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Estimates of availability and catchability for select rockfish species based on acoustic-optic surveys in the Gulf of Alaska

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A R T I C L E I N F O

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A B S T R A C T

Fishery-independent surveys, such as bottom trawl surveys, provide time-series abundance estimates, which inform many modern stock assessments. Area-swept biomass estimates from trawl surveys assume that fish densities do not differ between trawlable (T) and untrawlable (UT) areas. Bias and imprecision in the biomass estimates can occur when this assumption is not met. Thus, reliable estimates are needed for both the extent of T and UT habitat types in the surveyed area, and the relative densities of the fish species in the two habitat types to accurately assess groundfish populations. Acoustics and stereo-camera survey tools were used in the present study to determine the extent of T and UT habitat within 25-km^2 bottom trawl survey grid cells historically designated as T/UT. Splitbeam acoustics were used to compare the abundance of rockfishes (*Sebastes* spp.) between the T/UT grid cell areas. Acoustic data were collected along uniformly spaced transects within 52 T and 43 UT grid cells throughout the Gulf of Alaska during summers 2013, 2015, and 2017. The acoustic backscatter attributed to rockfishes in UT grid cells was approximately three times that in T cells, and the percentages available to the bottom trawl survey were 40 % for harlequin rockfish, 43 % for northern rockfish, 51 % for dusky rockfish, and 98 % for Pacific ocean perch (POP). These findings allowed for estimation of the trawl catchability coefficient (*q*; a scaler between estimates of the area-swept survey abundance and actual abundance) of 0.46 for harlequin rockfish, 0.50 for northern rockfish, and 0.64 for dusky rockfish, and 1.15 for POP. These values could be used to inform the relationship between trawl survey estimated and actual abundances of rockfishes to improve the accuracy of stock assessments for these species.

1. Introduction

Statistical catch-at-age assessments of marine fishes are the backbone of modern fishery stock assessments (Hilborn, 1992; Quinn and Deriso, 1999; Deriso, 1980). These assessments typically rely on fisheries-independent time series of stock biomass from sources such as standard bottom trawl surveys (von Szalay and Raring, 2016), acoustic-trawl surveys (Stienessen et al., 2017), longline surveys (Sigler, 2000), and/or underwater camera surveys (O'Connell and Carlile, 1993; Yoklavich et al., 2000). For some species such as rockfishes, which can be difficult to age, biomass estimates from fisheries-independent surveys can be used directly to set total allowable catch using methodologies such as Kalman filters (Spencer and Ianelli, 2005) or multi-year running averages (NPFMC, 2017). Stock assessments are thus largely dependent on unbiased estimates of stock size from fisheries-independent surveys.

For fisheries-independent surveys, the estimated abundance is a function of the catchability (*q*) of the trawl survey, which scales the area-swept survey estimates to population abundance. Catchability for a species and gear is composed of two primary components, the effectiveness of the gear in capturing the species (i.e., species vulnerability to capture) and the species availability in terms of the survey area and in relation to the gear (Arreguín-Sánchez, 1996; Cordue, 2007; Somerton et al., 1999). When components of the catchability coefficient are uncertain, error may be introduced into the assessment to bias resulting population estimates. Gear effectiveness could be related to length (age) selectivity based on such factors as gear mesh size, and could also be related to behavioral responses of the species to the gear such as herding or diving. The availability component of catchability is the probability

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of the fishing gear encountering individuals in the population (Marr, 1951). If a population is not uniformly distributed in time and space, or a fraction of the population is in habitat that is inaccessible to the sampling gear, a constant value or prior distribution on q based on auxiliary information is informative to account for availability, and thus catchability, of individuals of a species.

Population assessments for fisheries in the Gulf of Alaska (GOA) rely heavily on the biennial bottom trawl survey conducted by the Alaska Fisheries Science Center (AFSC). The bottom trawl survey routinely encounters areas deemed untrawlable due to high vertical relief. Many fish species, especially rockfishes, associate with, and find refuge in, high-relief substrate, where bottom trawl surveys are ineffective (O'Connell and Carlile, 1993; Yoklavich et al., 2000; Zimmermann, 2003). Abundance of many rockfishes can vary considerably between trawlable and untrawlable areas (Jagielo et al., 2003; Jones et al., 2012; Krieger and Sigler, 1996; Rooper et al., 2007, 2010; Stein et al., 1992). Nevertheless, mean estimates of species catch-per-unit-effort (CPUE) from locations sampled by the bottom trawl are expanded across the entire survey area, including untrawlable areas, to estimate the population biomass. This extrapolation of abundance from trawlable to untrawlable areas thus represents a substantial source of uncertainty (and potential bias) in absolute survey abundance estimates. Species that inhabit both habitat types to differing degrees should have corrections applied to their catchability coefficient to account for the proportion of the stock that is unavailable to the sampling gear (Cordue, 2007).

Acoustic-trawl surveys can effectively assess pelagic rockfish populations in areas of relatively low relief (Wilkins, 1986; Richards et al., 1991; Stanley et al., 2000; Krieger et al., 2001), to permit water-column estimates of abundance in untrawlable habitat. However, fishes on the seabed or in close proximity to the seabed within the acoustic dead zone will be largely undetected (Ona and Mitson, 1996), particularly in areas where the bottom terrain is rough or variable (Demer et al., 2009). In areas of high topographical relief, where abundance estimates are not possible near the seabed using acoustics and trawling, stereo camera surveys can provide information on species composition and abundance (Jones et al., 2012; Rooper et al., 2010).

The primary objective of this study was to use a combination of acoustic backscatter measurements and underwater imaging to improve estimates of availability of four rockfish species in the GOA; Pacific ocean perch (POP; *Sebastes alutus*), northern rockfish (*S. polyspinis*), dusky rockfish (*S. variabilis*), and harlequin rockfish (*S. variegatus*) to the NMFS GOA bottom trawl survey. This objective was accomplished by conducting acoustic surveys and deploying a lowered stereo camera (LSC) in grid cells designated as trawlable or untrawlable to determine substrate trawlability and fish species abundance. These data were used to develop estimates of density in the different habitat types and ultimately determine the availability, and thus catchability, of specific rockfish species to a survey bottom trawl.

2. Methods

This study was conducted across the GOA shelf during the biennial GOA acoustic-trawl surveys that took place June 8 - Aug. 9, 2013 (Jones et al., 2014), June 11 - Aug. 16, 2015 (Jones et al., 2017), and June 12 - Aug. 14, 2017 (Jones et al., 2019). All of the surveys were conducted aboard the NOAA ship, *Oscar Dyson.* At the completion of daily survey activities, sampling areas were selected from nearby "trawlable" or "untrawlable" grid cells as designated by the AFSC GOA bottom trawl survey (BTS; von Szalay and Raring, 2018). The GOA BTS follows a random-stratified design where stations are defined by a 7.3 nmi^2 (25 km^2) grid pattern overlaid on the entire survey area. Each grid cell visited throughout the survey time series has been designated as either trawlable or untrawlable based on 1) the captain's evaluation of the bottom hardness and terrain as determined from the echosounder returns, and/or 2) whether a successful tow with bottom contact for 15 min at 3 knots is possible within the grid cell. Sites were selected opportunistically close to where daytime survey activities ended. Grid cells were surveyed at night between ~0000 and 0600 Alaska local time. Five grid cells were surveyed opportunistically during daylight hours in 2015 and one grid cell was surveyed in 2017 during daylight hours. Grid cells were chosen with the goal of surveying a similar number of trawlable and untrawlable grid cells by the completion of the Gulf-wide survey each year. Once a grid cell was selected to sample, acoustic data were collected along three parallel transects spaced ~0.9 nmi (1.7 km) apart within the cell. While surveying transects, areas with high amounts of backscatter or uneven topography were identified as potential sites for lowered stereo camera sampling to characterize the seabed vertical relief and composition (e.g., boulders, rock formations) and species composition of the fishes.

