ICES Journal of
Marine Science

ICES Journal of Marine Science (2021), 78(3), 1117–1130. doi:10.1093/icesjms/fsaa232

Downloaded from https://academic.oup.com/icesjms/article/78/3/1117/6134884 by NOAA Central Library user on 30 September 2021

On the development of acoustic descriptors for semi-demersal fish identification to support monitoring stocks

Réka Domokos *

Ecosystem Sciences Division, Pacific Islands Fisheries Science Center, National Marine Fisheries Service, NOAA, 1845 Wasp Blvd, Bldg. 176, Honolulu, HI 96818, USA

**Corresponding author: tel: +1 808 725 5368; fax: +1 808 725 5475; e-mail: reka.domokos@noaa.gov.*

Domokos, R. On the development of acoustic descriptors for semi-demersal fish identification to support monitoring stocks. – ICES Journal of Marine Science, 78: 1117–1130.

Received 10 December 2019; revised 20 November 2020; accepted 23 November 2020; advance access publication 14 February 2021.

Despite worldwide economic importance of lutjanid snappers, there are critical data gaps hindering accurate abundance estimates of these species, thereby impeding stock management efforts. Development of an active acoustics method could fill many of these data gaps, significantly benefiting stock assessment of snapper species that form typically mixed-species assemblages in non-trawlable regions. These methods are well suited for resource surveys but require the ability to derive accurate size estimates from target strength (TS) and the separation of echoes from species within the stock. This work evaluates the feasibility of active acoustics for surveying a Hawaiian bottomfish stock, referred to as the Deep-7 complex, consisting of six species of lutjanid snappers and a single grouper. Acoustic backscatter data and complementary methodologies were used to model TS and develop acoustic descriptors such as aggregation shape, size, and density, individual swimming pattern, distance from bottom, and bottom depth for Deep-7 species. Paired observations of *in situ* TS and fork length (FL) gave an estimated bulk relationship of $23.01 \cdot \log_{10}(FL) - 72.18$. The success of 25 accuracy tests indicates the effectiveness of the developed echo allocation parameters. Preliminary results imply that acoustics could be successfully used to monitor Deep-7 with broader applicability upon adapting methodology to other regions.

Keywords: acoustic descriptors, acoustic species allocation, acoustically derived biomass/abundance, acoustics for stock assessment and management, fisheries acoustics, semi-demersal fish, Hawaii bottomfish, snappers, TS

Introduction

Snappers (family Lutjanidae) are ubiquitous in near-shore tropical and subtropical oceans and are an important target species of fisheries worldwide (Coleman *et al.*, 2000; Moura and Lindeman, 2007; WPacFIN, 2013a, b, c, Gastauer *et al.*, 2017a, b; Langseth *et al.*, 2018). Stocks in several regions are assessed as one "bottomfish stock" that includes other species, such as groupers and jacks. Snappers, as other species in this stock, are semi-demersal fish that form loose or dense mixed-species aggregations inhabiting highly rugose hard-bottom areas, generally unsuitable for bottom trawling. Stock assessment of these economically important bottomfish relies mostly on fishery-dependent methods (e.g. catch-per-unit-effort as an abundance index) that are known to be affected by numerous factors, such as fishing pattern of the fleet, fishing depth, catchability, gear type, size-specific targeting, misreported and unreported catch, market and fuel pricing, weather, and availability and density of prey. These factors can introduce biases, reduce precision, and result in potential data gaps that impact stock assessments.

One economically important localized stock consisting almost exclusively of lutjanid snappers is the main Hawaiian Islands (MHI) "Deep-7 bottomfish complex" (hereafter, Deep-7), heavily targeted by the local bottomfish fishery. The Deep-7 consists of six lutjanid deepwater snappers (ruby snapper, *Etelis coruscans*, "onaga"; red snapper, *Etelis carbunculus*, "ehu"; lavender jobfish, *Pristipomoides sieboldii*, "kalekale"; pink snapper, *Pristipomoides filamentosus*, "opakapaka"; Brigham's snapper, *Pristipomoides zonatus*, "gindai"; and rusty jobfish, *Aphareus rutilans*, "lehi";

Published by International Council for the Exploration of the Sea 2021. This work is written by a US Government employee and is in the public domain in the US.

Hawaiian names in double quotes) and the Hawaiian grouper, *Hyporthodus quernus*, "hapuʹupuʹu" (Brodziak *et al.*, 2011). Most concerns are placed on two main target species, pink snapper and ruby snapper, which dominate the catch (Brodziak *et al.*, 2014; Langseth *et al.*, 2018). To assist the reader, Deep-7 species will be marked in italics in the following text.

Recently, fisheries-independent research to support the stock assessment of the Deep-7 complex has incorporated stereo-camera- and research fishing-based methods, collectively referred to as the Bottomfish Fishery Independent Survey for Hawaii, BFISH (Richards *et al.*, 2016). Augmenting fisheries-dependent data with estimates from fishery-independent surveys can improve stock estimates (Langseth *et al.*, 2018) by providing accurate species identification and size estimates/measurements that are less susceptible to aforementioned factors associated with fishery-dependent data. However, significant data gaps still exist due to limitations of the optical and research fishing methodologies. Optical observations are limited by the availability of light, restricting observations to daylight hours and to the photic layer (0 to ~250 m), missing significant portions of the habitat that extends from about 75- to 400-m depth (Kelley *et al.*, 2006; Parke, 2007; Ault *et al.*, 2018). Optical observations are also limited by visibility and camera field-of-view, the representativeness and volume of which are not well understood (Ault *et al.*, 2018). Research fishing methods remove several fishery-dependent concerns; however, catch remains influenced by selectivity of fishing gear, catchability, and availability of forage. Furthermore, both optical and research-fishing methods are influenced by avoidance/attraction behaviour of the fish, the functions of which are not well understood. For these reasons, it is unclear whether these methods alone can provide fully adequate biomass estimates for input into stock assessment models.

In the past few decades, active acoustic methods have been increasingly used to estimate abundance of economically important fish (MacLennan, 1990; Simmonds and MacLennan, 2005) and provide much-needed fisheries-independent data for stock assessment models. Active acoustic methods have the advantage of rapidly and efficiently collecting data over broad spatial scales day and night and throughout the entire water column. This non-lethal and non-extractive method can be used to obtain simultaneous information on the interactions and spatiotemporal distribution of fish and their prey (Josse *et al.*, 1998; Ménard and Marchal, 2003; Lezama-Ochoa *et al.*, 2014) to improve the accuracy of stock assessment models. Furthermore, it can provide data with resolution appropriate for the spatiotemporal scales of many ecosystem processes, especially using rapidly evolving unmanned autonomous platforms, scales that traditional technologies cannot capture but are necessary for effective ecosystem-based management (Trenkel *et al.*, 2011; Godø *et al.*, 2014).

Active acoustics have been successfully applied in other non-trawlable areas to assess biomass of economically important bottom-associated rockfishes (Stanley *et al.*, 2000; Ressler *et al.*, 2009; Rooper *et al.*, 2010, 2012; Jones *et al.*, 2012). Estimation of fish abundance at species level requires information on the target strength (TS) (dB re 1 m^2) or backscattering cross section of individual organisms (Simmonds and MacLennan, 2005), as well as the ability to distinguish the species of interest from other intermixed species. In regions of high species diversity, separation of relevant echoes from those of other fish is a challenging task since a variety of fish with different sizes and orientations could produce the same TS. Equations for the relationship between TS and fish-length have been estimated for some species of lutjanid snappers, including those of Deep-7, in prior work from *in situ* (Benoit-Bird *et al.*, 2003b; Gastauer *et al.*, 2017c) and a combination of *ex situ* and model data (Benoit-Bird *et al.*, 2003a; Gastauer *et al.*, 2016).

While Deep-7 species are known to have similar physiology and morphology, separating Deep-7 echoes from those of other species would provide much-needed complex-level fishery-independent data by filling gaps that exist in current methods, since current assessments consider Deep-7 as a single stock. The method of treating multiple species as a single assemblage and using bulk backscatter metrics are common for mesopelagic scattering layer organisms, including micronektonic fish (e.g., Burgos and Horne, 2008; De Robertis *et al.*, 2010; Xie *et al.*, 2012; Trenkel and Berger, 2013; Davison *et al.*, 2015; Jech *et al.*, 2015; Béhagle *et al.*, 2017).

The objective of this study is the development of narrowband acoustic descriptors for the Hawaii Deep-7, such as a TS–fork length (FL) relationship, aggregation shape, size, and density, individual swimming pattern, distance from bottom, and bottom depth (hereafter, acoustic descriptors), which can be used to separate Deep-7 echoes from those of other semi-demersal species occupying the same habitat. The development of acoustic descriptors was aided by *in situ* TS measurements of fish with known sizes and simultaneous complimentary methodologies such as stereo-video observations and experimental fishing. Information gained from these measurements was used during surveys to obtain preliminary abundance and biomass estimates over predetermined grids in a small section of the stock domain within the MHI archipelago frequented by commercial fishermen.

Methods

The development of acoustic descriptors for separation of Deep-7 echoes as a group (acoustic descriptors in following text) from those of other fish to estimate their densities required a combination of approaches. To obtain TS of fish with known sizes, paired observations of TS and FL were conducted using tethered fish and simultaneous acoustics with either stereo-video camera or deep-line bottomfishing operations. To obtain information on aggregation shape, size, and density, individual swimming pattern, distance from bottom, and bottom depth (hereafter, non-TS-specific acoustic descriptors), simultaneous acoustic and stereo-video observations were used. To estimate Deep-7 abundance a combination of echo counting and, for tight aggregations, echo integration was applied. This combined method allowed for retaining TS for size-distribution estimates from loosely grouped fish. Tethered fish operations were conducted on juvenile pink snapper (*P. filamentosus*) of known sizes in near-shore environments that required the use of the 7-m NOAA small boat *Kumu*, while acoustic recordings with simultaneous optical and fishing operations, as well as surveys for abundance estimates, were conducted in open waters on board the NOAA Ship *Oscar Elton Sette* (*Sette*).

