the issues associated with *Parastichopus.* The tests allow for temporally stable size measurements, aging studies (e.g. Ebert and Southon, 2003), and long-term tagging experiments (e.g. Ebert et al., 1999) to assess growth and natural mortality. However, mature gonads are the marketable tissue harvested in urchin fisheries. Therefore, the traditional management strategy of a closure during reproductive periods to promote recruitment is unavailable to managers. The appropriate spatial management scale for both sea urchins and sea cucumbers is also unknown; echinoderm populations with patchy distributions dominated by local population dynamics may be best managed at a very fine scale (Johnson et al., 2013) that would be unrealistic given the resources currently available to managers in Washington.

Echinoderm fisheries in Washington State are concentrated in the San Juan Archipelago (Fig. 1), where there is an abundance of hard-substrate seafloor habitat these animals favor (Endris and Picard 2010; results below) compared to other areas of the Puget Sound. 72% of sea cucumber and 78% of red sea urchin harvest in the last decade has occurred in this district. Both dive fisheries are conducted by hand harvest using surface-supplied air or SCUBA. Most non-tribal harvesters hold licenses in both fisheries, engaging primarily in sea cucumber harvest in the late summer and fall, and primarily in sea urchin harvest in the late fall and winter. The two fisheries were established in the same year, have very similar harvest and management histories, occur in the same locations, and are performed by largely the same fishers. Additionally, as we discuss below, population assessment of both species is done simultaneously (i.e., both species are counted on the same SCUBA transect), resulting in parallel data sets for each fishery.

Here we aim to use this parallel data to compare the status of both echinoderm fisheries in the San Juan Islands in the context of the historic intensive harvest of both. We use data collected from a remotely operated vehicle (ROV) survey (depth and habitat-associated abundance), a time series of SCUBA surveys of fixed index stations (relative abundance), and harvester log book information to compare current fishery status. We conclude by discussing the appropriate harvest rates and the rate of recovery from historic overfishing for both species, and outlining steps recently taken by state and tribal co-managers to contribute to the continued viability of Washington echinoderm fisheries.

2. Methods

2.1. Remotely operated vehicle (ROV) surveys

ROV surveys were conducted aboard the 13-m R/V Molluscan using a Seaeye Falcon system (Saab Seaeye Ltd., Houston, TX) equipped with an ECI-330 high-resolution color zoom camera (Sony Corporation, Tokyo, Japan). A total of 165 near-bottom transects (vehicle traveling ~1 m above the seafloor) were surveyed between October 2010 and April 2011. Transects were evenly dispersed throughout the San Juan Islands at the intersections of a standardized 3-nautical-mile grid generated from a random start point (Fig. 1). This design avoids bias in site selection while providing representative coverage of the extent of San Juan Island waters. The depths of the surveys were dictated by the randomly selected map coordinates, and ranged from 5 to 290 m.

Videos were captured over the course of 30-min transects, which resulted in transect lengths ranging from 134 to 675 m long (mean 364 m) depending on currents, bottom complexity, and other factors. Width of the visible transect area was calculated with the aid of two parallel lasers projecting dots exactly 10 cm apart onto the seafloor and visible on screen. Transect widths ranged from 1 to 3 m (mean 1.6 m) depending on the height of the vehicle above the bottom and bottom complexity. Detailed ROV methods for the overall survey technique are available in Pacunski et al. (2008).

The resulting videos were reviewed twice by two different technicians who counted all macrofauna present in 30-s increments. Although adult sea urchins and sea cucumbers are easily recognized on the seafloor, 10% of the stations were reviewed by an echinoderm biologist to ensure accurate counts from these technicians tasked with counting a broad variety of species. Each 30-min transect was divided into approximately 60 segments of 30 s duration each. Each segment was assigned a location, dominant substrate type (mud, sand, gravel, shell hash, cobble, boulder, or bedrock), and average depth. Segments on the same transect with the same dominant substrate were pooled, for one density estimate per sub-
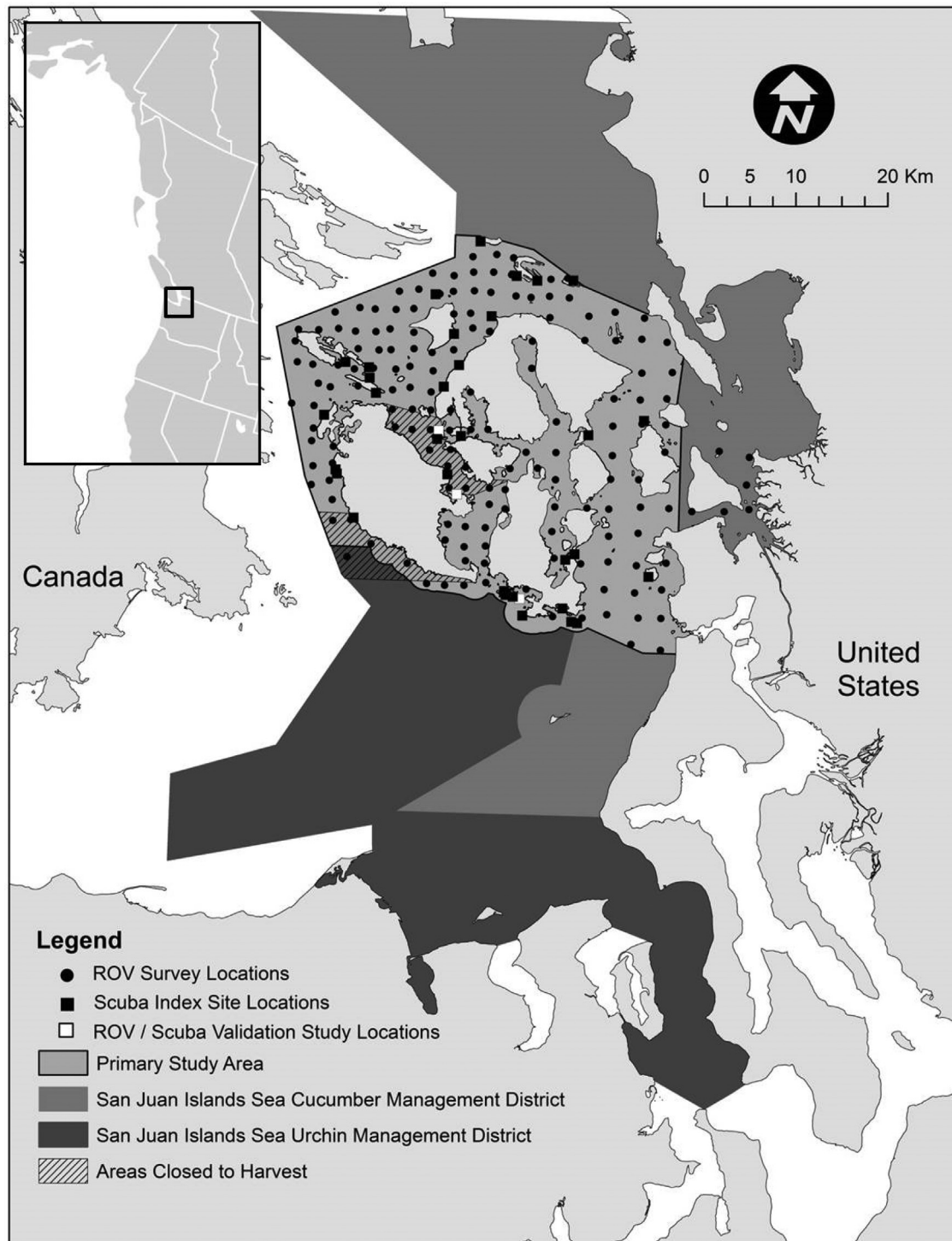
Fig. 1. Map of study area and sea cucumber (*Parastichopus californicus*) and sea urchin (*Mesocentrotus franciscanus*) management districts in the San Juan Islands, Washington State, USA. The study area is a subset of the sea cucumber management district, which is itself a subset of the sea urchin management district.