2.1. Acoustic equipment and backscatter processing

Acoustic measurements were collected along transects using a calibrated Simrad (Kongsberg AS, Horten, Norway) EK60 scientific echo sounding system (Simrad et al., 2008) with five split-beam transducers (18, 38, 70, 120, and 200 kHz). The split-beam transducers were mounted on the bottom of a retractable centerboard, positioning the transducers 9.15 m below the water surface during survey activities. A pulse length of 0.512 ms and ping rate of 1.0 s were used for all EK60 data collections. Nominal half-power beam widths were 7° for the 38, 70, 120, and 200 kHz transducers and 11° for the 18 kHz transducer. Acoustic instruments on the vessel, other than the split-beam system, were turned off (e.g., bridge echosounder, acoustic Doppler speed log) during acoustic data collections. Myriax Echoview (version 4.70.48) was used for all post-processing and analyses of the acoustic data. The 38 kHz echosounder data were used for all quantitative rockfish backscatter measurements in this study. The EK60 system was calibrated following standard sphere calibration methods of Foote et al. (1987) prior to and following the surveys and the results were averaged in the linear domain.

For splitbeam data processing, the bottom discrimination line (i.e., resolution of seafloor range/depth) was determined for each frequency from the echo sounder's amplitude-based bottom detection as implemented in the echosounder software (Simrad ER60, version 2.1.2). For bottom discrimination, S_v (the backscatter strength of targets in a specified volume (MacLennan et al., 2002)), was set at a threshold of -36 dB re 1 m^{-1}. The mean of the sounder-detected bottom discrimination lines from all five frequencies was used as the bottom integration line (Jones et al., 2011). All echograms were examined for bottom integrations. Backscatter was designated to a category (rockfish species, pollock, bubbles, or zooplankton mix) based on results of nearby research trawl catch data, location relative to the bottom, depth in the water column, acoustic frequency response (De Robertis et al., 2010), and results of lowered camera deployments. Acoustic backscatter was integrated from 16 m below the surface to within 0.25 m of the bottom integration line and averaged at 0.5 nmi horizontal by 1.0 m vertical resolution. All data were exported using an S_V threshold of -70 dB re 1 m^{-1}. Backscatter among years and between trawlability designations were compared using ANOVA with a significance level of 0.05.

2.2. Lowered stereo camera

Up to 4 locations within each grid cell with detectable near bottom backscatter or topographical features were selected for lowered stereo camera deployments (Supplemental Table 1; LSC) to identify and quantify fish species and to characterize seafloor topographic features and trawlability. The LSC system is similar to that described in Rooper et al. (2016) and consisted of two parallel-mounted machine-vision cameras spaced approximately 30 cm apart in underwater housings connected via ethernet cables to a computer in a separate underwater housing enclosed in a protective aluminum cage. A monochromatic/color camera pair was used each year, with image resolution varying as follows: In 2013, the monochromatic camera (JAI, CM-140GE) collected images at 1.45 megapixels, and the color camera (JAI, AB-201GE) collected images at 1.73 megapixels; In 2015, the monochromatic camera (JAI, AM-800GE) collected images at 2.05 megapixels, and the color camera (JAI, AB-800GE) collected images at 2.04 megapixels; In 2017, the monochromatic camera (Point Grey, BFLY-PGE_50S5M) collected images at 5.01 megapixels, and the color camera (Point Grey, BFLY-PGE_50S5C) collected images at 5.01 megapixels. Four high intensity strobe LED illuminators provided lighting and were activated at the surface when the camera unit entered the water and deactivated at the end of the deployment when the unit returned to a depth of approximately 10 m. In 2013 and 2015, each strobe was constructed of four Bridgelux® BXRA-C2002 arrays capable of producing 13,000 lumens at 200 W. In 2017 each strobe was constructed of two Cree CXB3590 arrays capable of producing 25,000 lumens at 200 W. The computer, cameras, and lights were powered by a 28 V NiMH battery pack. All camera systems were calibrated (Williams et al., 2010) to correct for intrinsic optical distortion parameters and extrinsic inter-camera epipolar geometry. Synchronous images were recorded at a frequency of one image per second. Images were processed with software that allowed direct measurements to be made from calibrated stereo camera images (Williams et al., 2016).

The LSC was deployed and retrieved using an electric winch with 6.35 mm (¼-inch) diameter coaxial cable. The monochromatic camera images were viewable in real time aboard the vessel at a rate of four images per second, which facilitated control of the camera distance above the seafloor. The camera system was suspended 1–2 m off the seafloor at an angle of approximately 30°. This position allowed a viewing path width of ~2.8 m which extended ~3 m in front of the LSC, although this varied with the distance of the LSC off the seafloor and the clarity of the water. As the ship drifted, the LSC surveyed the seafloor at a target speed of 1.9–3.7 km/h (1–2 knots) for transects lasting 15 min. During low current periods, the unit was towed slowly by the vessel to maintain constant movement over ground. However, the direction of drifting and towing was with the prevailing current or wind direction, and therefore directed transects were generally not possible. This was considered when positioning for the deployment. The area swept by the LSC was calculated as the viewable LSC path width multiplied by the distance traveled during a deployment determined using the ship's GPS.

Trawlability was determined at LSC locations based on measurements of substrate relief from camera images. The seafloor substrate was classified as trawlable or untrawlable based on substrate size and vertical relief. Untrawlable areas were defined as any substrate containing boulders rising higher than 25 cm off the seafloor, or bedrock with vertical relief and/or ruggedness that would likely prevent a bottom-trawl with rockhopper gear from passing over it without damage. If untrawlable features were detected during a deployment, the entire transect covered by the LSC was classified untrawlable based on the LSC images. An overall LSC trawlability for each BTS grid cell was determined based on combined LSC deployments within each BTS grid cell. If trawlability determination was mixed between LSC deployments within a grid cell, overall LSC grid cell trawlability was designated based on the total amount of UT grounds in camera images and consideration of BTS grid cell trawlabililty designation.

Fish observed in LSC images were identified to species and total lengths estimated when possible. Density in number per hectare for each species and deployment was calculated as:

$$\text{Species Density} = \#/(w*D)*10,000 \tag{1}$$

where # is the number of individuals observed in the deployment, w is the average width of the viewable path in meters, D is the distance in meters the LSC traveled over ground, and 10,000 is the conversion to hectares. The mean density was determined for each habitat type each year and for all years combined.

The availability of each species to the bottom trawl survey was calculated as:

$$\text{Species availability} = \frac{\rho_T * A_T}{\rho_T A_T + \rho_{UT} A_{UT}} \tag{2}$$

where ρ_T and ρ_{UT} are densities in trawlable and untrawlable grid cells, and A_T and A_{UT} are the total areas of trawlable and untrawlable habitat. Total trawlable and untrawlable areas across the GOA shelf from the Islands of Four Mountains to Yakutat Bay was determined from two sources: 1) BTS grid cells designated as trawlable (7%) or untrawlable (39 %) with 54 % of the area not yet classified, and 2) smooth sheet models of trawlable (88 %) versus untrawlable (12 %) areas generated by Baker et al. (2019). Availability data were randomly re-sampled with replacement 1000 times to obtain bootstrapped 95 % confidence intervals for the availability estimates.

An estimate of the component of catchability ($\widehat{q}$) that reflects the difference in densities between trawlable and untrawlable grounds was obtained by dividing the area-swept trawl abundance estimate by the estimated "true" abundance with:

$$\widehat{q} = \frac{\rho_T (A_T + A_{UT})}{\rho_T A_T + \rho_{UT} A_{UT}} \tag{3}$$

where ρ_T and ρ_{UT} are densities in trawlable and untrawlable grid cells, and A_T and A_{UT} are the total area of trawlable and untrawlable habitat. Note that this estimate ignores potential differences in gear efficiency between the habitat types that would affect catchability, but does give an estimate of how catchability is affected from expanding densities from trawlable areas to untrawlable areas. Catchability estimates were calculated from GOA BTS grid cell areas to compare with estimates currently used in stock assessment models, as well as from trawlable area based on smooth sheet models and densities in T and UT habitats from LSC designation.