Equipment

The acoustic equipment used for this study included a pole-mounted and a hull-mounted split-beam, multi-frequency Simrad EK60 echosounder system operating at 38-, 70-, and 120-kHz frequencies, each set to standard power (Korneliussen *et al.*,

Downloaded from https://academic.oup.com/icesjms/article/78/3/1117/6134884 by NOAA Central Library user on 30 September 2021

2008). The pole-mounted system was installed on the *Kumu* with beam-angles 12° for the 38-kHz and 7° for the 70- and 120-kHz channels, and was set to operate at 256-μs pulse-width for obtaining TS measurements of tethered fish of known sizes. The hull-mounted system was installed on the *Sette* with uniform beam-angles of 7°. This system was set to operate at 1024-μs pulse-widths and was used for development of acoustic descriptors with the aid of simultaneous optical and fishing operations, as well as for acoustic surveys for biomass/abundance estimates and for obtaining information on spatiotemporal distribution. Each system was calibrated prior to data collection using a 38.1-mm tungsten carbide sphere according to standard methods (Demer *et al.*, 2015). Data collected for this study are publicly available at the National Centers for Environmental Information portal (Pacific Islands Fisheries Science Center, 2011, 2012, 2013a, b, c).

Acoustic descriptors

TS of fish with known sizes could only be obtained from loosely grouped or separated fish, while depth and distance from bottom were collected from both loosely and densely aggregated fish. When individuals could be detected on the echogram, swimming pattern and number in group were also recorded. However, smaller Deep-7 typically formed tight groups that prevented single-target detection. In these cases, aggregation shape, size, and density were obtained. All non-TS-specific descriptors were obtained exclusively during simultaneous acoustic and stereo-video recordings, as fish exhibited unusual behaviours during fishing operations.

TS–FL pair selection

To broaden the size spectrum and help improve quality of the derived TS–FL relationship, TS of juvenile *pink snapper* (*P. filamentosus*) of known sizes were obtained in and outside of Kaneohe Bay, off the east coast of Oahu, Hawaii (Figure 1a). A total of 8 TS–FL pairs were obtained by measuring the length of fish obtained from holding tanks or captured in their natural habitat, then collecting TS measurements by lowering them into the water tethered to monofilament lines. Linear means of ~30 min TS recordings were used to form TS–FL pairs. Details of the procedure are provided in Supplementary Section 1.

Simultaneous acoustic and optical observations were conducted to obtain TS–FL pairs and to develop non-TS-specific acoustic descriptors of adult fish (see Section "Deep-7 echo allocation" below) in the protected waters of Maui Nui, a region between Lanai, Maui, and Kahoolawe Islands (Figure 1b). This area was selected due to its calm waters and rich substrate types known to be preferred by Deep-7 species that are heavily targeted by commercial fishermen in the area. Optical data were collected using low-light stereo-video camera systems mounted on 1) a weighted frame (Botcam), 2) an autonomous underwater vehicle (AUV), and 3) a remotely operated vehicle (ROV). Deployments were conducted off the *Sette* between the hours of 8 am and 4 pm in waters of 120–220-m depth. TS–FL pairs were carefully constructed using species and size of a single fish from optical recordings that could be matched to one specific individual fish track on the ecograms. Fish track selection is described in detail below (Section "TS Data Processing"), while details of data collection and TS–FL pair selection is presented in Supplementary Section 2.

In addition to the simultaneous acoustic and optical observations, deep-line bottomfishing operations were conducted in the Maui Nui area between 17:00 and 21:00 HST on board the *Sette*. Fishing location was selected based on the high number of fish observed on the echograms. Water depth at the start and end of fishing operations was ~110 and 260 m as the *Sette* was freely drifting with periodic repositioning when reaching deeper depths. As opposed to TS–FL pairs from the simultaneous acoustic and optical observations, specific fish tracks could not be matched unequivocally to the fish caught as the location of hooks could only be estimated with ~5–10 m precision. Instead, linear means of TS from individual fish in a 20-m diameter circle around the estimated position of the fish caught was used (more details are found in Supplementary Section 3).

TS data processing

Initial data processing of the acoustic signals was performed using Echoview Software Ply Ltd (Hobart, Tasmania), while processing was completed and data analysed using Mathworks Matlab software (Natick, Massachusetts). Though all frequencies were used in separating fish from smaller organisms, and when possible, for TS measurements, 70-kHz data were used for quantitative backscatter analyses. This decision was made because strong micronekton backscatter at the 38-kHz frequency often "masked" acoustic returns from larger demersal fish, while the 120 kHz, although providing the cleanest echograms with the least amount of noise from smaller organisms, could not penetrate to the depths of Deep-7 habitat (for limited multi-frequency observations, see Supplementary Section 7).

Prior to processing, noisy pings were eliminated from the echograms, followed by background noise removal. To eliminate the chance of TS calculated from multiple targets, regions of schools and dense micronekton and/or plankton layers were removed from the echograms prior to single-target detection, and the detected TS were validated by ensuring that Sawada indices (Sawada *et al.*, 1993) were met. For details of noise removal and TS validation, see Supplementary Section 4.

After manual scrutiny, TS was thresholded to −55 dB for juvenile *pink snapper* and −42 dB for adult fish based on the TS validation results. To avoid the inclusion of random single targets that likely included multiple targets or other than Deep-7 species in significant numbers, Echoview's 4D Fish Track Detection algorithm was utilized (settings are given in Supplementary Section 4). While the approach used was more restrictive, it resulted in higher quality data since including all single targets would result in the inclusion of a significant number of single targets from unintended species or from multiple fish with lower TS (see Supplementary Section 4).

To develop a TS vs. FL equation for Deep-7 species, 70 kHz TS from loosely aggregated or separated individuals were paired with FL identified from the tethered, optical, or fishing operations. These 70-kHz TS–FL pairs were used to estimate a and b of the TS vs. length relationship equation, $\mathrm{TS} = a\log_{10}(L) + b$ (Foote, 1980), by regression analysis.

Deep-7 echo allocation

Non-TS-specific acoustic descriptors were assessed exclusively from simultaneous acoustic and optical observations as fish exhibited altered aggregative behaviour and movement patterns during crepuscular periods when fishing operations were

Downloaded from https://academic.oup.com/icesjms/article/78/3/1117/6134884 by NOAA Central Library user on 30 September 2021

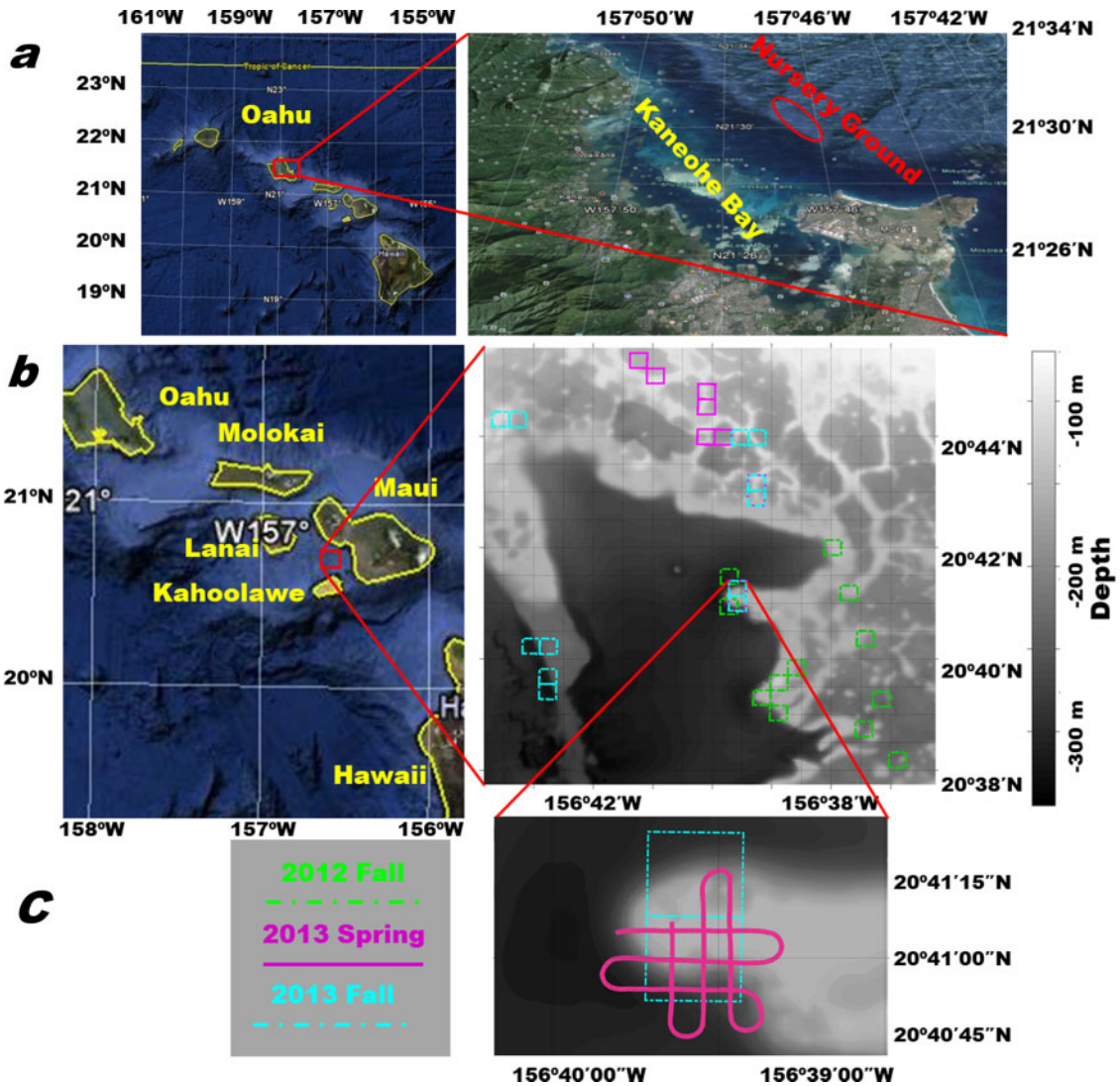

Figure 1. Study locations (a) for tethered measurements and for (b) simultaneous optical and fishing operations and surveys, with (c) showing an example of the survey design. (a) Kaneohe Bay and (b) Maui Nui, where right panels show details of the rectangular areas marked on the left panels. Grids surveyed in the Maui Nui Survey Area are shown on the right panel of (b), overlain on greyscale topography and colour coded for Survey as annotated in (c), left. (c) Example of a Transect from the Surveys, where greyscale is as in right panel of (b).

conducted. Two parameters, depth and distance from bottom could be utilized for both loosely and densely grouped fish. For loosely swimming individuals, number in group and swimming pattern could also be assessed (for details see Supplementary Section 5). As simultaneous optical observations showed, Deep-7 fishes often exhibited aggregative behaviour that prevented single-target detection. In these cases, acoustic descriptors representating the aggregation, such as shape, size, and density, were assessed using Echoview's School Detection algorithm on MVBS (mean volume backscattering strength in dB re 1 m^{-1}) echograms (see Supplementary Section 5). Acoustic descriptors for an aggregation were used only when optical data confirmed 95% species homogeneity. It should be noted that after manual inspection of echograms with regions assigned to Deep-7 species, a small fraction of regions required manual adjustments with decisions based on results obtained from the simultaneous acoustics and complementary studies.