strate type on each transect. This by-substrate analysis alleviated a common problem with assigning the echinoderm densities on an entire transect to the dominant substrate type of the entire transect—animals located in patchy, heterogeneous areas are often misallocated to a seafloor habitat on which they were not actually occurring (e.g., a group of animals on bedrock or boulder patches surrounded by sand or mud). To estimate a density for a particular depth bin and substrate type (Tables 1 and 2), a weighted mean of the densities from all applicable transects was calculated using the area swept as the weighting factor. For the purposes of this manuscript we define "harvestable depth" or "harvestable biomass" to apply to the 0–36 m depth range. Where insufficient transects with particular substrates existed in the two harvestable depth bins (0–18 m, 18–36 m), one density was calculated using information from all transects shallower than 36 m.

Table 1
Harvestable biomass calculations and 95% confidence intervals for sea cucumber (*Parastichopus californicus*) in the San Juan Islands District, excluding areas closed to harvest, for the 0–18 m (top) and 18–36 m (bottom) depth bins.

Substrate	Study area (km²)	Cucumber density (m⁻²)	Number of cucumbers	Pounds split-drained	District biomass	Lower 95% CI	Upper 95% CI
0–18 m depth bin							
Bedrock	15.4	0.0593	912,945	575,155	695,938	491,223	900,653
Boulder	7.1	0.0109	77,744	48,979	59,265	22,139	96,391
Cobble	7.8	0.0092	71,428	45,000	54,449	8,860	100,039
Shell	1.3	0.0123	15,594	9,824	11,887	8,384	15,390
Gravel	18.6	0.0092	170,926	107,683	130,297	58,866	201,728
Sand	52.5	0.0021	110,262	69,465	84,053	62,474	105,632
Mud	42.5	0.0002	8,509	5,360	6,486	3,563	9,409
Total	145.2		1,367,407	861,467	1,042,375	655,507	1,429,242
18–36 m depth bin							
Bedrock	16.4	0.1577	2,582,196	1,626,784	1,968,408	1,702,461	2,234,355
Boulder	3.1	0.0500	153,322	96,593	116,877	69,052	164,702
Cobble	8.6	0.0662	571,173	359,839	435,405	294,688	576,123
Shell	1.9	0.0511	98,480	62,042	75,071	53,719	96,423
Gravel	26.1	0.0662	1,726,667	1,087,800	1,316,238	1,243,661	1,388,816
Sand	54.1	0.0212	1,147,928	723,195	875,065	302,733	1,447,398
Mud	28.2	0.0046	129,944	81,865	99,056	–	374,503
Total	138.5		6,409,710	4,038,117	4,886,122	3,666,314	6,282,320
Harvestable depth total							
Total	238.7		7,777,117	4,899,584	5,928,496	4,321,821	7,711,562

Table 2
Harvestable biomass calculations and 95% confidence intervals for red sea urchin (*Mesocentrotus franciscanus*) in the San Juan Islands District, excluding areas closed to harvest, for the 0–18 m (top) and 18–36 m (bottom) depth bins.

Substrate	Study area (km²)	Urchin density (m⁻²)	Number of sea urchins	Number of legal-sized	Pounds	District biomass	Lower 95% CI	Upper 95% CI
0–18 m depth bin								
Bedrock	15.4	0.2504	3,854,998	1,272,149	1,151,295	1,391,916	870,596	1,913,236
Boulder	7.1	1.3046	9,305,087	3,070,679	2,778,964	3,359,768	2,353,485	4,366,050
Cobble	7.8	0.1125	873,438	288,235	260,852	315,370	245,887	384,854
Shell	1.3	0.0179	984,682	324,945	294,075	355,537	329,567	381,507
Gravel	18.6	0.0530	22,693	7,489	6,777	8,194	1,010	15,378
Sand	52.5	0.0043	225,775	74,506	67,428	81,520	74,453	88,587
Mud	42.5	0.0056	238,238	78,619	71,150	86,020	79,494	92,547
Total	145.2		15,504,911	5,116,621	4,630,542	5,598,325	3,954,491	7,242,159
18–36 m depth bin								
Bedrock	16.4	0.1582	2,590,383	854,826	773,618	935,304	848,272	1,022,336
Boulder	3.1	1.1962	3,668,067	1,210,462	1,095,468	1,324,421	1,168,163	1,480,679
Cobble	8.6	0.1125	970,649	320,314	289,884	350,470	273,254	427,687
Shell	1.9	0.0179	1,382,377	456,184	412,847	499,132	462,673	535,591
Gravel	26.1	0.0530	34,497	11,384	10,302	12,456	1,535	23,376
Sand	54.1	0.0070	379,033	125,081	113,198	136,857	88,799	184,914
Mud	28.2	0.0056	158,193	52,204	47,244	57,118	52,785	61,452
Total	138.5		9,183,198	3,030,455	2,742,562	3,315,758	2,895,480	3,736,035
Harvestable depth total								
Total	238.7		24,688,109	8,147,076	7,373,104	8,914,083	6,849,971	10,978,194

2.2. Evaluation of ROV methodology

In July 2014 a separate study was performed to compare the counts of sea cucumbers and sea urchins detected by the ROV to counts made by human divers on similar transects in the same vicinity. Three areas were selected in the San Juan Islands that contained expanses of rugose, bedrock substrate (where substrate complexity, compared to other habitats, would be more likely to obscure individuals and create a difference between ROV and diver counts) in diveable depths: outside Friday Harbor, South Lopez Island, and the Wasp Islands (Fig. 1). A total of 17 transects were surveyed in these 3 areas by both dive teams and the ROV on the same dates. Divers, aided by scooter propulsion (Dive Xtras, Mukil-teo, WA) swam 2 m-wide transects along depth contours between 10 and 20 m, preferentially selecting bedrock seafloor with aggregations of sea urchins and sea cucumbers. Divers counted all adult-sized sea cucumbers and sea urchins in the transect. An ultra-short baseline acoustic transponder (Linkquest Inc., San Diego, CA) with a transmission interval of 1 s was placed on the divers so that each transect could be replicated by the ROV immediately following completion. After video review, the densities of each species detected were compared between the two methodologies using a paired *t*-test. These videos were not divided into segments as with the biomass survey; whole transects were the unit of analysis. It was necessary to use density per area rather than counts because the width of the ROV survey track varies with height above bot-

tom, and various factors made it difficult for the ROV to exactly replicate each transect, including routine error in GPS positioning, current speeds, and vessel movement. Later analysis revealed that the separation between the ROV and diver positions at any given point along the transect averaged 5 m apart.