Densities of select fish species from the current study were compared to the bottom trawl survey estimates, which were from trawlable grid cells only. Densities (kg/ha) reported in bottom trawl cruise reports (von Szalay and Raring, 2016, 2018; Raring and von Szalay, 2013) from similar depths and areas in the current study (i.e., – depths $\leq$ 300 m and excluding southeastern Alaska area) were converted to numbers/ha using reported area coverage and average fish weights provided in the respective cruise reports. Fish lengths from BT surveys for the same years, areas, and depths were obtained from the BTS database at AFSC.

3. Results

A total of 110 BTS grid cells were surveyed in all years combined, of which 52 were designated as T, 43 were designated as UT, and 15 were not yet classified as T or UT (Fig. 1, Supplemental Table 1). A total of 228 lowered stereo camera deployments were conducted (Supplemental Table 1). The majority of grid cells (82 %) had at least two camera deployments completed within them. LSC images were not collected within 6 acoustically surveyed grid cells due to connectivity issues or weather limitations. The average distance covered by the LSC was 311 m (range: 42–937 m) with 91 % of the deployments covering between 100 and 700 m. Of the BTS grid cells classified as T, 43(83 %) were also designated as T by LSC. Of the BTS grid cells classified as UT, 25(58 %) were also designated as UT by LSC. Of the BTS grid cells not yet classified, 8 (53 %) were determined by LSC designation to be T and 5 (33 %) were determined to be UT (Technical issues with the LSC prevented image data collections for an additional 2 T, 2 UT and 2 unclassified BTS grid cells so no LSC designations of trawlability could be made for these cells). Bottom depths of surveyed grid cells ranged from 40 m to 304 m and averaged 133 m for all years.

Acoustic backscatter classified as rockfish was averaged by year and BTS grid cell trawlability designation (Fig. 2). Analyses were performed both including and excluding the 5 daylight hour surveys that were

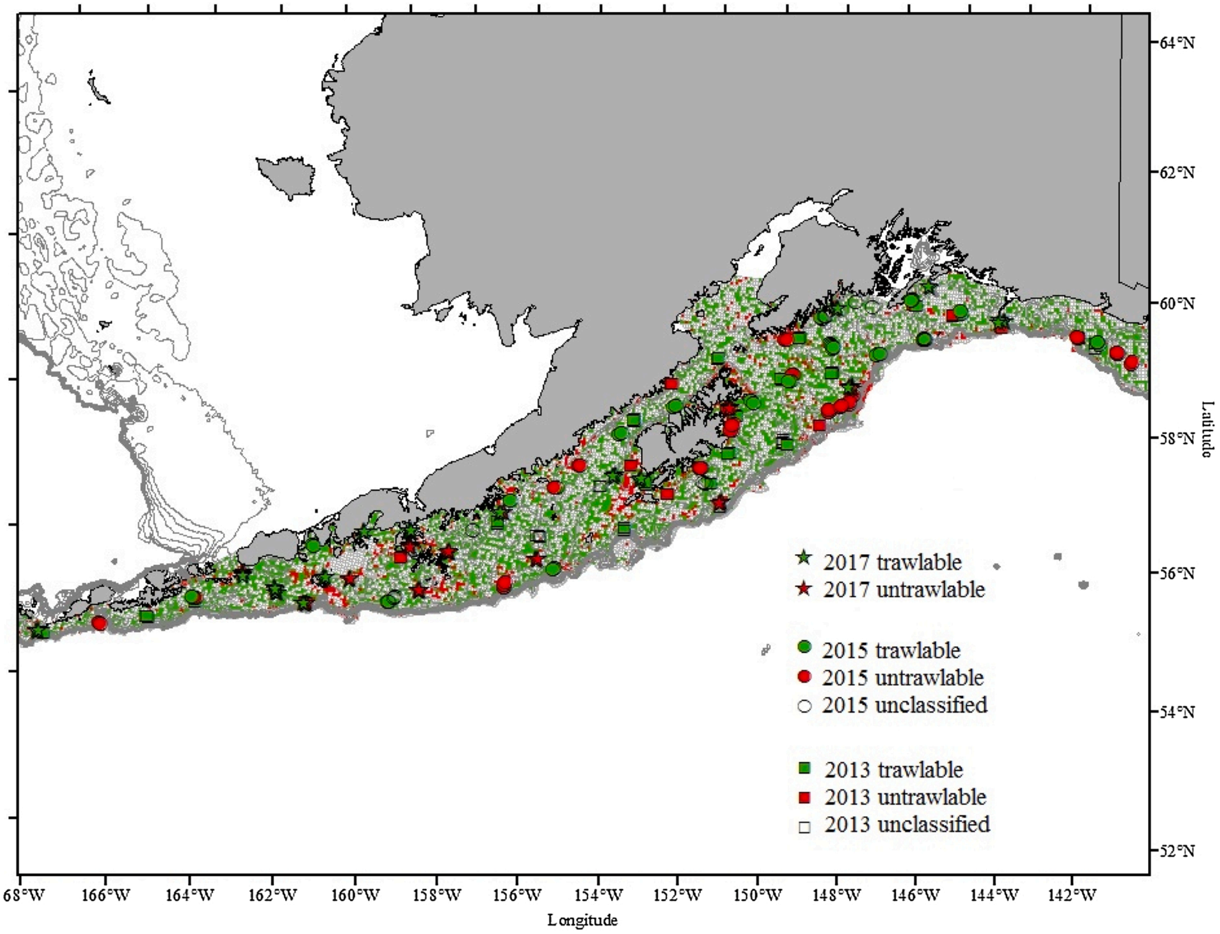

Fig. 1. Trawlability as determined by the AFSC bottom trawl survey, and associated lowered stereo camera deployment locations in trawlable (green), untrawlable (red), and unclassified (clear) grids, surveyed during the 2013 (squares), 2015 (circles), and 2017 (stars) GOA surveys (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

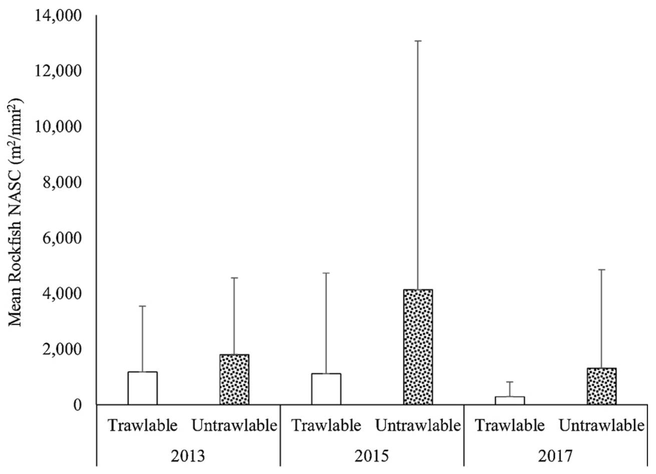

Fig. 2. Mean backscatter (Nautical area scattering coefficient; NASC) attributed to rockfish for bottom trawl survey (BTS) trawlable (white) and untrawlable (stippled) grid cells surveyed in 2013, 2015, and 2017. Error bars equal 1 standard deviation.