A priori knowledge of species-specific depth range and distance from bottom (Merritt *et al.*, 2011; Kelley and Moriwake, 2012; Misa *et al.*, 2013; Sackett *et al.*, 2014) and acoustic descriptors from fishermen, such as aggregation shape, size, density, and depth, were also used in echo allocation. Fishermen commonly use simple echosounders ("fish-finders") to find species of interest for targeting and have vast accumulated experience in identifying targeted and non-targeted fish on their instruments.

Acoustic descriptor validation

The performance of the echo allocation developed in this study was tested at the final stages using simultaneous acoustic and optical data not used for echo allocation. Echoes were initially assigned to species and/or groups of species based exclusively on their acoustic descriptors as developed in this study. The performance of these determinations was then evaluated by comparing

Downloaded from https://academic.oup.com/icesjms/article/78/3/1117/6134884 by NOAA Central Library user on 30 September 2021

the results to the optical observations. The accuracy of the echo allocation was also assessed qualitatively on a larger scale; patterns of abundance and biomass, schooling behaviour, and size distribution calculated from survey data were compared to expected horizontal distribution patterns of Deep-7 fishes based on *a priori* information from literature.

Abundance estimation from surveys

Surveys

Surveys were conducted in the Maui Nui region (Figure 1b, the "Survey Area"), selected from a small subset of 425 500-m × 500-m primary sampling units (PSU) within the overall sampling domain, chosen by BFISH (Richards *et al.*, 2016). The PSUs were selected based on variance-weighted stratified-random sampling to be representative of the 25,892 PSUs in the stock area (~6500 km^2), hereafter "Grids" (Figure 1b). Grids were chosen to develop an acoustics sampling design which, once developed, could be efficiently implemented across the entire stock domain. Note that during surveys, no optical or other complementary operations were conducted to avoid any possible bias in abundance and biomass estimates due to avoidance/attraction behaviour in response to the presence of the platforms.

To minimize variance (see Supplementary Section 8), transects were conducted during daytime over Grids by passing over a Grid six times: three times along the meridional and three times along the zonal axes (a "transect"). Passes were designed to traverse approximately each third of a Grid in the zonal and the meridional direction (Figure 1c). This decision was made to reduce possible effects due to differences in diel distribution patterns and to decrease standard error in abundance and biomass estimates for a Grid. The surveys were conducted during 25 September–02 October 2012 (2012 Fall Survey), 18–28 April 2013 (2013 Spring Survey), and 02–10 August 2013 (2013 Fall Survey).

Abundance estimation

Echo counting for loosely grouped fish and echo integration where single targets could not be detected were used to assess Deep-7 species distributions and estimate their abundances and biomass. Echo counting and the combination of echo counting and integration have been used successfully in the past on fish that exhibit spatial relationships to each other that are similar to those of Deep-7 fishes (Josse *et al.*, 1999, 2000; Bertrand and Josse, 2000; Costa *et al.*, 2014). Using this methodology allowed investigation of spatial variability in aggregative behaviour by estimating abundance and biomass for loose and aggregated Deep-7 fishes separately. To ensure independence of samples for biomass and abundance estimates, Elementary Data Sampling Units (EDSUs) were set to 50-m length along a pass over a Grid, the distance given by the range of semivariograms. Abundance and biomass of Deep-7 fishes were estimated from mean densities of loosely and tightly aggregated fish from EDSUs along a pass. For loose fish, densities were obtained as number of tracks per EDSU, while for dense aggregations TS, estimated assuming 36-cm FL based on optical observations, were converted to backscattering cross section that was used to divide area backscattering coefficients to obtain densities (for details, see Supplementary Section 6). These densities were expanded to the 500-m x 500-m area of the Grid, assuming that the passes were representative of the Grids.

Abundance and biomass were adjusted by estimated values from the deadzone (Ona and Mitson, 1996), a region close to the bottom where fish echoes cannot be effectively separated from those of the sea floor. At present, there are no Deep-7 density estimates available for the deadzone. Camera recordings from this study were deemed unreliable as cameras could not see into the deadzone due to high rugosity in most cases, and density information from camera observations were biased by attraction/avoidance behaviour. In any case, camera recordings did not indicate that density in the deadzone differed significantly from that immediately above. For details of abundance and biomass estimation in the deadzone, see Supplementary Section 6.

Results

TS estimates

Simultaneous acoustic and complementary observations resulted in a total of 95 Deep-7 FL-TS pairs with 77% *pink snapper*, 11% *red snapper*, 5% *ruby snapper*, 4% *lavender jobfish*, and 3% *rusty jobfish* (Figure 2, reddish symbols). Of these observation pairs, 70% came from fishing, 21% from AUV, 8% from tethered juvenile *pink snapper*, and 1% from Botcam. Unfortunately, AUV-acoustics observation pairs failed to provide consistent size-specific data due to failure of one of the cameras, incorrect camera syncing, or bad image quality. In addition to Deep-7 FL-TS pairs, simultaneous observations gave 15 of two *Seriola* spp., both commonly referred to as "kahala", a name adapted throughout this text for simplicity (mostly greater amberjack, *Seriola dumerili*, "kahala", with some almaco jack, *Seriola rivoliana*, "kampachi") and five each unicornfish (*Naso* spp., "opelu kala") and bluestipe snapper (*Lutjanus kasmira*, "ta′ape") data pairs (Figure 2, blueish symbols).

The available Deep-7 70-kHz measurements gave $a = 23.01 \pm 5.40$ and $b = -72.18 \pm 8.03$ with 95% confidence for the length vs. TS relationship with $r^2 = 0.65$ (Figure 2, magenta line). Results from two previous studies using broadband *ex situ*, dorsally oriented *pink snapper* with 60–200-kHz modulated signals (Benoit-Bird *et al.*, 2003a) and *in situ* 35-kHz bandwidth dolphin-like clicks with 120-kHz centre frequency from *pink snapper*, *ruby snapper*, and *red snapper* (Benoit-Bird *et al.*, 2003b), were within the 95% confidence interval (Figure 2). These measurements at different frequencies and at different depths were comparable for the following reasons: (i) available 38 and 120 kHz values showed insignificant differences in frequency responses (Supplementary Section 7 and Supplementary Table S2) and (ii) Benoit-Bird *et al.* (2003b) showed that TS of three Deep-7 species were independent of depth, indicating that Benoit-Bird *et al.* (2003a) surface measurements were directly comparable to those of this study. Note that since in Benoit-Bird's equations a and b were given for SL and with TS not referred to the distance of 1 m from the transducer face, the original equations were modified for a and b in TS vs. FL and by subtracting $10\log_{10}(4\pi)$ from the TS values.

All observed non-Deep-7 FL-TS pairs fell within the 95% confidence interval for the Deep-7 curve, almost exclusively at the two ends of the observed adult Deep-7 size distribution (Figure 2, blueish tones). Note the downward looking triangles at the small end of the Deep-7 range are all from tethered juveniles.

Downloaded from https://academic.oup.com/icesjms/article/78/3/1117/6134884 by NOAA Central Library user on 30 September 2021

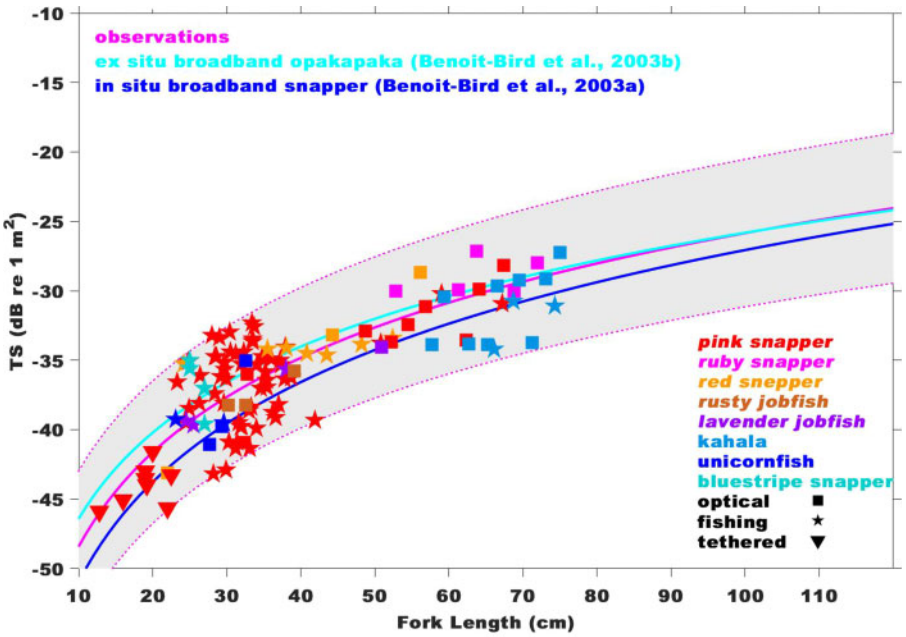

Figure 2. TS–FL curves from (magenta) *in situ* Deep-7 observations at 70 kHz, and previous results from broadband (blue) *in situ* pink, ruby, and red snapper (Benoit-Bird *et al.*, 2003a) and (cyan) *ex situ* dorsally oriented pink snapper observations (Benoit-Bird *et al.*, 2003b). Markers represent observed data pairs, colour coded for species. Deep-7 species are shown in reddish tones and italics, while non-Deep-7 species in bluish tones and regular text. Shaded area is the 95% confidence interval around the curve calculated from present observations.