2.3. Seafloor habitat

In order to estimate total abundance, densities of sea cucumbers and sea urchins by depth and substrate type can be extrapolated to a management district if the total area of each habitat type is known. Digitized maps of the San Juan Islands seafloor habitat derived from sonar backscatter data (Endris and Picard 2010) were obtained from the SeaDoc Society. These maps had some gaps in coverage, particularly in the nearshore, amounting to approximately 20% of the area covered by the ROV survey. To extend the coverage to include the entire study area, scattered blank areas were subdivided and assigned a habitat designation by interpolating from information obtained from three sources: Washington Department of Fish and Wildlife (WDFW) drop-camera surveys in the early 1990s, National Oceanic and Atmospheric Administration (NOAA) hydrographic surveys, and Washington Department of Ecology sediment sampling. Lastly, the complete habitat map was subdivided into 18-m-wide depth strata using available bathymetry contours from NOAA nautical charts. Total area of each habitat type by depth, subtracting areas closed to harvest, was calculated using ArcMap 10.1 software (ESRI, Redlands, CA). We have no estimate of uncertainty for the calculated seafloor habitat areas. The derived biomass estimates could be highly sensitive to area adjustments, particularly for some substrates such as sea urchin boulder habitat (Tables 1 and 2).

2.4. Sea cucumber and sea urchin abundance estimates

Sea cucumber and sea urchin densities by depth and substrate were extrapolated to the total area of each stratum and habitat area (Tables 1 and 2). We converted the estimated number of individuals to the fishery unit of split, drained sea cucumber weight (in pounds) using the conversion factor of 0.63 pounds per cucumber (Bradbury et al., 1998). We then calculated a harvestable biomass for the area using the estimates for depths shallower than 36 m (harvestable depths), and excluding areas closed by regulation to commercial harvest on either side of San Juan Island (Fig. 1).

For urchins, the total number of animals was adjusted to estimate the proportion of this population of legal harvest size (between 83 and 127 mm test diameter, exclusive of spines). Because urchin size could not be reliably measured from the ROV videos, we employed the most recent survey of test diameter distributions in the area, which was conducted in 2008 (WDFW unpubl. data). To apply the test diameter data to the ROV results, it was necessary to estimate the smallest diameter urchin detectable on the videos. Using serendipitous video segments wherein the 100 mm width lasers passed over smaller urchins, we estimated ~50 mm to be the minimum size detected. On the basis of the test size distribution data, we used a factor of 0.330 to convert from total urchins viewed to total legal-sized urchins. We converted the estimated number of legal-sized individuals to the fishery unit of pounds using the conversion factor of 0.905 pounds per legal urchin. That was the average weight of 1191 legal-sized red urchins collected during the most recent dockside sampling studies in 2003 and 2004 (WDFW unpubl. data). Obtaining updated size-frequency distributions and size-weight relationships is a management priority to reduce these potentially large sources of uncertainty in biomass estimation.

We had access to both ROV survey data and seafloor habitat data from only a portion of the total San Juan Island sea urchin and sea cucumber management districts (Fig. 1). However, this study area was also where the majority of animals have been harvested his-

torically. In the absence of information about the remainder of the districts, the biomass estimates were extrapolated to the entirety of the management district for each species using proportional harvest data. This method assumes that the amount harvested in the various subareas is proportional to abundance, i.e., the harvesters know where the harvestable animals are located. Using records stretching back to the year 2000, we calculated that only 18% of San Juan Island sea cucumber harvest occurs outside the study area. Therefore we multiplied the harvestable biomass estimate made for the study area by 1.210 to extrapolate to the rest of the management district. Coincidentally, a very similar correction factor (1.209) was calculated on the basis of proportional sea urchin harvest in the San Juan Islands, despite a difference in urchin and cucumber management districts (Fig. 1).

2.5. Relative abundance over time

Since 1984, red sea urchins and sea cucumbers have been counted on a number of index sites in the San Juan Islands during late summer and early autumn. These permanently marked index sites consist mainly of shallow (<20 m depth), hard-substrate habitats, and were selected to be representative of high-density urchin and cucumber habitat. SCUBA divers surveyed one fixed transect per site that was 46 m long and 2 m wide, counting all red sea urchins and sea cucumbers. Transects were not subdivided and densities from the single, fixed transect at each site were the unit of analysis. Densities from multiple sites were averaged to produce one index site survey density for each year (Fig. 4). Although these survey locations are biased toward certain habitats and depths, and cannot be used to estimate absolute biomass, they can serve as an index for the relative abundance of animals on such habitats. Various sites have been established and abandoned over the years, but for this analysis we restricted the data to the 30 most-visited sites (Fig. 1). These sites were visited a minimum of 6 different years over the time series, and have observations on either side of a gap in data collection between 1995 and 2005. We eliminated survey years in which less than ten of the sites were surveyed (1987, 1989, and 2010). We separately report data from 3 additional sites, visited in 2005, 2008, and 2011, that were established in areas closed to harvest. These two areas on either side of San Juan Island (Fig. 1) have been closed to commercial harvest since 1987, but were subject to harvest before that time.

2.6. Harvester logbook data

Non-tribal harvesters are required to complete harvest logbooks during each harvest day that include: coordinates of harvest; number of divers; hours of diving; pounds of split, drained product harvested; and harvest depths. From these logbooks an annual average catch-per-unit-effort (CPUE) can be calculated for each fishery using the units of pounds diver^{-1} hour^{-1}. Between 2001 and 2013, harvesters completed a total of 12,637 logbook entries for sea cucumber, and 1,560 entries for sea urchin in the San Juan Islands District.

2.7. Estimates of virgin biomass

To place current harvest management in the context of pre-fishing population levels, we attempted to approximate the biomass of sea cucumbers and red sea urchins that may have existed before any harvest occurred. We employed the method of Uthicke et al. (2004), who applied densities found in areas closed to fishing to total habitat area to estimate virgin biomass. In September 2015 we surveyed seven sites in the areas closed to fishing that had an abundance of sea cucumber and red sea urchin. SCUBA survey methods were identical to text Section 2.5 above.

We applied the resulting densities to the habitat areas calculated in text Section 2.3 above, but only to the bedrock, boulder, and cobble areas represented by the substrate found at the survey sites. Although other habitats, such as sand and mud, could potentially have reduced densities compared to pre-fishing levels, they are not commonly harvested.