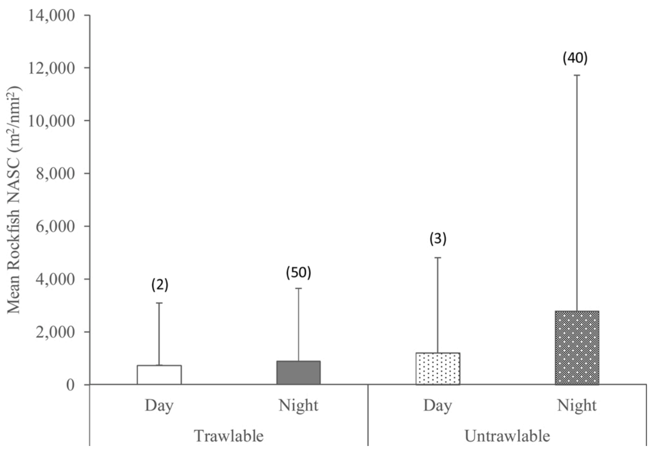

Fig. 3. Mean backscatter (Nautical area scattering coefficient; NASC) attributed to rockfish for bottom trawl survey (BTS) trawlable (solid) and untrawlable (stippled) grid cells surveyed during night time (dark shading) or daytime (light shading) hours in 2013, 2015, and 2017. Sample size indicated in parentheses. Error bars equal 1 standard deviation.

performed in classified grid cells. Results indicated no significant difference in backscatter amounts between day and night surveys in trawlable or untrawlable grid cells ($p = 0.44$), but backscatter detected in untrawlable grid cells tended to be greater at night compared to daylight hours (Fig. 3). Because no significant difference was detected between the backscatter amounts in daytime and nighttime surveys, the data were pooled for subsequent analyses. There was no difference in backscatter between years ($p = 0.33$). Backscatter tended to be greater in untrawlable grid cells than in trawlable grid cells for all years but the difference was not significant (p = 0.17). The increased amount of backscatter in untrawlable grid cells in 2015 was primarily due to the occurrence of one grid cell with large aggregations of several rockfish species that year.

Fish seen in LSC images were identified to species when possible. A total of 675 fish were seen in camera images in 2013, and 50 % were identified as rockfishes. A total of 2762 fish were observed in 2015, and 68 % were rockfishes. A total of 1555 fish were observed in 2017, and 36 % were rockfishes. Overall, 39 % of the rockfishes seen in camera images were not identifiable to species because they were too far away, they were obscured behind a rock or other structure, or the fish was a juvenile or otherwise too small to be identified accurately. Of all rockfishes that were identified to species across all study years, 29 % were identified as harlequin rockfish, 10 % were identified as dusky rockfish, 12 % were identified as northern rockfish, and 40 % were identified as POP (Supplemental Table 1; Fig. 4).

Harlequin rockfish were identified in 16 % of the 228 LSC deployments completed over the three years. This species occurred primarily in areas designated as untrawlable (81 %) and containing low-relief boulders and cobble based on LSC images (Fig. 5). Northern rockfish were observed in 13 % of all LSC deployments. They occurred primarily in areas classified as untrawlable habitat (83 %) and having interspersed large boulders based on LSC images. Dusky rockfish were observed in 9% of the LSC deployments. They occurred predominately in areas classified as untrawlable (95 %) and containing large boulders. POP were observed in 23 % of the LSC deployments. Almost half of the sightings (43 %) were from areas classified as trawlable (i.e., silt/sand substrates).

Fish lengths measured from LSC deployments were within the range of those seen in the bottom trawl survey over similar years, areas, and depth strata (Fig. 6). POP and northern rockfish measured in either T and UT grid cells surveyed with the LSC were very similar in length to fish measured in T grid cells in the BTS. However, dusky and harlequin rockfish measured in either T and UT grid cells in the LSC survey were slightly shorter on average than those from the BTS.

When species occurrence is examined as a function of LSC trawlability classification, a few general geographic patterns emerge. POP were identified more often than other species in areas that were designated as trawlable (Fig. 7). Also, the majority of the LSC deployments in trawlable areas that included rockfishes were east of Kodiak Island and south of the Kenai Peninsula on Portlock Bank and farther to the east. In areas that were designated as UT, northern rockfish were mostly seen clustered around the shelf south of the Shumagin Islands and Sanak Island in the western portion of the GOA (Fig. 8). Harlequin rockfish, dusky rockfish, and POP were observed fairly evenly across the GOA in untrawlable areas.

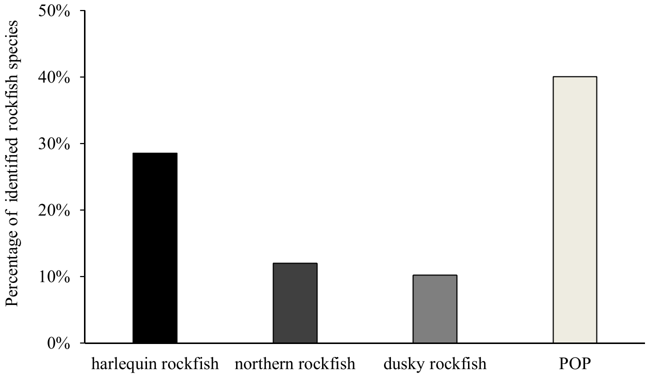

Fig. 4. Percentage of all rockfishes identified to species, which were harlequin rockfish, northern rockfish, dusky rockfish, or Pacific ocean perch from lowered stereo camera images in trawlable and untrawlable grid cells during the 2013, 2015, and 2017 GOA surveys combined.

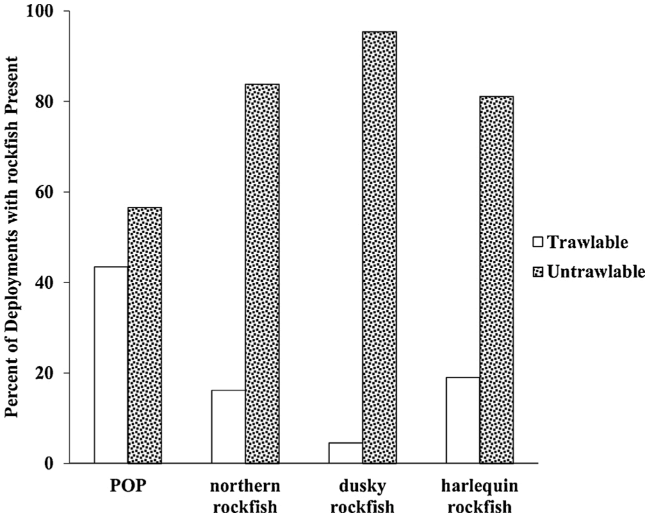

Fig. 5. Percentage of lowered stereo camera deployments in trawlable or untrawlable habitats with harlequin rockfish, northern rockfish, dusky rockfish, or Pacific ocean perch present during the 2013, 2015, and 2017 GOA surveys combined.

Based on BTS designation of trawlability, densities of harlequin, dusky, and northern rockfishes were higher in UT grid cells compared to T grid cells for all years combined (Fig. 9). However, in 2017, a large school of northern rockfish observed in an LSC deployment in T habitat within an UT BTS grid cell resulted in a higher overall density for that combination in that year (Table 1). The difference in densities between T and UT BTS grid cells was significant ($p < 0.03$) for each species (Fig. 9). Furthermore, harlequin and northern rockfish both had more than 7 times greater densities in UT grid cells compared to T grid cells. Dusky rockfish were approximately 3 times denser in UT compared to T grid cells. POP exhibited the opposite trend with over 9 times more fish present in T BTS grid cells compared to UT grid cells.

Mean BTS density estimates for T grid cells were generally similar to those based on LSC images (Fig. 9). When the trawlability designation is based on results from LSC images, as opposed to BTS designation, the density differences between T and UT areas are similar to those from BT grid cell designated trawlability for each species except POP (Figs. 9 and 10). When data from LSC images from all years are combined, all species have significantly more ($p < 0.03$) fish in areas determined to be untrawlable by LSC images. Dusky and northern rockfish abundances were more than 5 times denser in areas classified as UT, while harlequin rockfish were approximately 74 times denser in UT areas. POP were approximately 8 times denser in UT versus T areas; the opposite pattern occurred when the trawlability is defined by BTS grid cell designation.