Deep-7 echo allocation

Simultaneous optical and acoustic observations provided information on species-specific schools and individual fish attributes, such as depth, school width, height, shape, and density, swimming pattern, distance from bottom, and water depth. Examples of synchronous optical image and echogram pairs of *lavender jobfish* (top), kahala (middle), and *pink snapper* (bottom) are shown in Figure 3. Non-size-specific acoustic backscatter was obtained for five Deep-7 fishes: *pink snapper*, *lavender jobfish*, *rusty jobfish*, *red snapper*, and *ruby snapper*, and six other fish species: mackerel scad (*Decapterus macarellus*, "mackerel scad"), yellowfin goatfish (*Mulloidichthys vanicolensis*, "weke′ula"), unicornfish, bluestripe snapper, kahala, and deepbody boarfish (*Antigonia capros*). These observations are summarized in Supplementary Table S2.

A total of 25 determinations of individuals or groups of fishes, applying the derived acoustic descriptors, could be tested using optical and fishing data. Seven individuals identified *a priori* as either kahala or possibly larger *pink snapper* were confirmed as five kahala and two *pink snapper*; two individuals identified and confirmed as *ruby snapper*; six aggregations identified as *lavender jobfish* and/or smaller *pink snapper* confirmed as three *lavender jobfish*, one *pink snapper*, and two mixed (*lavender jobfish*/*pink snapper*) aggregations; two aggregations identified as *lavender jobfish* and/or possibly yellowfin goatfish or bluestripe snapper confirmed as one *lavender jobfish* and one *lavender jobfish*/bluestripe snapper aggregation; five aggregations identified and confirmed as unicornfish; and three aggregations identified and confirmed as mackerel scad. Between ∼100- and 180-m depths, all aggregations within 20 m from the bottom and all loose fish further than ∼60 m from the bottom were identified correctly as Deep-7 or non-Deep-7 fishes, with all grouping identified correctly below ∼180 m (Table 1, left). All aggregated and loosely grouped non-Deep-7 species that could not be separated from Deep-7 were at the small and large ends of the Deep-7 size range, respectively (Table 1, top right).

Overall, the contribution of Deep-7 fishes to all fishes observed was 94, 61, and 89% from Botcam, AUV, and ROV observations, respectively. These data showed species-specific aggregative and intermixing patterns. Of all observations, *pink snapper* and *lavender jobfish* occurred in the highest numbers of all Deep-7 fishes, occupying the shallower depths of Deep-7 range (≤170 m), with smaller (∼≤40–45-cm FL) individuals forming tight aggregations, extending to ∼20–60-m vertically (Figure 4a and b). These aggregations measured ∼70 m horizontally at the bottom, tapering off upwards to form a cone shape on the echograms.

Larger *pink snapper* and *rusty jobfish* were observed swimming in small, loose groups between about 100–170- and 100–140-m depths, respectively (Figure 4a and b). Kahala, with sizes at the larger end of Deep-7 size range (>60-cm FL), was also observed in loose groups in the depth range of larger *pink snapper*, and sometimes swam intermixed with larger *pink snapper* and *rusty jobfish* (Figure 4a and b). These fish typically occupied waters <30 m from the bottom but could be observed 50–60-m off the seafloor. Contrary to kahala, the other five non-Deep-7 species were observed at the smaller size range of Deep-7 (<30-cm FL), and all exhibited aggregative behaviour. Bluestripe snapper and yellowfin goatfish (*M. vanicolensis*, "weke'ula") occupied shallower waters than Deep-7 fishes, but their deeper range overlapped with the upper range of Deep-7 fishes between ∼90 and 110 m and their echoes could not be separated from those of Deep-7 fishes (Figure 4a). Mackerel scad were observed down to ∼170 m but occupied the water column farther up from the bottom (Figure 4a and e). However, since *pink snapper* and *lavender jobfish* were sometimes also observed away from the bottom, these species could not be separated on the echograms. Unicornfish was also observed down to about 170-m depth (Figure 4c) and

Downloaded from https://academic.oup.com/icesjms/article/78/3/1117/6134884 by NOAA Central Library user on 30 September 2021

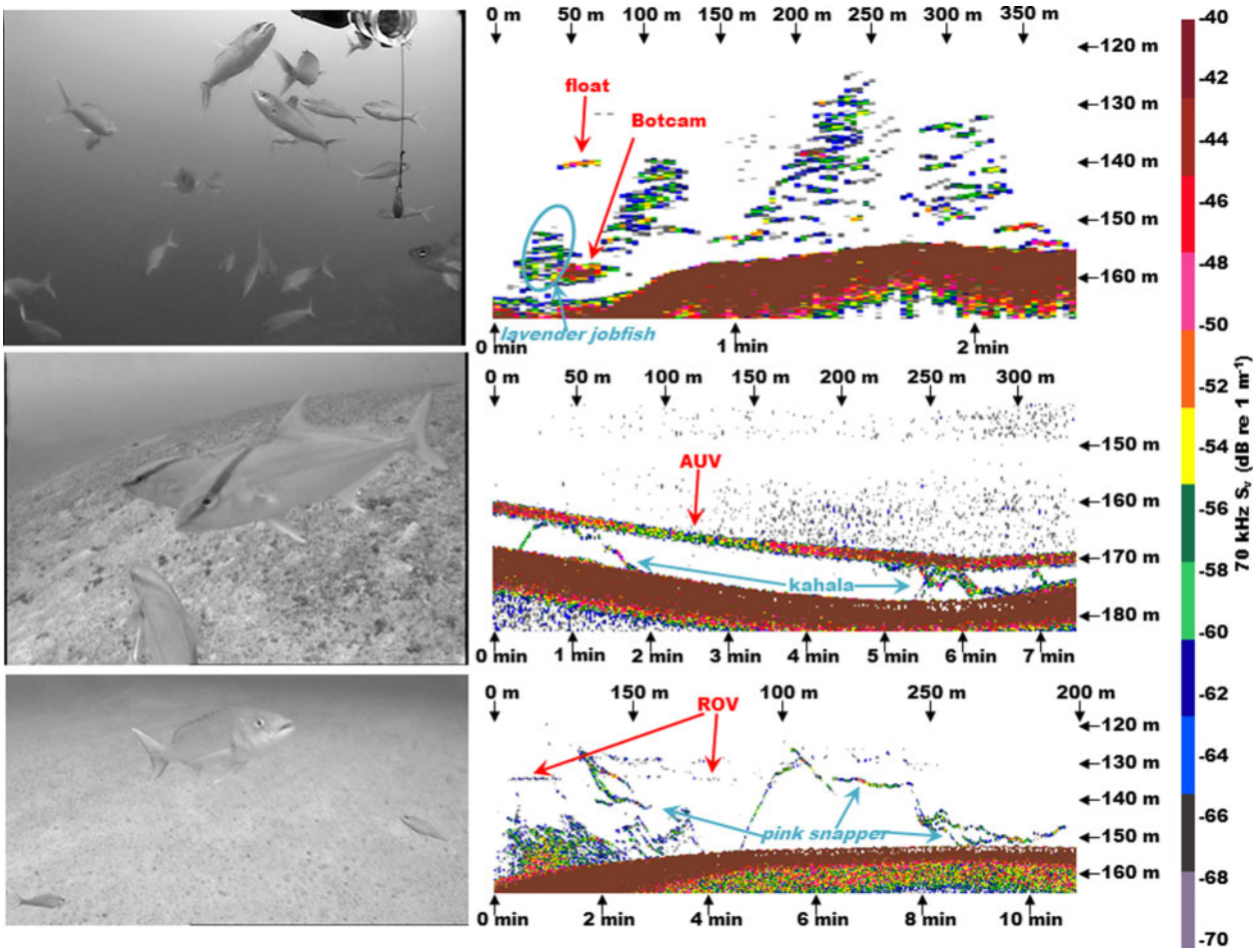

Figure 3. Examples of optical images and echograms during synchronous acoustics and Botcam (top), AUV (middle), and ROV (bottom) operations. Optical images are courtesy of Audrey Rollo, PIFSC, NOAA.

sometimes intermixed with smaller *lavender jobfish* and/or *pink snapper*. However, visually confirmed unicornfish aggregations exhibited a characteristic v-shape, not observed for any of the Deep-7 species (Figure 4a, b, c, and e). Below 170-m depth, the only aggregated fish observed was boarfish, occupying areas in close proximity to the bottom (Figure 4d). These depths (180–330 m) were also occupied by loosely swimming *ruby snapper* and *red snapper*. These fish were observed in low numbers with *red snapper* staying within 1 m of the bottom while *ruby snapper* could extend to about 10 m away from it (Figure 4d).

Abundance estimates

Mean abundance and biomass for loose and aggregated fish (Figure 5a and b) show some significant differences among Grids (see Supplementary Tables S3–S5 for mean and SE of abundance, biomass, FL of individuals, and aggregation volumes for each Grid, as well as the number of passes using Grid IDs; locations of Grids are shown in Supplementary Figure S6).

Regions with high relief, such as the north-south ledge along ~156°39′W surveyed in 2012, show higher abundance and biomass of both loose and aggregated fish, a higher ratio of loose to aggregated fish (Supplementary Figures S3 and S4, left panels), and larger FL (Figure 5c and Supplementary Tables S3–S5) than other regions. In relatively deep water (<250 m), almost all abundance and biomass were due to relatively large loose fishes (e.g. towards the southern tip of a north-south finger at ~20°40′N 156°43′W, shown by four Grids at the lower left corners on the right panels of Supplementary Figures S3 and S4).