3. Results and discussion

3.1. ROV survey, habitat and depth associations, and biomass estimates

Densities of both sea cucumber and sea urchin are relatively low below the 55 m depth contour (Fig. 2), although some animals were sighted in the deepest transects (below 274 m). Densities of both sea cucumber and sea urchin increased as water depth decreased, with the exception of the shallowest depth bin, where density was conspicuously low. Although a number of factors might contribute to the scarcity of both species in shallow water, the possibility exists that harvest is the primary agent. There are not sufficient ROV transects in areas closed to fishing to confirm that harvest is the primary cause of low densities in shallow water, although evidence from index stations located in the closed areas supports this assertion, particularly for sea cucumber (see text Section 3.3). According to the maximum depth of harvest reported in non-tribal harvest logbooks from 2001–2013, 86% of the red urchin and 62% of the sea cucumber in the San Juan Islands are harvested shallower than 18 m. The predominance of shallow harvest is most likely due to the constraints of diving. Harvesters can decrease the risk of decompression sickness and spend more time harvesting per day if they avoid deep water.

Both species occur in higher densities on hard substrates such as bedrock or boulders, in intermediate densities on cobble, pebble, and shell, and in lower densities on soft substrate such as sand or mud (ANOVA, sea cucumber $P = 0.003$, sea urchin $P < 0.001$, with post-hoc, pairwise Tukey tests). Boulder habitat, in particular, holds the highest densities of both species (Fig. 3).

The seafloor habitat map combined with ROV-derived, habitat-associated densities yielded a harvestable biomass estimate of 5.9 million pounds (4.3–7.7 million pounds 95% confidence interval) of sea cucumber in the San Juan Islands District (Table 1). The majority of these animals are located on hard-substrate habitat typical of traditional harvest areas, including bedrock and boulder (48%) and cobble, gravel, and shell (34%). Although sand- and mud-dominated habitats hold low densities of sea cucumber (Fig. 3), they still contain a significant portion of the population (18%) because of their large area relative to other habitats. Due to lower densities detected in the shallowest depth bin (Fig. 2), over 80% of harvestable biomass lies in the deeper half of the harvestable range (Table 1).

The harvestable biomass estimate for legal-sized red sea urchins is 8.9 million pounds (6.8–11.0 million pounds 95% confidence interval) in the San Juan Islands harvest district in 2010 (Tables 2). This distribution is even more skewed towards solid substrate like bedrock and boulder (79%) compared to cobble, gravel, and shell (17%) and sand and mud (4%).

The previous biomass estimates were made using drop-cameras in 1994 (Bradbury et al., 1998) and were surprisingly similar: 5.6 million pounds of sea cucumber and 8.8 million pounds of red sea urchin (after adjusting for changes in the management district areas). The two sets of estimates were made with different methods; the previous study lowered a tripod-mounted, 360° panning camera to the bottom at shallow and deep stations at 2 km intervals along San Juan Island shorelines (Bradbury et al., 1998). Despite considerable methodological differences, the results could be taken as evidence that the 16 years of harvest that occurred

between the two estimates did not reduce the harvestable biomass, and is therefore sustainable. On the other hand, the 1994 surveys were conducted immediately after the peak landings period for both species, and most likely represent significantly reduced populations that have not apparently recovered (see text Section 4.4). Also, there are doubts that the 1994 survey, originally designed for rockfish, accurately calculated the area swept by the drop camera in which benthic animals, as opposed to benthopelagic fish, could be detected on complex habitat. If so, the resulting biomass figures could be significant underestimates, meaning that echinoderm populations have continued to decline during the quota management era.

The brief 2015 SCUBA survey of areas closed to fishing found an average density of 0.34 sea cucumbers m^{-2} ($\pm$ 0.08 S.E.) on hard substrates, which may approximate the pre-fishing density. This estimate is higher than the average density found on index stations (see text Section 3.4 below) in the earliest survey year that included sea cucumber counts (1988, 0.22 sea cucumbers m^{-2}), although that survey occurred well into the rapid-developing fishery. Replacing the densities used in biomass calculation (Table 1) for bedrock, boulder, and cobble habitats with 0.34 sea cucumbers m^{-2} results in a rough virgin biomass estimate of 18 million pounds of sea cucumber, about three times the current estimate.

The same SCUBA survey showed an average density of 2.19 red sea urchins m^{-2} ($\pm$ 0.59 S.E.) in the areas closed to fishing. This estimate is more closely aligned to early surveys of index sites between 1984 and 1990, which found average densities between 2.12 and 2.40 urchins m^{-2} (Fig. 4). This density, applied to the hard substrates in Table 2, results in an approximate virgin biomass estimate of 47 million pounds of red sea urchin in the San Juan Islands district. That is about 5 times the current biomass estimate. There is no way to know the true virgin biomass of either species in the San Juan Islands, and it is important to remember that the closure areas used to approximate virgin biomass were founded in 1987, after significant fishing had occurred. We make these approximations to report current harvest quotas as a percentage of both the current biomass estimate and as a percentage of "virgin" biomass (see text section 3.5 below).

3.2. Evaluation of ROV methodology

There was no significant difference in sea cucumber or red sea urchin density calculated using the diver and ROV survey methodologies. Divers observed 1015 sea cucumbers over 17 transects, averaging 60 individuals per transect and a density of 0.091 cucumbers m^{-2}. After video review, the ROV observed 755 sea cucumbers over similar transects (smaller in area), averaging 44 individuals per transect for an average density of 0.084 cucumbers m^{-2}. In a paired t-test, this 7.5% difference between the two methods was not statistically significant ($P = 0.708$) and can most likely be attributed to random variation in distribution over similar, but not duplicate, transects. There were nearly an equal number of transects on which the diver density was higher ($n = 9$), as those on which the ROV density was higher ($n = 8$). Given the distribution of pairwise differences in density detected, the 17 transects would have been able to detect a 50% difference for sea cucumber ($\alpha = 0.05$, $1 - \beta = 0.7$), but ~60 transects would have been necessary to detect a 25% difference.