The estimated percent available to bottom trawl gear for northern and dusky rockfishes was similar between the LSC classification and BTS grid cell classification of trawlability. For example, the estimated percent of dusky rockfish available to the trawl was 36 % with the LSC classification and 51 % with the BTS grid cell classification (Fig. 11). The values were 52 % and 43 %, respectively, for northern rockfish. The estimated catchabilities q for dusky rockfish was 0.45 (CV 0.78) based on LSC trawlability classification and 0.64 (CV 0.47) based on BTS grid cell trawlability, and for northern rockfish q was 0.6 (CV 0.39) based on LSC trawlability classification and 0.50 (CV 0.37) based on BTS grid cell trawlability.

For harlequin rockfish, the LSC trawlability classification indicated that this species was almost entirely in untrawlable grounds with only 10 % available to the trawl survey, whereas the BTS grid cell classification indicated that the stock was divided more evenly between trawlable and untrawlable grounds with 40 % available to the trawl survey (Fig. 11). These differences result in an estimated q for harlequin rockfish of 0.11 (CV 0.60) based on the LSC classification of trawlability, but 0.46 (CV 0.45) with the BTS grid cell classification.

For POP, the LSC trawlability classification indicated that the stock

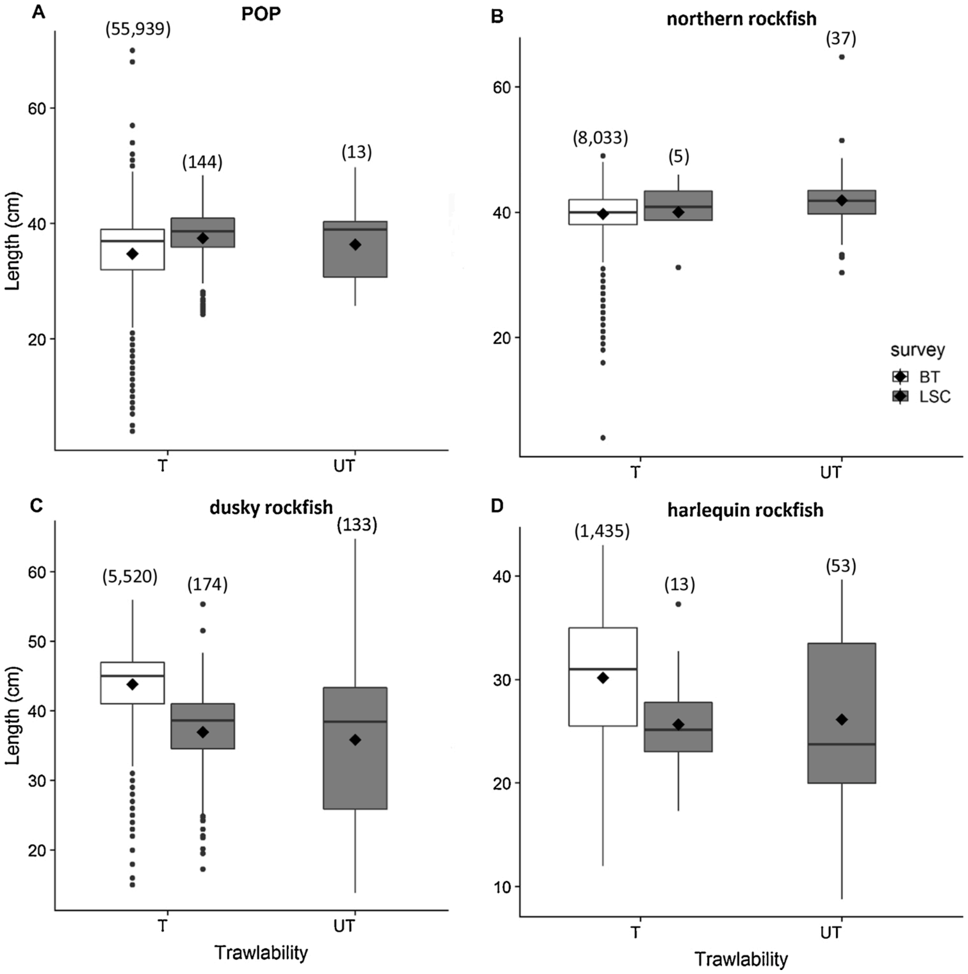

Fig. 6. Estimated lengths (cm) of Pacific ocean perch (POP) (A), northern rockfish (B), dusky rockfish (C), and harlequin rockfish (D) from lowered stereo camera (LSC - grey) images in trawlable (T) and untrawlable (UT) bottom trawl survey grid cells, and from the RACE bottom trawl survey data (BT – white, trawlable grid cells only) in 2013, 2015, and 2017 from similar geographic areas and depths in the GOA. Boxes represent the first and third quartiles with median as horizontal line and mean as black diamond. Whiskers extend to 1.5 times the interquartile range with outliers beyond. Sample size of each listed above box in parentheses.

was evenly divided between trawlable and untrawlable grounds (50 % available to the trawl survey), whereas the BTS grid cell classification indicated that the stock was nearly entirely in trawlable grounds (98 %) and thus completely available to the trawl survey. These differences result in an estimated *q* of 0.57 (CV 0.31) based on the LSC classification of trawlability, but 1.15 (CV 0.02) with the BTS grid cell classification.

4. Discussion

Trawlability designation of an area is determined by the scale at which it is evaluated. The AFSC bottom trawl survey determines trawlability based on topography and whether or not a 15-minute bottom trawl haul at 3.0 knots can be successfully placed in any portion of a 25 km^2 grid cell. This means that each trawlable grid cell could potentially have some portion of untrawlable habitat contained within it and vice-versa. In contrast, the determination of trawlability using the LSC was based on whether any untrawlable terrain was encountered during the 15-minute bottom time during the LSC deployment. The area covered by the LSC is much less than that covered by the bottom trawl even though bottom contact time for both is 15 min. If the ship is moving at 3 knots the trawl would cover approximately 1400 m. Compared to the average distance covered by the LSC (328 m), the bottom trawl covers more than 5 times greater distance along the seafloor. Additionally, the two gear types have vastly different horizontal coverage with the bottom trawl covering approximately 16 m and the camera only able to view approximately 3 m horizontally. Because these two gear types have different coverage areas, trawlability designations would not necessarily be similar and would need to be larger for the bottom trawl because of the more extensive areal coverage compared to the LSC system. Even though the LSC classification is a more accurate description of the terrain at smaller spatial scales, for BTS logistics and efficiency, the GOA must be more coarsely divided into the larger 25 km^2 grid cells. The BTS grid cells include a variety of habitat types, as evident from the present study, which have varying species compositions and densities, thereby making the designation of a single catchability factor difficult. Furthermore, even though most of the trawlability designations agreed between the two classifications systems, LSC deployment was not random, but was chosen based on acoustic backscatter and topography, which would likely encounter more UT habitat. Nonetheless, 34 % of the BTS grid cells designated as UT did not have UT habitat based on LSC images, most likely due to the difference in spatial coverage of the two survey methods outlined above. Furthermore, alternate methods of estimating trawlability are available based on, for example, multibeam acoustic characteristics (Pirtle et al., 2015) or analyzing hydrographic smooth sheet data (Baker et al., 2019), which may be suitable alternatives to the LSC or BTS method for estimating trawlability depending on the scale and purpose that the designation is to be used for.