Vertical distributions of fishes were consistent during the three surveys (Figure 6). Of all detections, 83.6% of schools and 88.1% of individuals were within 50-m of the bottom. More than three quarters of aggregations (78%) and loosely grouped fish (85%) were detected within two depth ranges: from 110 to 170 and 270 to 330 m. The mean number of fish per school was independent of depth or distance from bottom. However, FL calculated from TS of loosely grouped fish were larger (46.2 ± 0.6 cm) in the 110–170-m depth range than in the 270–330-m range (39.0 ± 0.5 cm), where ± values indicate the 95% confidence intervals around the means. In addition to depth differences, mean FL of loose fish was significantly larger within 50-m from the bottom (43.4 ± 0.4 cm) than those that were farther off the seafloor (39.2 ± 0.7 cm).

Based on the observed vertical distribution (Figure 6), Deep-7 fish density in the deadzone was assumed to be similar to that within 5 m of the seafloor. The estimated volume of the deadzone was 3.16% of total volume sampled above the deadzone. Mean ratios of biomass estimated for EDSUs above and within the deadzone increased the total biomass of Deep-7 fishes in the surveyed Grids by 4.8%.

Downloaded from https://academic.oup.com/icesjms/article/78/3/1117/6134884 by NOAA Central Library user on 30 September 2021

Table 1. Success of Deep-7 echo allocation using the current visual discrimination method.

Distance from bottom (m)	Bottom depth (m) < ~ 110	Bottom depth (m) ~ 110–170	Bottom depth (m) > ~ 170
	aggregated		
> ~ 60	mackerel scad unicornfish	mackerel scad	✓
~ 20–60	unicornfish mackerel scad	unicornfish mackerel scad	✓
< ~ 20	bluestripe snapper yellowfin goatfish	✓	✓
	loose		
> ~ 60	kahala	✓	✓
~ 20–60	kahala	kahala	✓
< ~ 20	kahala	kahala	✓

Fork length (cm)	Grouping: aggregated	Grouping: loose
	included non-Deep-7	
< ~ 35	mackerel scad unicornfish bluestripe snapper yellowfin goatfish	✓
~ 35–58	✓	✓
> ~ 58	✓	kahala
	likely discriminatory method	
< ~ 35	MVBS, patchiness, compactness, shape/size, δ dB, depth, depth distance	✓
~ 35–58	✓	✓
> ~ 58	✓	δ dB size threshold

Checkmarks indicate successful discrimination between Deep-7 and non-Deep-7 species, with names listing non-Deep-7 species that could not be separated. Left panels show allocation success per distance from bottom and bottom depth for aggregated- and loosely-grouped fishes. Right panels show allocation success per size-range for aggregated- and loosely-grouped fishes. Grey vs. black names indicate likely/unlikely discrimination with increased number of observations using the developed descriptors. Acoustic descriptors instead of non-Deep-7 names in bottom right list methods likely successful in discriminating remaining non-Deep-7 with further work.

Discussion

TS estimates

In this study, simultaneous acoustic and complementary methods provided valuable information on the acoustic characteristics of Deep-7 fishes. During AUV, Botcam, or ROV recordings, locations of single individuals and/or aggregations, when available, could be determined accurately. However, uncertainty of the TS–FL data from fishing were higher than those from optical observations as locations of fish caught are only estimates from time of catch, depth of the hook, line angle, and drift of the vessel. Since a majority of the TS–FL pairs were obtained from fishing, this uncertainty in the accuracy of the TS–FL pairs is clearly reflected in the wide spread of star markers along TS values at around 30-cm FL (Figure 2).

As Figure 2 shows, the present TS–FL regression equation at 70 kHz was comparable to those with *in situ* and dorsally oriented and *ex situ* surface broadband frequencies centring at 120–130 kHz. It is interesting to note that Benoit-Bird *et al.* (2003a) showed that TS of three Deep-7 species, including *pink snapper*, can vary as much as 30 dB with changes in tilt angle and roll. This could imply that TS of freely swimming fish obtained by a downward looking transducer is representative of values obtained from dorsally oriented fish.

Results of this study indicate that TS or MVBS alone cannot be used to separate Deep-7 echoes from those of other species, although differences between Deep-7 70–38-kHz TS and MVBS from those of kahala and mackerel scad, respectively, might prove to be suitable classifiers (Supplementary Section 7). Since all retained aggregative and loosely swimming non-Deep-7 were observed at the lower and larger ends of Deep-7 size and MVBS/TS ranges, respectively (Figure 2 and Table 1, lower right panel—see also Supplementary Table S1 and S2), thresholding MVBS and TS could provide some discriminatory power between Deep-7 fishes and all non-Deep-7 species.

Deep-7 echo allocation

Acoustic descriptors seem to successfully separate echoes from Deep-7 fishes from those of most other species, as ascertained by optically groundtruthed echo allocations and by horizontal distributions aligned with *a priori* knowledge of preferred association with high relief and rugose habitats (Merritt *et al.*, 2011; Kelley and Moriwake, 2012; Misa *et al.*, 2013; Sackett *et al.*, 2014). The

Downloaded from https://academic.oup.com/icesjms/article/78/3/1117/6134884 by NOAA Central Library user on 30 September 2021

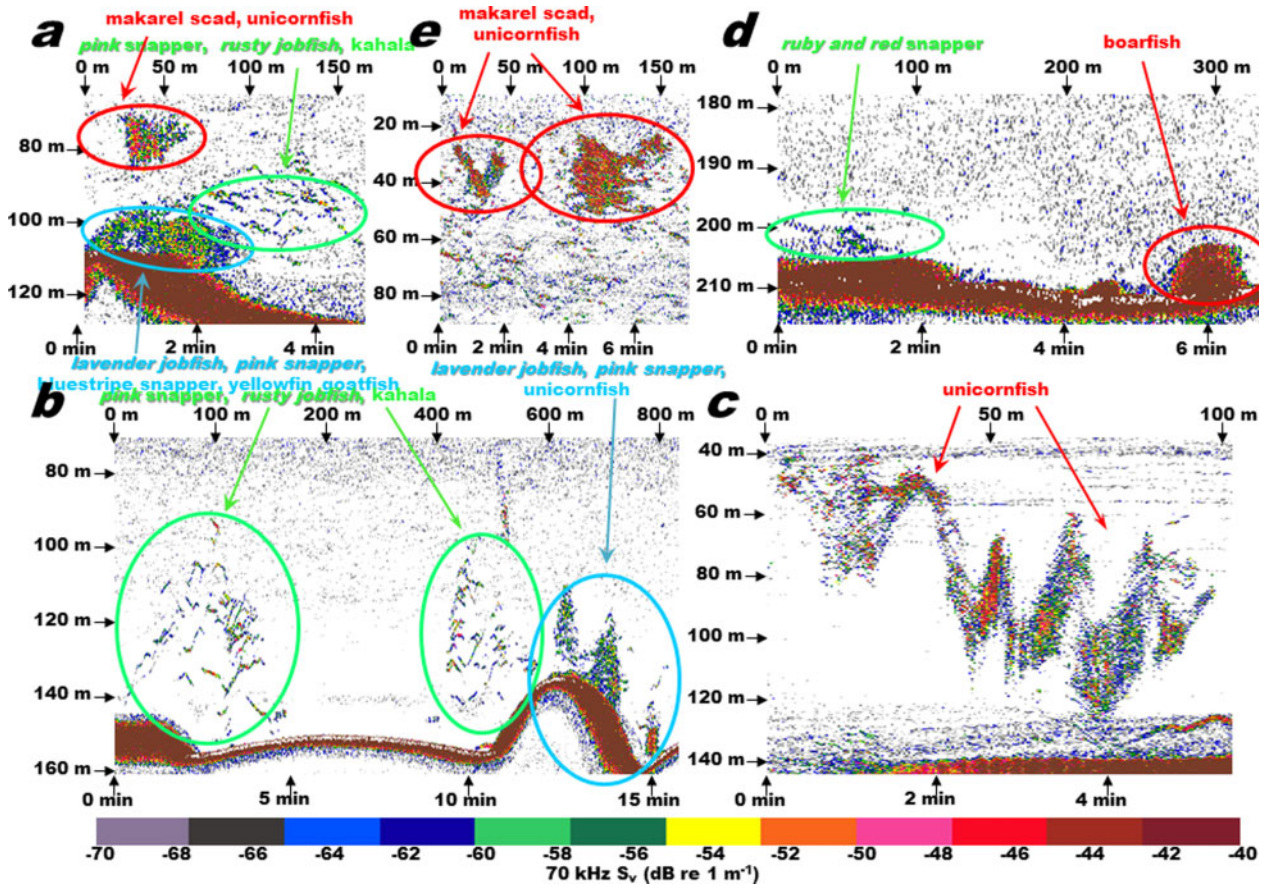

Figure 4. Example of echograms depicting aggregated and loosely swimming Deep-7 and other semi-demersal species with acoustic characteristics similar to those of Deep-7. Counterclockwise from top left: (a) shallow (90–120 m), (b–c) medium (120–170 m), and (d) deep (170–330 m) ranges of Deep-7 habitats, with (e) showing near-surface aggregations that are typically mackerel scad or unicornfish but may be formed by *pink snapper* and/or *lavender jobfish*.

high spatial variability and patchiness in the present observations are also in accord with expectations based on studies of Hawaii semi-demersal fish, including Deep-7 species (Kelley *et al.*, 2006; Merritt *et al.*, 2011; Misa *et al.*, 2013, 2016; Moore *et al.*, 2013; Sackett *et al.*, 2014) and other bottomfish in similar habitats (Costa *et al.*, 2014).