For urchins, divers observed 2877 individuals over the 17 transects, averaging 169 individuals per transect and a density of 0.228 urchins m^{-2}. After video review, the ROV observed 2242 red sea urchins over similar, smaller transects, averaging 132 individuals per transect for an average density of 0.225 urchins m^{-2}. In a paired t-test, this 1.2% difference between the two methods was not statistically significant ($P = 0.917$). Despite wide differences in urchin density between methodologies on some transects (mean difference 0.08 urchins m^{-2}), the overall average densities were
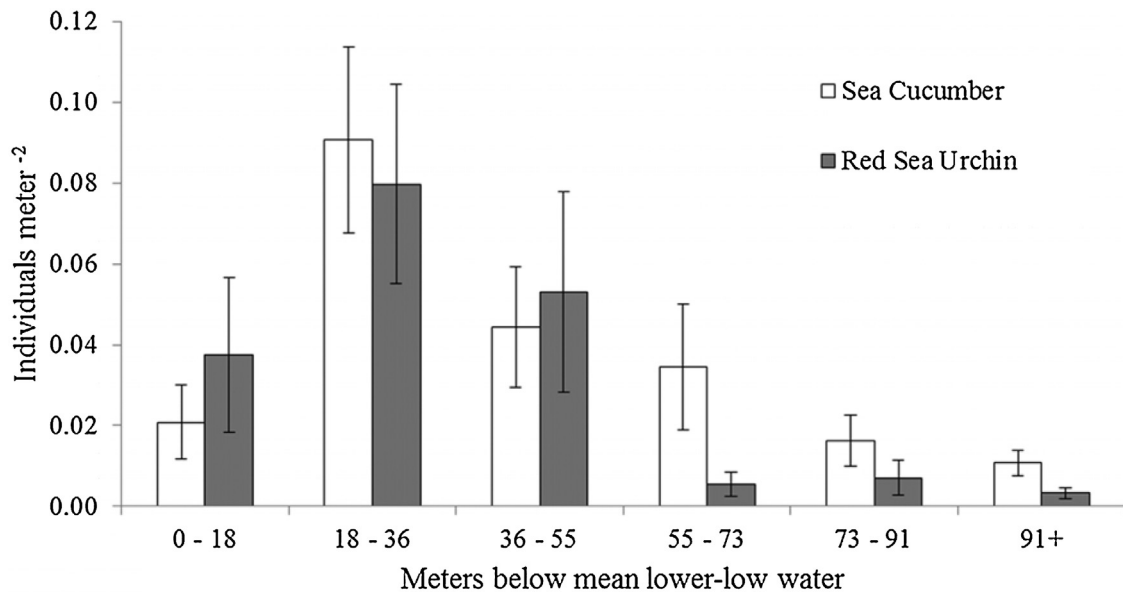
Fig. 2. Sea cucumber (*Parastichopus californicus*) and red sea urchin (*Mesocentrotus franciscanus*) densities by depth bin on ROV transects in the San Juan Islands. Error bars are the standard error of the mean.
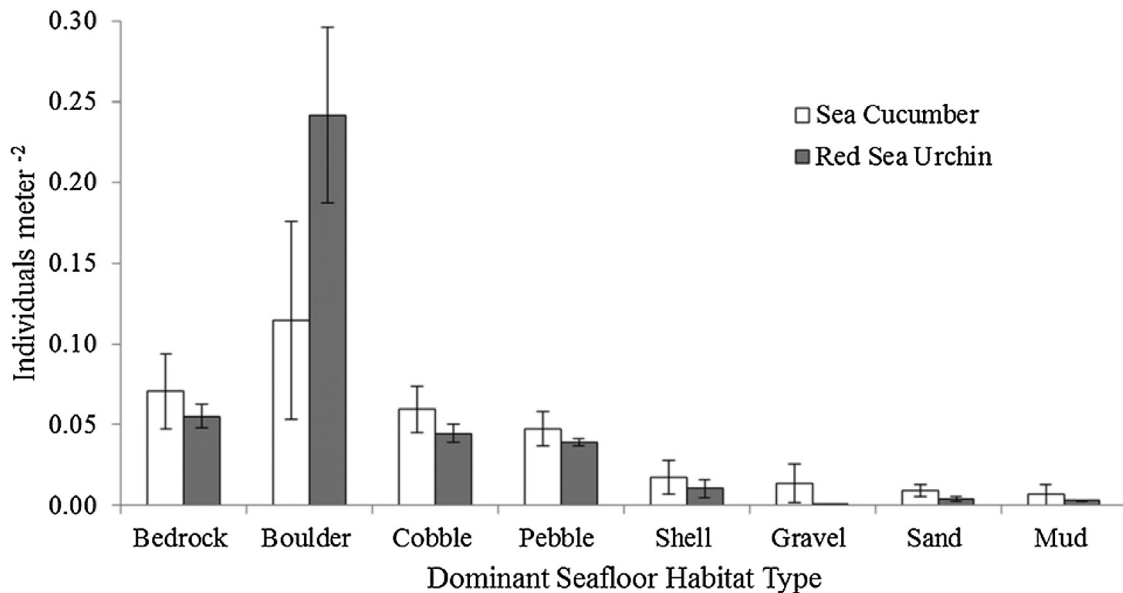

Fig. 3. Sea cucumber (*Parastichopus californicus*) and red sea urchin (*Mesocentrotus franciscanus*) densities by dominant seafloor habitat type on ROV transects in the San Juan Islands. Error bars are the standard error of the mean.

remarkably similar. There were a similar number of transects on which the diver density was higher ($n = 7$), as those on which the ROV density was higher ($n = 9$), with the final transect a tie. Given the distribution of pairwise differences in density detected, the 17 transects would have been able to detect a 35% difference between methods ($\alpha = 0.05$, $1 - \beta = 0.7$), but ~30 transects would have been necessary to detect a 25% difference.

Although the study design and equipment did not allow for the ROV to exactly replicate the diver transects, the results show that if either method had been employed to determine the density of echinoderms in the vicinity of the study sites, the resulting densities would not be significantly different. The differences in detection rates between the two methods are still potentially important; however, barring further study, fishery managers have opted not to use an adjustment factor for individuals that might have been missed by the video capture system and review process. Therefore

we report the ROV-derived biomass estimates here without any such adjustment.

The evaluation study was designed to detect differences in the two methodologies, and did not compare either to the "true" density of animals present. Divers did not conduct an exhaustive search – such as turning over kelp blades or rocks – and undoubtedly missed some obscured individuals. With the resources available, it would be prohibitively time consuming to exhaustively survey the substrate on each transect. Also, it is unclear whether such cryptic animals are commonly subject to harvest.

3.3. Relative abundance over time

Red urchin densities on 30 index stations in the San Juan Islands declined precipitously during the years of peak harvest (Fig. 4), at an average rate of 0.145 urchins m^{-2} year^{-1} ($R^2 = 0.868$, $P = 0.002$). In the beginning of the quota era in 1995, funding was unavailable to
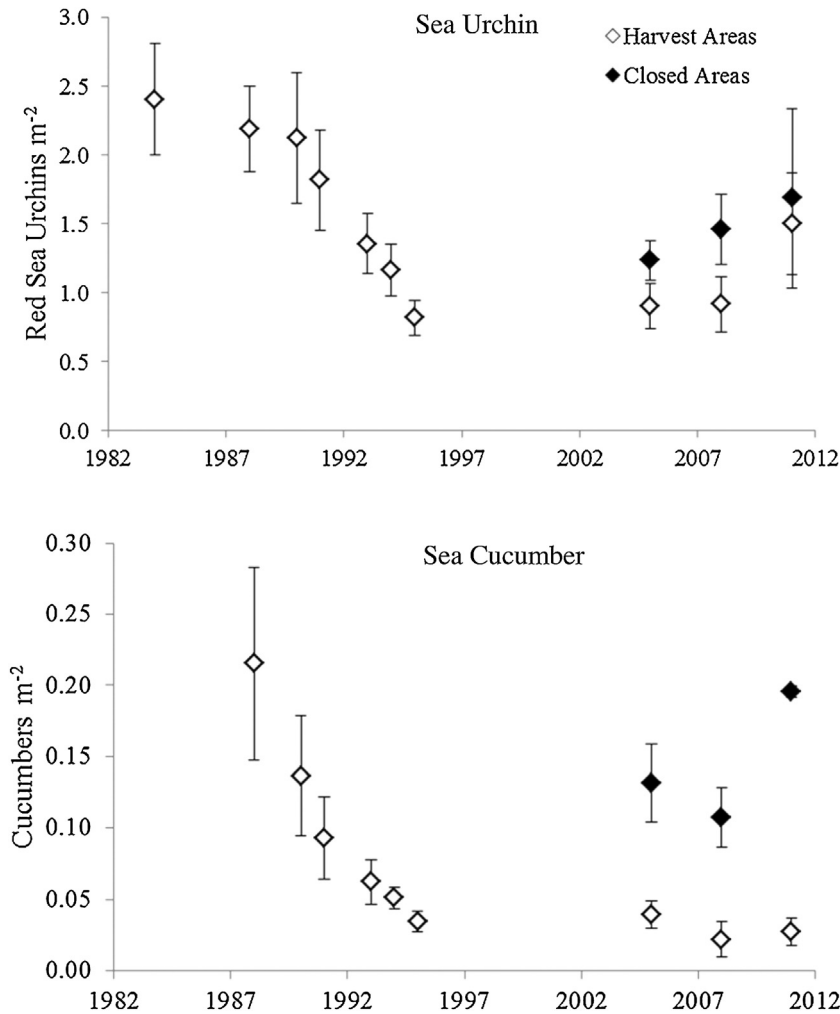
Fig. 4. Relative abundance of all sizes of red sea urchins *Mesocentrotus franciscanus* (top) and sea cucumbers *Parastichopus californicus* (bottom) on SCUBA index stations in areas open to harvest (open symbols) and areas closed to harvest (closed symbols) in the San Juan Islands. Error bars are the standard error of the estimated mean. Note that the *y*-axis scale for sea cucumber is one-tenth that of red sea urchin.