Catchability values (*q*) were estimated in several GOA rockfish assessment age-structured models using a lognormal prior distribution with an arithmetic median of 1 (Hulson et al., 2017). In the most recent stock assessments, the *q* for northern rockfish was 0.67 (Cunningham et al., 2018), for GOA dusky rockfish the model *q* was 0.81 (Fenske et al., 2018), and for POP it was 2.11 (Hulson et al., 2017). A catchability coefficient was not estimated for harlequin rockfish as it was not assessed like the other three stocks due to the lack of data to support an age-structured model. Harlequin rockfish is assessed as a component of

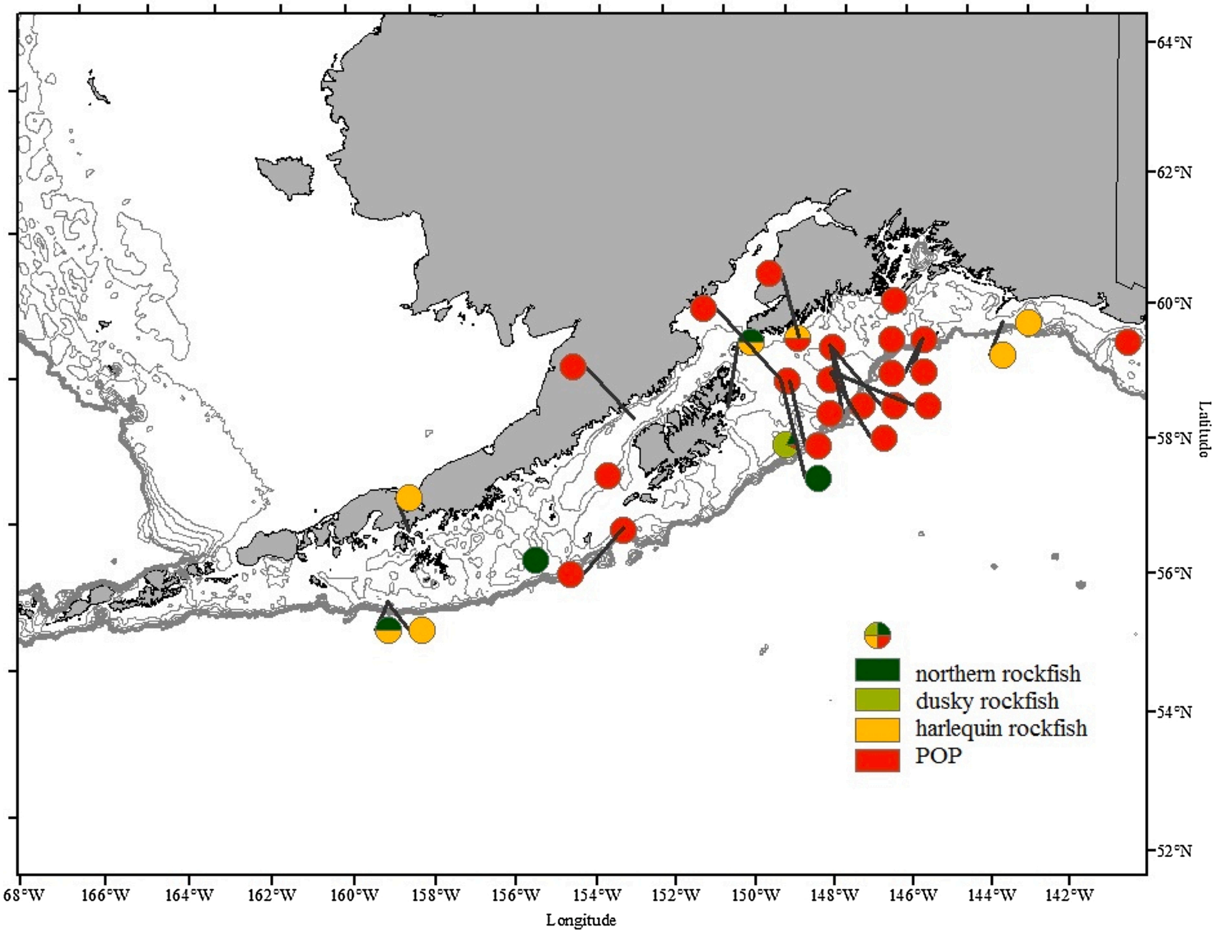

Fig. 7. Relative abundance of four rockfishes (northern rockfish, dusky rockfish, harlequin rockfish and Pacific ocean perch) based on lowered stereo camera images in areas determined to be trawlable for 2013, 2015, and 2017 surveys combined.

the "Other rockfish" stock complex in the GOA (Tribuzio et al., 2017). The current biomass of this complex is estimated with a random effects model applied to the time series of survey biomass estimates. The assessment for this rockfish complex, like other non-age-structured assessments in the GOA, where there are reliable survey biomass estimates, implicitly assumes that catchability is equal to one.

The availability and *q* reported here vary based on the trawlability classification used. However, roughly half of dusky and northern rockfishes in our study were found to be accessible to the bottom trawl regardless of the trawlability classification scheme. Note that the assessment model estimate of *q* for northern rockfish is highly uncertain (approximate 95 % confidence interval: 0.38–0.96). Nonetheless, the *q* values in this study generally align well with those used in the stock assessments.

The most useful *q* estimates to the rockfish assessments are from the BTS trawlability classification scheme. While the LSC classification is a more accurate description of the habitat that is truly T/UT, the biomass time series used in the assessment models are based on the BTS grid cells and not the LSC classification. Also, the assessment catchability is estimated based on biomass obtained from the bottom trawls, whereas the LSC classification obtain densities from counts, so the estimates reported here and the assessment estimates of catchability are operating on different scales. We did not estimate biomass for the species from LSC-based counts as the relatively low number of fishes within each trawlability type and species taxon within a year would make conversion of fish lengths to weights highly variable. Furthermore, the biomass obtained in the bottom trawl survey include fish caught during deployment and retrieval of the gear, which, along with the effects of herding, were not taken into account here. When these additional effects on the catch are considered, the estimates of catchability in this study may be smaller than what would be expected from the models using survey catch data. Similarly, the potential attraction or repulsion of fishes from the LSC could affect the densities seen in the camera images.

Higher values of *q* might be expected for adult POP relative to juvenile POP, reflecting ontogenetic changes in habitat use. Adult POP are often found in trawlable habitat (Krieger and Sigler, 1996), while juvenile POP occupy rocky untrawlable areas to a larger extent (Carlson and Haight, 1976; Rooper et al., 2007, 2010). The length compositions of POP sampled in untrawlable and trawlable areas during this study are consistent with these conclusions, as the majority of POP in trawlable areas were larger than 25 cm and likely part of the adult population whereas POP (and unidentified rockfishes) in untrawlable areas had a higher proportion of smaller and/or juvenile fish. Additionally, POP are susceptible to herding by trawl bridles and doors, meaning the effective area swept is greater for trawls than the physical net measurement would indicate (Krieger and Sigler, 1996). Very few studies have quantified the catchability of rockfishes outside of assessment models. Krieger and Sigler (1996) estimated catchability coefficients for rockfish spp. in Alaska based on area swept calculations from trawls and submersible transects and generated coefficients of up to 1.27 for POP (which accounted for 72 % of their catch), largely because of herding and diving responses of POP. In another study, Krieger (1993) estimated catchability coefficients of up to 2.1, but this larger value may be due to additional fish caught when the net was off bottom during retrieval. Lauth et al. (2004) estimated catchability of *Sebastolobus* spp. using a camera sled and found catchability ranged from <0.1 to 0.75 depending