Of all single targets retained, kahala, likely to be separated from Deep-7 based on dB differencing (Supplementary Table S2) and size thresholding (Figure 2 and Table 1), seems to be the only non-Deep-7 species to significantly affect biomass and abundance estimates of individual fish, assuming optical observations and catch are representative of abundance. Aggregative species that were most likely included in the biomass and abundance estimates were, at the shallowest Deep-7 depth range (~90–110 m) and within 20 m of the seafloor, bluestripe snapper and yellowfin goatfish, and predominantly further than 60 m from the seafloor, mackerel scad, as these species sometimes appeared similar to schools of *lavender jobfish* and/or *pink snapper* on the echograms. Unicornfish could also be retained in Deep-7 echoes in depths from 110 to 170 m. Mackerel scad, as stated above, might prove to have sufficiently different 70–38-kHz MVBS from those of Deep-7 fishes, while unicornfish aggregations consistently displayed a distinct v-shape on the echograms, a characteristic that can likely be used to separate echoes of this species from those of Deep-7 fishes.

The ability to separate Deep-7 echoes from those of other species could substantially be improved upon by removing the effects of the ship's motion from the acoustic signals and utilizing Echoview's fish tracking and school detection module outputs (Supplementary Section 5). The use of these values would allow for the development of a more robust supervised or unsupervised classification scheme, resulting in more accurate echo allocation and Deep-7 abundance estimates for stock assessment.

The 77% *pink snapper* in Deep-7 fishes complementary observations corresponds well with expectations from commercial fishery catch data showing that in the past 50 years, *pink snapper* comprised over 70% of total Deep-7 catch (Langseth *et al.*, 2018). The two Deep-7 species not sampled by fishing and optical observations (*Brigham's snapper* and *Hawaiian grouper*) are known to occur in low numbers (Kelley and Moriwake, 2012; Moore *et al.*, 2013; Brodziak *et al.*, 2014), contributing only ~1 and ~7% of total Deep-7 catch, respectively (Langseth *et al.*, 2018). It is important to note that while echoes of *Brigham's snapper* are expected to be included in echograms due to the similarity in backscattering properties of Deep-7 (lutjanid) snappers (Au and Benoit-Bird, 2003; Benoit-Bird *et al.*, 2003a), their preferred proximity to the seafloor and occupancy of small crevices likely result in decreased acoustic detectability. Acoustic reflective properties of *Hawaiian grouper* are unknown at this time and need to be investigated.

Downloaded from https://academic.oup.com/icesjms/article/78/3/1117/6134884 by NOAA Central Library user on 30 September 2021

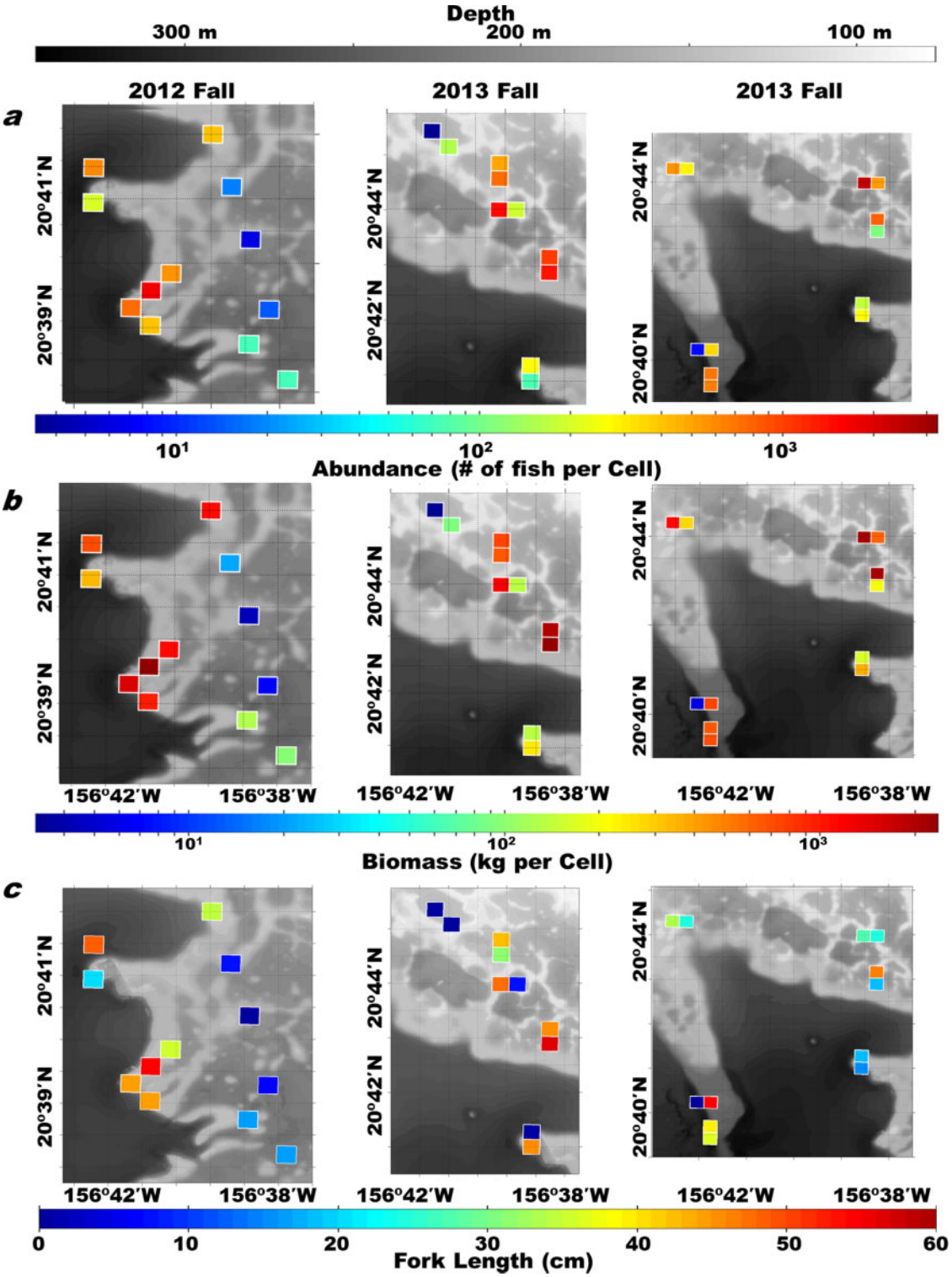

Figure 5. Mean abundance (a), biomass (b), and FL (c) from the three Surveys over greyscale bathymetry.

Of the three optical platforms used in this study, the manoeuvrable ROV with live feed provided the highest potential to yield large volumes of simultaneous acoustics and complementary data. Relative to the stationary or preprogramed platforms observing only near-bottom regions, the ROV could be deployed and kept near fish observed on echograms and within the transducers' beams far more frequently and anywhere in the water column. Optical observations, as well as experimental fishing, showed evidence of avoidance/attraction behaviour and selectivity, implying potential bias in the currently operational fishery-independent BFISH method used for Deep-7 stock assessment, and highlighting the need for the development and

Downloaded from https://academic.oup.com/icesjms/article/78/3/1117/6134884 by NOAA Central Library user on 30 September 2021

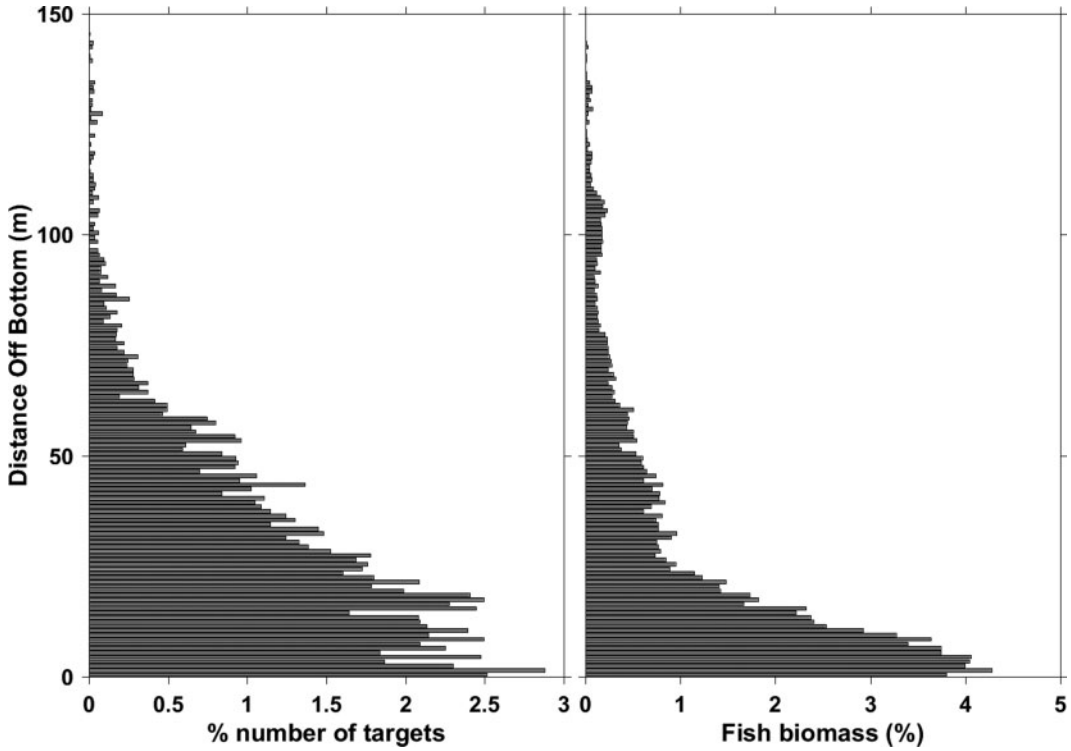

Figure 6. Percent vertical distribution of number of single targets considered as those of Deep-7 (left), and total biomass from aggregated and loose Deep-7 combined (right).

implementation of these complementary methods. During this study, *lavender jobfish* were observed exclusively with Botcam and kahala with AUV (Figure 2), as kahala actively swam and followed the slowly moving AUV. Similarly, 74% of catch from fishing operations resulted in smaller (FL <~40 cm) *pink snapper* (Figure 2). Interestingly, the baited Botcam did not attract fish when deployed as close as 15–20 m of a bottomfish aggregation, indicating a small sampling volume relative to that of the AUV, which attracted kahala from much greater distances.