continue monitoring index stations. Monitoring resumed in 2005, and showed that quota management had apparently arrested the population decline, but had not allowed for recovery. At that time, 3 index stations were established in the areas closed to fishing and showed that densities were apparently similar, if slightly higher, there. The most recent survey in 2011 showed a marked increase in urchin density, immediately following 3 years of very low effective harvest rates (0.2–0.5%) as calculated using total catch each year divided by the 2010–11 biomass estimate presented here.

Sea cucumber density on those same sites also declined during the peak harvest years, at an average rate of 0.025 sea cucumbers m^{-2} $year^{-1}$ ($R^2 = 0.932$, $P = 0.002$). In contrast to the sea urchins, however, the density has continued to decline in the quota era (Fig. 4), and the three sites within closed areas show densities apparently similar to those observed in the beginning of the fishery.

To examine possible site-effects caused by an inability to survey every index site every year, we analyzed a subset of the index sites ($\underline{n} = 11$) from the period of 1990–2011 that were surveyed in each of the study years. The underlying trends for both species, including a steep decline before quota management, and lack of recovery since that time (with the possible exception of 2011 sea urchins), remain essentially unchanged when the possibility for site-effect-bias is removed. The higher within-year variability in the earlier survey years (demonstrated by wider standard error bars in Fig. 4) can be attributed to some sites with extremely

high densities of sea urchin (up to 6.7 m^{-2}) or sea cucumber (up to 0.9 m^{-2}). No such densities were detected in later years, significantly reducing the variance around each year's average density.

The results of red urchin index station surveys track the harvest history of the fishery, with sharp declines before quota management, stability afterward, and a recent sign of possible recovery (Fig. 4). Of course, many factors other than harvest affect the abundance of sea urchins, not the least of which is an unknown and potentially highly variable recruitment rate. Anecdotal information from fishery managers in other states suggests that infrequent years of high recruitment may drive fluctuations in urchin abundance, as has been suggested in populations of purple sea urchin *Strongylocentrotus purpuratus* (Tegner and Dayton 1991) and other long-lived, broadcast-spawning marine invertebrates (reviewed in Hobday et al., 2000). The comparison between index stations inside and outside the harvest closure area suggests that factors independent of harvest are important, although more sites are needed in the closed areas to investigate this further. Other researchers have found that these harvest closure areas contain more numerous and larger red sea urchins (Tuya et al., 2000). Future surveys of the index stations are needed to confirm that relative abundance of red sea urchins is indeed continuing to increase, and include a larger variety of depths and habitats.

In contrast to the red sea urchins, sea cucumber density on index sites has continued to decrease after quotas were instituted (Fig. 4), possibly due to an effective harvest rate three times that of sea urchins (see text Section 3.5). Comparison to the 3 sites inside the closed areas, which have densities similar to that of the earliest surveys, provides further evidence that harvest is the main factor contributing to the lack of recovery and continued decline of sea cucumber relative abundance. More index sites within the closed areas will be established in the future, so that open and closed sites can be statistically compared in a suitable manner.

3.4. Harvest logbook data

In the San Juan Islands, non-tribal harvester logbooks show a decline in sea cucumber catch-per-unit-effort over the last 12 years (Fig. 5) that equates to an average of about 2.5 pounds less per diver hour each year. No such decline was detected from red sea urchin log books (Fig. 5), although that time series has been somewhat more erratic; a steep decline in CPUE from 2007 to 2010 has been negated by relatively high CPUE in the last 3 harvest seasons. Perry et al. (2002) suggest the analysis of median instead of mean CPUE to avoid influence of potential outliers in logbook information. The use of medians instead of means with the present data, however, did not significantly change the underlying relationships.

Another possible sign of overfishing that comes from harvest logbooks is the time series of mean maximum depths of harvest reported. If echinoderm stocks were declining in shallow water, we would expect harvesters to search deeper to find unexploited animals. However, there was no trend detected in mean harvest depth for either sea urchins or sea cucumbers over the last 12 years.

Biomass estimates derived from fishery-independent means such as SCUBA or ROV surveys are preferable to fishery-dependent methods, because fishery-dependent methods are fraught with difficulty (Maunder et al., 2006), particularly with dive fisheries (Schroeter et al., 2001). For instance, increases in fleet efficiency due to fisher experience level, new technology, and scouting, and/or aggregation behaviors from the animals themselves, can easily mask the signs of overfishing (Maunder et al., 2006). We have no evidence that the tribal or non-tribal fishing fleets are getting more efficient. The non-tribal fleet is primarily composed of seasoned fishers, meaning they have considerable experience locating harvestable animals. Whether or not this experience continues to increase catch-efficiency, or if instead the fleet is getting less efficient due to diver age or some other factor, is unknown.

Barring such changes in fleet efficiency, it should be more difficult for harvesters to locate and capture sea cucumbers or sea urchins if the stocks are declining. The number of pounds harvested per diver hour should then qualitatively reflect the relative abundance of the stock. Therefore, harvester logbook data from non-tribal harvest during 2001–2013 can still be examined to look for additional, but not primary, evidence for or against fishery sustainability. In the San Juan Islands, a decline in CPUE for sea cucumbers over the quota management era supports the results from index stations that stocks are not recovering from historic intensive harvest. There is no such decline detected in red sea urchin CPUE, and although this also agrees with stability of the index station results for urchins, is not necessarily evidence of population stability.