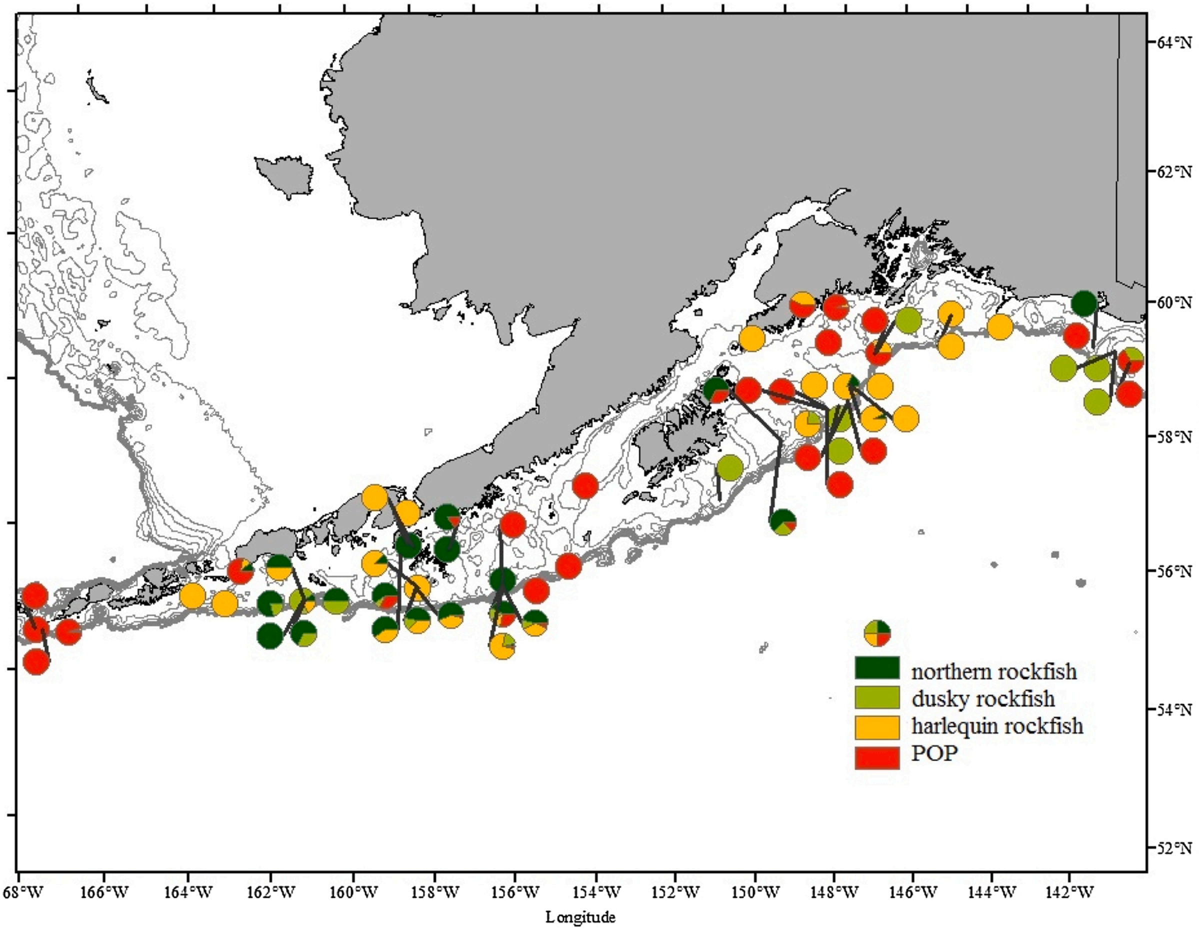

Fig. 8. Relative abundance of four rockfishes (northern rockfish, dusky rockfish, harlequin rockfish and Pacific ocean perch) based on lowered stereo camera images in areas determined to be untrawlable for 2013, 2015, and 2017 surveys combined.

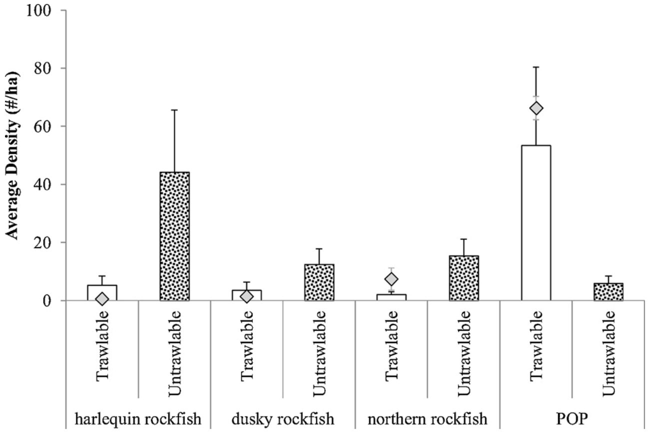

Fig. 9. Average density (number of fish per hectare) of harlequin rockfish, dusky rockfish, northern rockfish, and Pacific ocean perch in lowered camera surveys in areas determined to be trawlable (T - white) or untrawlable (UT - stippled) based on the BTS grid cell designation of trawlability for 2013, 2015, and 2017 combined. Grey diamonds represent the densities of each fish species from BTS results for 2013, 2015, and 2017 combined. Error bars represent one standard error.

on fish length. The authors suggested that the lower catchability estimates for fish >30 cm might indicate that catchability varied with age for *Sebastolobus* spp. The assessment models for rockfishes addressed in our study do account for age-dependent differences in catchability by estimating a selectivity curve, whereas the catchability estimates we generated in our study do not take fish size or age into account.

Even though a catchability coefficient is not estimated for harlequin rockfish in the stock assessment, our results indicate that the bottom trawl survey most likely underestimates this population size as the vast majority of harlequin rockfish are within untrawlable habitat. Stock assessment reports have noted harlequin rockfish occur in very few survey hauls (~7%) in the GOA, but it is the dominant species in the "Other Rockfish" complex and comprised 77 % of the commercial catch in this complex in the western GOA from 2009 to 2013 (Tribuzio et al., 2017). Harlequin rockfish catch was also the primary reason that the acceptable biological catch for the "Other Rockfish" complex was regularly exceeded by the fishery in certain areas. The high catch of harlequin rockfish is likely primarily due to the ability of the commercial fishery to successfully target fish in areas that are untrawlable for the NOAA bottom trawl survey. Results from this study could be used to provide an estimate of harlequin rockfish catchability that is lower than 1, and would be further improved by estimates of the expected survey availability (which may be similar to other rockfish species with similar habitat requirements). For species such as harlequin rockfish, where biomass estimates from the survey are used to directly assess population levels, not accounting for availability to the survey gear decreases the estimated abundance and thus the allowable commercial catch. A more robust estimate of the harlequin population size would greatly benefit the management of the "Other Rockfish" species complex and perhaps allow for an increased catch of other more commercially desirable species.

Some potential sources of error for gear efficiency studies, and this

Table 1
Average density in number/hectare (with associated number of contributing camera deployments) of select rockfishes in AFSC bottom trawl survey (BTS) grid cells designated as trawlable (green), untrawlable (red), or unclassified (grey), and additionally designated as trawlable or untrawlazble based on lowered stereo camera images, within BTS grid cells.

	BTS Trawlable Grid Cells			BTS Untrawlable Grid Cells			BTS Unclassified Grid Cells		
	Camera Trawlable	Camera Untrawlable	Total	Camera Trawlable	Camera Untrawlable	Total	Camera Trawlable	Camera Untrawlable	Total
2013	7.0 (30)	220.1 (3)	26.4 (33)	0 (11)	42.1 (10)	20.0 (21)	9.7 (4)	10.8 (5)	10.3 (9)
Dusky Rockfish	10.7	-	9.7	0	6.1	2.9	0	7.8	4.3
Harlequin Rockfish	0.8	14.4	2.0	0	156.6	74.6	0	-	-
Northern Rockfish	5.1	14.4	5.9	0	5.5	2.6	0	29.3	16.3
POP	11.5	851.5	87.9	0	0	0	38.7	6.2	20.6
2015	5.1 (27)	51.1 (10)	17.6 (37)	0 (14)	39.6 (29)	26.7 (43)	1.7 (7)	49.4 (2)	12.3 (9)
Dusky Rockfish	0	3.5	0.9	0	37.0	25.0	0	17.0	3.8
Harlequin Rockfish	0.7	3.0	1.3	0	78.1	52.7	0	0.0	0.0
Northern Rockfish	0.4	0	0.3	0	25.9	17.5	0	110.2	24.5
POP	19.5	198.0	67.7	0	17.5	11.8	6.9	70.4	21.0
2017	0.7 (34)	31.9 (8)	6.6 (42)	7.6 (12)	10.4 (21)	9.4 (33)	0 (0)	0 (0)	0 (0)
Dusky Rockfish	0	4.6	0.9	0.0	3.0	1.9	0	0	0
Harlequin Rockfish	1.3	54.5	11.4	1.4	19.3	13.1	0	0	0
Northern Rockfish	0.0	3.1	0.6	28.9	16.6	20.8	0	0	0
POP	1.5	65.5	13.7	0.0	2.9	1.9	0	0	0
Total	4.1	67.9	16.1	2.0	29.8	19.5	4.6	21.8	11.3