Information provided by fishers on species-specific vertical distribution patterns, aggregative behaviours, and qualitative acoustic signatures and characteristics on echograms proved to be an integral part in the development of non-size-specific acoustic descriptors. While qualitative, fisher's knowledge is a highly valuable resource that is overlooked too often (Hind, 2015), although some studies do take advantage of this invaluable resource (e.g. Ressler *et al.*, 2009).

Surveys

The survey design adopted in this study aimed to balance the number of repetitions and elapsed time to minimize variance. Obtaining the lowest variance using six repetitions over individual Grids is not surprising given the known high spatiotemporal variability of Deep-7 fishes. However, while Grid-size for BFISH was kept at 500 m × 500 m to ensure that fishing operations and optical platforms deployed from surface did not drift outside of individual Grids, shortening the length of acoustic passes by surveying a subsection of a Grid and adjusting the number of repetitions could further reduce acoustic transect coefficients of variation in future surveys. It is important to note that significant differences between daytime and night-time abundance and biomass estimates from the 2011 pilot survey (Supplementary Section 8) imply that the currently used fishery-independent BFISH or fishery-dependent stock assessment methods, conducted exclusively during daytime or night-time, could supply biased Deep-7 abundance estimates.

Height of the deadzone and biomass estimation of target species within it poses a critical concern for surveys of these and other semi-demersal species and have been estimated in several studies in other regions (e.g. Ona and Mitson, 1996; Rooper *et al.*, 2010, 2012; Jones *et al.*, 2012). At first approximation, Deep-7 biomass estimates in the deadzone were shown to be <5% of total biomass, typically occupying steep slopes and/or highly rugose habitats. The success of biomass estimation in the deadzone greatly depends on predictability of vertical movement patterns of fishes. Vertical distribution of Deep-7 species, with the exception of *ruby snapper*, tends to be relatively stationary in depth (Kelley *et al.*, 2006; Kelley and Moriwake, 2012; Misa *et al.*, 2013). Species either stay at depths that are within or at depths that are outside the deadzone, which would aid in the development of a relative index over time.

Conclusions

This study serves as a valuable first step in the development of an effective, fisheries-independent acoustic method to monitor distribution and abundance of the Deep-7 complex in support of stock assessment and management. Once developed, the methodology could be adapted to other areas where lutjanid snappers comprise a significant portion of stocks, benefiting stock assessment efforts worldwide.

With present accuracy of the acoustic descriptors, echoes from all but one loosely grouped (kahala) and four tightly aggregated

Downloaded from https://academic.oup.com/icesjms/article/78/3/1117/6134884 by NOAA Central Library user on 30 September 2021

non-Deep-7 species (mackerel scad, unicornfish, bluestripe snapper, yellowfin goatfish) were likely not separated from those of Deep-7 fishes. Results indicate that dB differences between frequencies and aggregation shapes could be used to further separate echoes from three of the five retained non-Deep-7 fishes (kahala, mackerel scad, and unicornfish), leaving only echoes from two tightly grouped species (bluestripe snapper and yellowfin goatfish) at the smallest size range (<∼28 cm FL) and shallowest depth range (∼90–110 m) of Deep-7 fishes, and within ∼20 m of the seafloor. However, the available methodology could be used to monitor changes in abundance and biomass of Deep-7 fishes, assuming insignificant changes in the ratio of Deep-7 fishes and non-Deep-7 species retained in the data.

To improve acoustic discriminatory power, the accuracy of present descriptors could be improved by increasing the number of observations and by the ability to remove the effects of ship-motion from the acoustics signals for the use of more robust classification parameters. The incorporation of these parameters would allow for the development of a classification scheme that would most likely further acoustic discriminatory power. Classification accuracy experiments should be included to provide a quantitative measure of performance. The discriminatory power of broadband signals should also be investigated. While species-specific broadband responses found by Benoit-Bird *et al.* (2003b) and Au and Benoit-Bird (2003) might not provide appropriate discriminatory power at the species level, they would likely prove effective in separating Deep-7 stocks from other fishes as non-Deep-7 species are expected to differ morphologically from Deep-7 species more than Deep-7 snappers from each other. Furthermore, the significantly higher resolution given by the broadband signals compared to that of the narrowband should reduce deadzone volume and allow for the separation of individual echoes at a much higher number, providing improved biomass estimates and more TS values for fine-tuning acoustic descriptors. Abundance estimates could further be improved by incorporating *a priori* knowledge of vertical species distributions (Kelley and Moriwake, 2012), habitat associations (Misa *et al.*, 2013), and fishermen's expertise in the reading of echograms to interpret acoustic signals, as well as improving deadzone estimates by data from complimentary methodologies, such as optical or tagging studies.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Acknowledgements

The author recognizes the help and support of many who made this project possible. I thank Amy Comer, Aimee Hoover, and Adrienne Copeland for their help in calibrating, collecting data, and removing transient, impulse, and background noise from echograms. I thank Frank Parrish and Ray Boland for their help and hands-on expertise in catching, tethering, and handling juvenile pink snapper and operating the Kumu, as well as for facilitating the juvenile *pink snapper* operations. I thank Audrey Rollo for performing video analyses and providing valuable information on optical data processing and images to help better visualize organisms on echograms. I thank Heidi Hansen for her help with assembling TS–FL pairs, and Alex De Robertis and David Demer for their invaluable comments to the early version of this manuscript. I thank the crew and officers of the *Sette*, and the scientific parties of the 2011, 2012, and two 2013 Surveys in helping with optical and fishing operations, species identification, and size estimates. And finally, I wish to acknowledge local bottomfish fishermen, especially Eddie Ebisui, in providing invaluable information on their knowledge of distribution of Deep-7 and their experience identifying fish species using fish-finders. This research was funded by the National Oceanic and Atmospheric Administration through the Pacific Islands Fisheries Science Center and the Joint Institute for Marine and Atmospheric Research.

References

Au, W. W. L., and Benoit-Bird, K. J. 2003. Acoustic backscattering by Hawaiian lutjanid snappers. II. Broadband temporal and spectral structure. Journal of the Acoustical Society of America, 114: 2767–2774.

Ault, J. S., Smith, S. G., Richards, B. L., Yau, A. J., Langseth, B. J., O'Malley, J. M., Boggs, C. H., *et al.* 2018. Towards fishery-independent biomass estimation for Hawaiian Islands deepwater snappers. Fisheries Research, 208: 321–328.

Béhagle, N., Cotté, C., Lebourges-Dhaussy, A., Roudaut, G., Duhamel, G., Brehmer, P., Josse, E., *et al.* 2017. Acoustic distribution of discriminated micronektonic organisms from a bi-frequency processing: the case study of eastern Kerguelen oceanic waters. Progress in Oceanography, 156: 276–289.

Benoit-Bird, K. J., Au, W. W. L., and Kelley, C. D. 2003a. Acoustic backscattering by Hawaiian lutjanid snappers. 1. Target strength and swimbladder characteristics. Journal of the Acoustical Society of America, 114: 2757–2766.

Benoit-Bird, K. J., Au, W. W. L., Kelley, C. D., and Taylor, C. 2003b. Acoustic backscattering by deepwater fish measured in situ from a manned submersible. Deep-Sea Research Part I: Oceanographic Research Papers, 50: 221–229.

Bertrand, A., and Josse, E. 2000. Acoustic estimation of longline tuna abundance. ICES Journal of Marine Science, 57: 919–926.

Brodziak, J., Courtney, D., Wagatsuma, L., Malley, J. O., Lee, H., Walsh, W., Andrews, A., *et al.* 2011. Stock Assessment of the Main Hawaiian Islands Deep7 Bottomfish Complex through 2010. pp. 1–243.

Brodziak, J., Yau, A., O'Malley, J., Andrews, A., Humphreys, R., DeMartini, E., Pan, M., *et al.* 2014. Stock assessment update for the main Hawaiian Islands Deep7 bottomfish complex through 2013 with projected Annual Catch Limits through 2016, pp. 1–68.

Burgos, J. M., and Horne, J. K. 2008. Characterization and classification of acoustically detected sh spatial distributions. ICES Journal of Marine Science, 65: 1235–1247.

Coleman, F. C., Koenig, C. C., Huntsman, G. R., Musick, J. A., Eklund, A. M., Mcgovern, J. C., Chapman, R. W., *et al.* 2000. Long-lived reef fishes: the grouper-snapper complex. Fisheries, 25: 14–21.

Costa, B., Taylor, J. C., Kracker, L., Battista, T., and Pittman, S. 2014. Mapping reef fish and the seascape: using acoustics and spatial modeling to guide coastal management. PLoS One, 9: e85555.

Davison, P., Lara-Lopez, A., and Anthony Koslow, J. 2015. Mesopelagic fish biomass in the southern California current ecosystem. Deep-Sea Research Part II: Topical Studies in Oceanography, 112: 129–142.

De Robertis, A., McKelvey, D. R., and Ressler, P. H. 2010. Development and application of an empirical multifrequency method for backscatter classification. Canadian Journal of Fisheries and Aquatic Sciences, 67: 1459–1474.

Demer, D. A., Berger, L., Bernasconi, M., Bethke, E., Boswell, K., Chu, D., and Domokos, R. 2015. Calibration of Acoustic Instruments. Internnational Council for the Exploration of the Sea. ICES CRR: 133.

Downloaded from https://academic.oup.com/icesjms/article/78/3/1117/6134884 by NOAA Central Library user on 30 September 2021

Foote, K. G. 1980. Importance of the swimbladder in acoustic scattering by fish: a comparison of gadoid and mackerel target strengths. Journal of Acoustical Society of America, 67: 2084–2089.

Gastauer, S., Scoulding, B., Fässler, M. M. S., Benden, P. L. D., and Parsons, M. 2016. Target strength estimates of red emperor (Lutjanus sebae) with Bayesian parameter calibration. Aquatic Living Resources, 29: 301.

Gastauer, S., Scoulding, B., and Parsons, M. 2017a. Towards acoustic monitoring of a mixed demersal fishery based on commercial data: the case of the Northern Demersal Scalefish Fishery (Western Australia). Fisheries Research, 195: 91–104.

Gastauer, S., Scoulding, B., and Parsons, M. 2017b. An unsupervised acoustic description of fish schools and the seabed in three fishing regions within the Northern Demersal Scalefish Fishery (NDSF, Western Australia). Acoustics Australia, 45: 363–380.