3.5. Vulnerability of the sea cucumber and red sea urchin fisheries to over-exploitation

Both species are harvested in the same habitats, by largely the same harvesters, and share a common history of exploitation—most notably intensive harvest in the late 1980s and early 1990s. Available information on each stock, collected in parallel, suggests that the status of each has diverged over the ensuing quota management period. The red urchin fishery appears to have stabilized, and may be showing signs of population increase (Fig. 4). In contrast, the San Juan Island sea cucumber fishery has not demonstrated recovery from historic intensive harvest, as relative abundance and catch-per-unit-effort have continued to decline during the quota management era. It is possible that the sea cucumber fishery is slower to recover from over-exploitation than the sea urchin.

A key difference in management between the two fisheries is the minimum and maximum harvest size restriction in place for sea urchin. These likely add to the population's resilience to exploitation, as individuals are allowed to spawn at least once before harvest, and the largest individuals are preserved to maintain reproductive output (Ebert 1998). Larger individuals may also provide refuge for juvenile recruitment and survival in the "spine canopy" (Pfister and Bradbury 1996), although the importance of juvenile survival in these long-lived animals has been questioned (Ebert 1998). On the other hand, the plasticity of the sea cucumber body, which can rapidly expand and contract in length, width, and weight, makes setting a minimum or maximum size for the fishery impossible to enforce. Fishers report an informal agreement to not harvest small individuals that may not yet have reproduced, and processors report that they reject or devalue loads with a high percentage of small cucumbers. However, it is not clear how closely these agreements are followed, and there are reports of a demand specifically for smaller individuals in some markets.

Differing stock status may be partly due to changes in market demand, which has shifted the harvest fleet's primary focus from one species to the other. The Chinese market price for sea cucumbers from Washington and other countries has increased in recent years (reviewed in Toral-Granda et al., 2008). The ex-vessel price per pound for Washington sea cucumbers has increased over two-fold, from less than US$2 per pound (adjusted to today's dollars to account for inflation) in the early 1990s to the current level of over US$5, and the quotas are fully utilized. Meanwhile the price of sea urchins has dropped two-fold after adjusting for inflation to between US$0.5 and US$1 a pound, and approximately 50% of the quotas are harvested in most years (WDFW unpubl. data). This shift may be due to the economics of the nations to which the products are primarily exported. China, which imports the majority of sea cucumbers harvested from Washington, has recently had rapid economic growth compared to that of Japan, which receives the majority of exported Washington sea urchins.

Varying management practices have also likely impacted the differing status of each species. The quotas for the San Juan Island management areas through the 2013–14 management year represented a 3.9% harvest rate for red sea urchins, while the quota for sea cucumbers translates to an 11.4% harvest rate, based on the biomass calculated in the 2010–11 ROV survey. These quotas are 0.7% and 3.8%, respectively, of our coarse estimates of virgin biomass for red sea urchin and sea cucumber. The appropriate harvest rates for either species in Washington State waters are unknown. The urchin harvest rate in Washington lies midway between harvest rates in Southeast Alaska (6%)[1] and British Columbia (2%).[2] The 11.4% harvest rate of sea cucumbers, however, is well above management schemes from neighboring jurisdictions. British Columbia uses a 4.2% harvest rate for sea cucumbers, and according to a recent experimental fishery and modeling paper (Hajas et al., 2011), that rate "appears to be conservative and sustainable for all but very

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[1] http://www.adfg.alaska.gov/index.cfm?adfg=redseaurchin.management last accessed October 2015.

[2] http://www.dfo-mpo.gc.ca/science/publications/uww-msm/articles/urchin-oursin-eng.htm last accessed October 2015.
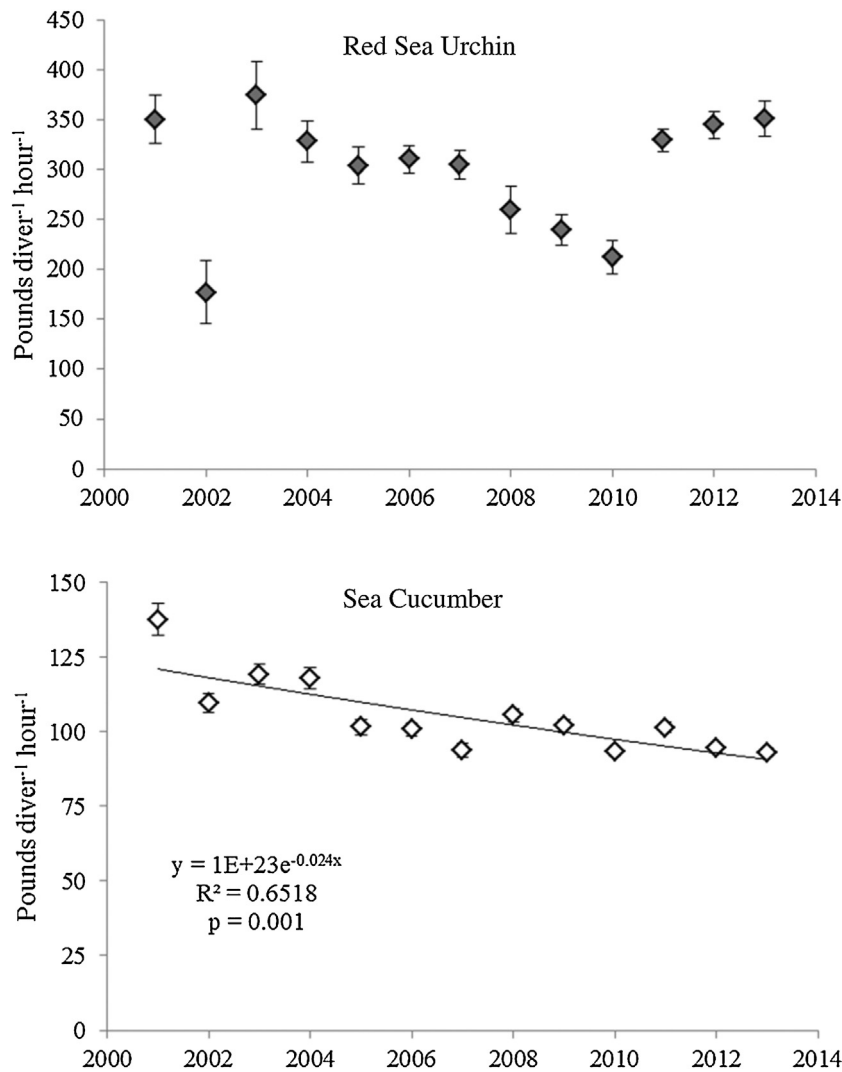
Fig. 5. Mean catch-per-unit-effort over the last 12 harvest seasons for red sea urchin (top) and sea cucumber (bottom) in the San Juan Islands. Error bars are standard error of the estimated mean. Statistics reported for sea cucumber are from an exponential regression. Note that the *y*-axis scale for sea cucumber is one-third that of red sea urchin.

unproductive areas." Alaska uses a 6.4% sea cucumber harvest rate,[3] but that rate is applied to the lower-bound confidence interval of harvestable biomass and so, in effect, likely matches the British Columbia rate. Oregon and California do not manage their echinoderm fisheries using biomass estimates, quotas, or target harvest rates.