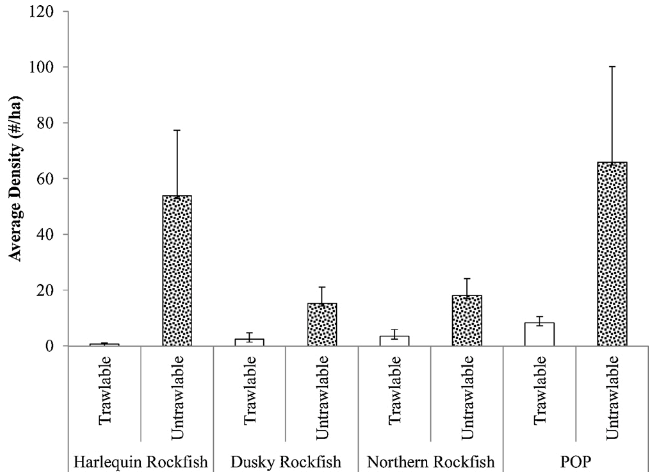

Fig. 10. Average density (number of fish per hectare) of harlequin rockfish, dusky rockfish, northern rockfish, or Pacific ocean perch in surveys of areas determined to be trawlable (white) or untrawlable (stippled) based on lowered stereo camera deployments for 2013, 2015, and 2017 combined. Error bar represents one standard error.

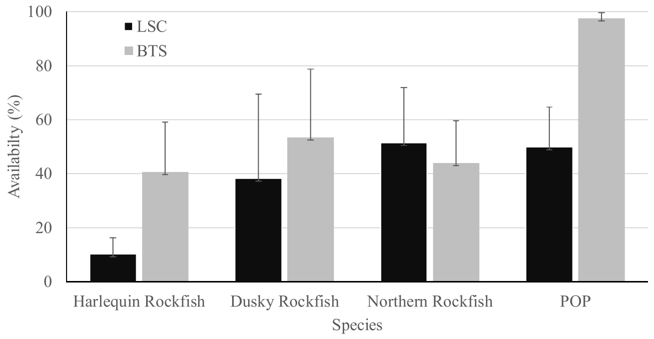

Fig. 11. Availability (%) of harlequin rockfish, dusky rockfish, northern rockfish, and Pacific ocean perch to the AFSC GOA bottom trawl survey, based on fish abundances and substrate trawlability as determined by the bottom trawl survey (BTS – grey bars) grid cell designations or by the lowered stereo camera (LSC – black bars) in 2013, 2015, and 2017 combined. Error bars represent one standard deviation.

study in particular, include small sample sizes, potential differences in diel fish behavior, vertical availability, species responses to the sampling gear, environmental conditions, and season. Due to survey time restrictions, it was generally not possible to use daylight hours to survey grid cells and deploy cameras. However, in 2015, five grid cells (1 trawlable, 3 untrawlable, and 1 unclassified) were surveyed during daylight hours, and in 2017, one trawlable grid cell was surveyed during daylight hours. Our results did not detect a significant difference in acoustic backscatter between night and day surveys, however, average backscatter detected at night in untrawlable grid cells tended to be larger than what was detected during the day, similar to results reported by Stanley et al. (1999) for yellowtail rockfish in Canada. Parker et al. (2008) also reported observations of diel vertical movement of blue rockfish which varied based on the time of year in which they were observed. Diel vertical movement has the potential for biasing acoustic results if fish avoid detection by moving into the near bottom acoustic dead zone. However, in the present study near bottom fish counts using camera images would have detected those fish in the near bottom acoustic dead zone. The combination of midwater acoustic and near bottom camera observations should account for both the fish in the water column and in the near bottom environment if vertical diel movement is occurring. However, if nighttime behavior involves movement between T and UT areas, then there would be large implications to applying our predominately nighttime-derived catchability estimates to the bottom trawl survey, which is conducted during daylight hours. It would be extremely useful in the future to conduct night versus day surveys on the same grid cells to investigate potential diel differences in rockfish densities in trawlable and untrawlable areas. Additional research into diel, seasonal, or trawl related effects on gear efficiency and catchability for different species would also be extremely beneficial.

Another consideration for the current study is the potential reaction of fishes to the camera unit and/or strobe lights. Response to the LSC appears to be related to the size and species of the observed fish. Anecdotally it was noticed during our surveys that larger rockfishes such as yelloweye rockfish or dusky rockfish do to not appear to react to the strobes in that they do not actively swim towards or away from the unit as it approaches. Smaller fishes such as harlequin rockfish and juvenile

POP, which are typically seen in more rugose habitats, appear to swim into cracks or crevices as the camera unit approaches. Some mid-sized rockfishes such as northern rockfish were unpredictable and would sometimes actively swim away and other times show no reaction at all. Rooper et al. (2015) generally found similar results when looking at the response of rockfishes to red vs. white strobed or continuous lighting using a similar LSC unit in Washington state. They found no effect of lighting color or method on larger rockfishes, but higher densities of smaller rockfishes when red light was used, indicating that smaller rockfishes presumably reacted to the white light by hiding or taking cover. However, a major drawback of using red light is the decreased range of visibility relative to white light due to higher attenuation. Additionally, Rooper et al. (2015) found that all rockfishes that were observed moved closer to the seafloor as they were approached by the camera unit, but there were no apparent changes in rockfish detection from the beginning to the end of a transect (C. Rooper, unpublished data). An avoidance response to the strobed light in this study would have resulted in an underestimate of the proportion of rockfish observed in rocky habitat, since presumably a hiding response would have led to lower detection. However, based on the previous research using the LSC system, the effect on observed density would have only been significant for small fish less than 20 cm (Rooper et al., 2015).

Accounting for the availability of fishes to bottom trawl surveys is important as it provides more accurate results for stock assessments. Stock assessment modeled catchability estimates must take into account all aspects of catchability including the selectivity and effectiveness of the gear, not just the availability and density of species in trawlable and untrawlable habitats. The estimates we present from the current study are associated with the spatial availability of the fish to the gear. Even though occupancy of trawlable and untrawlable habitats may be the most important determinant of catchability (Cordue, 2007), further research is needed to incorporate other aspects such as fish behavior (e.g., vertical distribution) in relation to the trawl, which could affect gear efficiency. Nonetheless, our estimates of q represent an improvement over current values used for stock assessment. That is, our estimates are derived from the BTS trawlability grid cells, and are thus most informative as they are derived from a similar underlying framework. It is critical to develop independent estimates for rockfish availability to the bottom trawl survey gear, and changes in these estimates should be monitored over time to provide the most accurate survey information for fish stock assessments.

CRediT authorship contribution statement

Darin T. Jones: Investigation, Formal analysis, Writing - original draft, Writing - review & editing. **Christopher N. Rooper:** Conceptualization, Methodology, Funding acquisition, Resources, Formal analysis, Writing - review & editing. **Christopher D. Wilson:** Conceptualization, Methodology, Funding acquisition, Resources, Supervision, Writing - review & editing. **Paul D. Spencer:** Validation, Writing - review & editing. **Dana H. Hanselman:** Validation, Writing - review & editing. **Rachel E. Wilborn:** Formal analysis, Writing - review & editing.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fishres.2020.105848.

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