Gastauer, S., Scoulding, B., and Parsons, M. 2017c. Estimates of variability of goldband snapper target strength and biomass in three fishing regions within the Northern Demersal Scalefish Fishery (Western Australia). Fisheries Research, 193: 250–262.

Godø, O. R., Handegard, N. O., Browman, H. I., Macaulay, G. J., Kaartvedt, S., Giske, J., Ona, E., *et al.* 2014. Marine ecosystem acoustics (MEA): quantifying processes in the sea at the spatio-temporal scales on which they occur. ICES Journal of Marine Science, 71: 2357–2369.

Hind, E. J. 2015. A review of the past, the present, and the future of fishers' knowledge research: a challenge to established fisheries science. ICES Journal of Marine Science, 72: 341–358.

Jech, J. M., Horne, J. K., Chu, D., Demer, D. A., Francis, D. T. I., Gorska, N., Jones, B., *et al.* 2015. Comparisons among ten models of acoustic backscattering used in aquatic ecosystem research. The Journal of the Acoustical Society of America, 138: 3742–3764.

Jones, D. T., Wilson, C. D., De Robertis, A., Rooper, C. N., Weber, T. C., and Butler, J. L. 2012. Evaluation of rockfish abundance in untrawlable habitat: combining acoustic and complementary sampling tools. Fishery Bulletin, 110: 332–343.

Josse, E., Bach, P., and Dagorn, L. 1998. Simultaneous observations of tuna movements and their prey by sonic tracking and acoustic surveys. Hydrobiologia, 371: 61–69.

Josse, E., Bertrand, A., and Dagorn, L. 1999. An acoustic approach to study tuna aggregated around fish aggregating devices in French Polynesia: methods and validation. Aquatic Living Resources, 12: 303–313.

Josse, E., Dagorn, L., and Bertrand, A. 2000. Typology and behaviour of tuna aggregations around fish aggregating devices from acoustic surveys in French Polynesia. Aquatic Living Resources, 13: 183–192.

Kelley, C. D., Moffitt, R. B., and Smith, J. R. 2006. Mega- to micro-scale classification and description of bottomfish essential fish habitat on four banks in the Northwestern Hawaiian Islands. Atoll Research Bulletin, 543: 319–332.

Kelley, C. D., and Moriwake, V. N. 2012. Appendix3: essential fish habitat species descriptions Part 1: Hawaiian bottomfish. In WPRFMC Final Fishery Management Plan for Coral Reef Ecosystems of the Western Pacific Region. Essential Fish Habitat for Management Unit Species, III, pp. 1–597.

Korneliussen, R. J., Diner, N., Ona, E., Berger, L., and Fernandes, P. G. 2008. Proposals for the collection of multifrequency acoustic data. ICES Journal of Marine Science, 65: 982–994.

Langseth, B., Syslo, J., Yau, A., Kapur, M., and Brodziak, J. 2018. Stock assessment for the main Hawaiian Islands Deep 7 bottomfish complex in 2018, with catch projections through 2022. NOAA Technical Memorandum NMFS-PIFSC, 69: 217.

Lezama-Ochoa, A., Irigoien, X., Chaigneau, A., Quiroz, Z., Lebourges-Dhaussy, A., and Bertrand, A. 2014. Acoustics reveals the presence of a macrozooplankton biocline in the Bay of Biscay in response to hydrological conditions and predator–prey relationships. PLoS One, 9: e88054.

MacLennan, D. N. 1990. Acoustical measurement of fish abundance. The Journal of the Acoustical Society of America, 87: 1–15.

Ménard, F., and Marchal, E. 2003. Foraging behaviour of tuna feeding on small schooling Vinciguerria nimbaria in the surface layer of the equatorial Atlantic Ocean. Aquatic Living Resources, 16: 231–238.

Merritt, D., Donovan, M. K., Kelley, C., Waterhouse, L., Parke, M., Wong, K., and Drazen, J. C. 2011. BotCam: a baited camera system for nonextractive monitoring of bottomfish species. Fishery Bulletin, 109: 56–67.

Misa, W. F. X. E., Drazen, J. C., Kelley, C. D., and Moriwake, V. N. 2013. Establishing species-habitat associations for 4 eteline snappers with the use of a baited stereo-video camera system. Fishery Bulletin, 111: 293–308.

Misa, W. F. X. E., Richards, B. L., DiNardo, G. T., Kelley, C. D., Moriwake, V. N., and Drazen, J. C. 2016. Evaluating the effect of soak time on bottomfish abundance and length data from stereo-video surveys. Journal of Experimental Marine Biology and Ecology, 479: 20–34.

Moore, C. H., Drazen, J. C., Kelley, C. D., and Misa, W. F. X. E. 2013. Deepwater marine protected areas of the main Hawaiian Islands: establishing baselines for commercially valuable bottomfish populations. Marine Ecology Progress Series, 476: 167–183.

Moura, R. L., and Lindeman, K. C. 2007. A new species of snapper (Perciformes: Lutjanidae) from Brazil, with comments on the distribution of Lutjanus griseus and L. apodus. Zootaxa, 1422: 31–43.

Ona, E., and Mitson, R. B. 1996. Acoustic sampling and signal processing near the seabed: the deadzone revisited. ICES Journal of Marine Science, 53: 677–690.

Pacific Islands Fisheries Science Center. 2011. Water Column Sonar Data Collection (SE1102L1, EK60). National Centers for Environmental Information, NOAA, NODC Acces.

Pacific Islands Fisheries Science Center. 2012. Water Column Sonar Data Collection (SE1208, EK60). National Centers for Environmental Information, NOAA, NODC Acces.

Pacific Islands Fisheries Science Center. 2013a. Water Column Sonar Data Collection (SE1302, EK60). National Centers for Environmental Information, NOAA, NODC Acces.

Pacific Islands Fisheries Science Center. 2013b. Water Column Sonar Data Collection (SE1306_BeforeCalib, EK60). National Centers for Environmental Information, NOAA, NODC Acces.

Pacific Islands Fisheries Science Center. 2013c. Water Column Sonar Data Collection (SE1306_AfterCalib, EK60). National Centers for Environmental Information, NOAA, NODC Acces.

Parke, M. 2007. Linking Hawaii fisherman reported commercial bottomfish catch data to potential bottomfish habitat and proposed restricted fishing areas using GIS and spatial analysis. NOAA Technical Memorandum NMFS-PIFSC, 11. 45 pp.

Ressler, P. H., Fleischer, G. W., Wespestad, V. G., and Harms, J. 2009. Developing a commercial-vessel-based stock assessment survey methodology for monitoring the U.S. west coast widow rockfish (Sebastes entomelas) stock. Fisheries Research, 99: 63–73.

Richards, B. L., Smith, S. G., Ault, J. S., Dinardo, G. T., Kobayashi, D., Domokos, R., Anderson, J., *et al.* 2016. Design and Implementation of a Bottomfish Fishery-Independent Survey in the Main Hawaiian Islands. 66 pp.

Rooper, C. N., Hoff, G. R., and De Robertis, A. 2010. Assessing habitat utilization and rockfish (Sebastes spp.) biomass on an isolated rocky ridge using acoustics and stereo image analysis. Canadian Journal of Fisheries & Aquatic Sciences, 67: 1658–1670.

Rooper, C. N., Martin, M. H., Butler, J. L., Jones, D. T., and Zimmermann, M. 2012. Estimating species and size composition of rockfishes to verify targets in acoustic surveys of untrawlable areas. Fishery Bulletin, 110: 317–331.

Downloaded from https://academic.oup.com/icesjms/article/78/3/1117/6134884 by NOAA Central Library user on 30 September 2021

Sackett, D. K., Drazen, J. C., Moriwake, V. N., Kelley, C. D., Schumacher, B. D., and Misa, W. F. X. E. 2014. Marine protected areas for deepwater fish populations: an evaluation of their effects in Hawai'i. Marine Biology, 161: 411–425.

Sawada, K., Furusawa, M., and Williamson, N. J. 1993. Conditions for the precise measurement of fish target strength in situ. The Journal of the Marine Acoustics Society of Japan, 20: 73–79.

Simmonds, J. E., and MacLennan, D. N. 2005. Fisheries Acoustics. Blackwell Science, Oxford. 437 pp.

Stanley, R. D., Kieser, R., Cooke, K., Surry, A. M., and Mose, B. 2000. Estimation of a widow rockfish (Sebastes entomelas) shoal off British Columbia, Canada as a joint exercise between stock assessment staff and the fishing industry. ICES Journal of Marine Science, 57: 1035–1049.

Trenkel, V. M., Ressler, P. H., Jech, M., Giannoulaki, M., and Taylor, C. 2011. Underwater acoustics for ecosystem-based management: state of the science and proposals for ecosystem indicators. Marine Ecology Progress Series, 442: 285–301.

Trenkel, V. M., and Berger, L. 2013. A fisheries acoustic multi-frequency indicator to inform on large scale spatial patterns of aquatic pelagic ecosystems. Ecological Indicators, 30: 72–79.

WPacFIN. 2013a. American Samoa fisheries statistics report. *In* Fisheries Statistics of the Western Pacific. Resources, Network Western Pacific Fisheries Information Network, American Samoa Department of Marine and Wildlife Resources. pp. 1–48.

WPacFIN. 2013b. Commonwealth of the Northern Mariana Islands fisheries statistics report. *In* Fisheries Statistics of the Western Pacific. Western Pacific Fisheries Information Network, Division of Fish and Wildlife. pp. 1–41.

WPacFIN. 2013c. Guam fisheries statistics report. *In* Fisheries Statistics of the Western Pacific. Western Pacific Fisheries Information Network; Guam Division of Wildlife Resources. pp. 1–40.

Xie, Y., Michielsens, C. G. J., and Martens, F. J. 2012. Classification of fish and non-fish acoustic tracks using discriminant function analysis. ICES Journal of Marine Science, 69: 313–322.

Handling editor: Olav Godø

Downloaded from https://academic.oup.com/icesjms/article/78/3/1117/6134884 by NOAA Central Library user on 30 September 2021