There is also a major difference in the way that sea cucumber biomass is calculated in Washington compared to neighboring jurisdictions to the north. Biomass is calculated to the 15 m depth contour in Alaska (ADFG, personal communication), and 18 m in British Columbia (Duprey et al., 2010) in contrast to the 36 m depth used in Washington. This additional depth not only increases the area estimate used in calculation, but given the current distribution of both species (Fig. 2), increases the total harvestable biomass estimate considerably. According to log books, non-tribal harvesters take 62% of their catch from the 0–18 m depth bin, which holds only 18% of the sea cucumbers in the harvestable range (Table 1). The effective harvest rate on sea cucumbers in shallow water, then, is likely much higher than the target rate for the fishery as a whole. This potential for depletion in shallow water not only

could drive harvesters deeper, but also could reduce the ecosystem services sea cucumbers provide to shallow habitats, including bioturbation, nutrient recycling, and acting as prey (reviewed in Anderson et al., 2011; Purcell et al., 2016, in press). Although red sea urchin harvest is more heavily skewed to shallow water (86% of non-tribal harvest occurs in the 0–18 m depth bin), the animals' current distribution is more aligned to harvest effort, with the majority (63%) of the harvestable biomass located in the shallow half (Table 2).

If sea cucumber stocks in Washington are slower to recover from overharvest, it would be far from unprecedented. Sea cucumbers have been exploited around the world for much longer than the Washington State fishery (Toral-Granda et al., 2008). Although those fisheries target different species and often occur in very different habitats (e.g., tropical coral reefs, seagrass meadows) the vast majority have experienced the same pattern of exploitation seen currently in Washington (Anderson et al., 2011), sometimes over multiple cycles. Lessons from past collapsed sea cucumber fisheries, therefore, may be relevant to our management decisions (Purcell et al., 2013). In several fisheries that have been closed due to concerns of overharvest, the recovery of sea cucumbers has been non-existent or slow (Lincoln-Smith et al., 2000; Uthicke et al., 2004; Ahmed and Lawrence 2007; Skewes et al., 2010). Taken

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[3] http://www.adfg.alaska.gov/index.cfm?adfg=redseacucumber.management last accessed October 2015.

together, a recent review suggested that recovery of stocks in the complete absence of fishing can take "on the order of decades" and that harvest rates on virgin biomass should be less than 5% (Anderson et al., 2011; Purcell et al., 2013).

One reason why Washington sea cucumbers could potentially recover faster than their counterparts on coral reefs or seagrass meadows are the unharvested individuals located below diveable depths that may act as a reproductive reservoir to replenish fished depths. However, this "depth refuge" does not appear to be significantly contributing to the resilience of sea cucumber populations to intensive harvest in Washington. The sea cucumbers observed by the ROV in deep water (Fig. 2) or on habitat not typically harvested such as sand or mud (Fig. 3) may be at densities below some threshold of fertilization efficiency of broadcast spawning, making them poor reproductive reservoirs no matter their collective abundance.

The Allee threshold for *Parastichopus* fertilization, below which gamete production is severely reduced due to the low density of adults, is unknown. The threshold in other broadcast spawning invertebrates varies considerably according to degree of aggregation, synchrony of spawning, flow regime, and mechanics of fertilization (reviewed in Levitan 1995). Observations of tropical sea cucumbers in the field documented 73–96% fertilization efficiency at densities around 1–2 individuals m^{-2}, and close to 0% efficiency at densities of 0.0025 m^{-2} (Babcock et al., 1992). What happens in between those two density extremes would be useful to know for sea cucumber stock management and restoration (Bell et al., 2008). A "rule of thumb" density for natural spawning success, used as a target in abalone recovery efforts, is 0.15–0.30 individuals m^{-2}, derived from laboratory and field studies (Babcock and Keesing 1999). Densities of sea cucumbers below harvestable depths or on unfavorable habitats in this study averaged less than 0.05 individuals m^{-2}.

3.6. Management response

The 11.4% effective harvest rate for sea cucumbers is likely too high to be sustainable. State and tribal managers have agreed to a stepwise approach for reducing the harvest rate over consecutive years. The quota for the 2014–15 management year represents a 10% harvest rate, with that rate to decrease by 1% each management year until indicators such as absolute biomass or relative abundance begin to increase. Fishery managers have also implemented a spring/summer fishery closure that occurs during the estimated time of peak spawning (Cameron and Fankboner, 1989; McCrae, 1994; Muse, 1998) and during a time when the animals' body wall and musculature (i.e., marketable portions) is thinnest. Percent recovery of the marketable portions after water and viscera are removed is lowest during the spawning period, which means that more individuals are taken to produce the same quota poundage. The closure period following the 2014–15 management year occurred in June and July, to be adjusted when the results of a two-year Lummi Nation Natural Resources study on sea cucumber gonad development is completed. Recent anecdotal evidence from harvesters and processors suggests this closure may be better placed in April and May.

The ability to efficiently mark and recapture sea cucumbers over long periods of time, either by genetic (e.g., Uthicke et al., 2004) or other means, would greatly aid in fishery research. This would not only allow for the estimation of growth and mortality of individuals in Washington waters, but could also elucidate important behaviors. For instance, there is considerable anecdotal evidence that some individuals migrate seasonally among depths, which if true has implications to the scheduling of monitoring efforts and the interpretation of past results. Published evidence for this species moving shallower in the summer months is based on observations of spawning individuals in shallow water, and not on actual movement studies (reviewed in Woodby et al., 2000) and is contradicted by other studies (e.g., Cripps and Campbell, 2000). Actual movement studies show random movement only (Da Silva et al., 1986) and recent observations from the San Juan Islands suggest *the opposite*—that cucumbers are concentrated in the shallows during winter (Britton-Simmons et al., 2012).

An interesting feature of dive fisheries in Washington State is multi-party management. Although dive fisheries in other jurisdictions have a variety of stakeholders whose needs must be balanced by managers, in Washington the actual research and management is shared by the state and up to 15 sovereign American Indian Tribes or tribal collectives. Scientific and policy discussions, therefore, resemble international negotiations more common in open-ocean fisheries. This decentralized system relies on trust and collaboration among parties, emerging out of a historical context of physical and legal conflict (Woods, 2005) to avoid gridlock and further litigation. It also limits the fisheries management tools available. For instance, in the early fisheries sea urchin and sea cucumber stocks were managed using a rotational system where the fishing fleet was directed to a different region each year. More recently, modeled rotational harvest schemes have been shown to increase yields and reduce the risk of collapse in tropical sea cucumber fisheries (Plagányi et al., 2015). Treaty fishing rights, however, occur in exclusive and overlapping zones particular to each treaty tribe, and therefore a statewide rotational harvest scheme would exclude many fishers each year and is not a realistic approach (*see also* Purcell et al., 2015). In fact, making any spatial adjustment to harvest pressure based on the observed abundance of animals is likely to benefit some parties at the expense of others. The overall goal of all Washington State fisheries managers, however, is to ensure that red sea urchins and sea cucumber populations provide ecosystem services and fishing opportunity in perpetuity.

Disclosures

Acknowledgments

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