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Towards Fishery-Independent Biomass Estimation for Hawaiian Islands Deepwater Snappers

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Abstract

The Hawaiian deep-slope (75-400 m) Deep7 bottomfish fishery, consists of seven (i.e., six snappers and one grouper) species. This study developed a sampling survey and modeling methodology for estimating biomass for this complex in the Main Hawaiian Islands. The island-wide fishery-independent sampling survey using two gears (commercial fishers with hook-and-line, 3D stereo camera) was conducted to generate estimates of relative abundance- and biomass-at-length for the complex. A length-based modeling approach was applied to the opakapaka fishery and survey size-structured abundance data, life history demography, and total fishery catches to estimate a feasible range of effective sampling area for the standard survey gear (i.e., cameras). These sampling area estimates were then used to expand survey estimates of relative biomass to population total biomass. The longer-term focus of this effort is to improve stock assessments of the Deep7 complex. The survey and modeling methods developed in this study provide the underpinnings of an integrated information and modeling system for assessment that enables multiple levels of comparison and validation with respect to data sources (fishery-dependent and fishery-independent) and modeling approaches (biomass-dynamic and cohort-structured).

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1. Introduction

Commercial and recreational fishing are extremely important to the economy and culture of Hawaii (Haight et al., 1993). The Hawaiian deep-slope (75-400 m) Deep7 "bottomfish" fishery, a culturally and economically important domestic fishery, consists of seven (i.e., six snappers and one grouper) species (Western Pacific Regional Fishery Management Council, WPRFMC 2010). Bottomfish have been targeted for hundreds of years throughout the eighteen islands of the Hawaiian archipelago by native Hawaiians, and have been under a formal federal fishery management plan since 2005, when it was determined that the stock was experiencing overfishing (Moffitt et al., 2006). Fishing became restricted to the eight Main Hawaiian Islands with the designation of the Papahānaumokuākea Marine National Monument in 2006.

The Pacific Islands Fisheries Science Center of the National Oceanic and Atmospheric Administration (PIFSC) is responsible for assessments of the Deep7 complex. These assessments include determination of resource status relative to management-determined limit reference points, and future projections of overfishing risks associated with various catch limits, which depend upon estimates of recent stock biomass. These findings are then presented to the Western Pacific Region Fishery Management Council who recommends harvest control rules that ensure sustainability. The assessment process typically requires reliable time-series of fishery catches, effective fishing effort, and life history demographics to make these determinations and estimate abundance trends relative to sustainability benchmarks (Quinn and Deriso, 1999; Ault et al., 2014). Until recently, Deep7 assessments relied exclusively on fishery-dependent estimates of resource relative abundance (i.e., catch per unit effort CPUE) as the principal index of abundance and biomass (Brodziak et al., 2014). It is not clear whether these data were in fact proportional to resource abundance, for example, given the non-random effort distribution pattern of the fishery. Fishery-dependent CPUE data may be biased due to size and catch limits, gears, market forces and fishers behaviors (Hilborn and Walters, 1992; Maunder and Punt, 2004). Quantitative assessments can greatly benefit from use of auxiliary abundance indices (e.g., average length in the exploited phase) estimated from fishery catch sampling and fishery-independent surveys (Ault et al., 2005, 2014). A key advantage of fishery-independent surveys is that they obtain similar size-structured abundance as those from catch sampling programs, but with greater statistical rigor (Ault et al., 1999; Smith et al., 2011). Fishery-independent surveys can also be designed to estimate relative and absolute population abundance, which provides an important calibration mechanism for assessment models that infer stock abundance from fishery catches and effort, and life history demographic characteristics.

In 2011, the PIFSC began to develop a multi-gear, fishery-independent survey for the Main Hawaiian Islands Deep7 complex to improve the data used for stock assessments (Richards et al., 2016), by estimating recent size-structured abundance and biomass. We present a new method for estimating biomass for the Deep 7 complex derived from the first Main Hawaiian Islands-wide fishery-independent survey of Deep 7 bottomfish. Survey relative abundance and biomass are calculated, and estimated total abundance and biomass based on feasible effective sampling areas for the principal survey gear are validated using a length-based modeling approach.

2. Methods and materials

2.1. Fishery independent survey

A fishery-independent sampling survey was conducted throughout the eight Main Hawaiian Islands (Fig. 1) to estimate key population metrics for the Deep7 bottomfish complex (Fig. 2). The development of the sampling methods and statistical design are detailed in Richards et al. (2016). The survey domain encompassed the full extent of mapped bottomfish habitats from 75 to 400 m depths, extending from the Big Island of Hawaii 600 km northwest to the island of Niihau. The survey frame was comprised of 500 x 500 m sample units (G) stratified according to three depth categories (75 to <200 m, ≥200 to <300 m, ≥300 to 400 m), and three substrate composition-complexity categories (softbottom-all slopes, hardbottom-low slope, hardbottom-high slope) (Fig. 1, Table 1). Analyses of pilot experiments conducted in the Maui-Nui region during 2011 to 2015 showed that this stratification scheme effectively spatially partitioned the variance of Deep7 species density (Richards et al., 2016). Samples were allocated among strata following a Neyman scheme (Cochran, 1977), and sample units within strata were randomly selected without replacement from a discrete uniform probability distribution to ensure equal probability of selection (Law and Kelton, 2000). To ensure geographical coverage with respect to islands, sample units were proportionally allocated within strata to island area.

At a selected sampling unit within a stratum, species-specific number and length composition were obtained using one of two principal survey gears: (1) hook-line fishing; or (2) stationary stereo-video cameras (Richards et al., 2016). A standard hook-line sample was 30 minutes of active fishing within a sample unit by one vessel using two lines, each with four hooks and two bait types (i.e., squid and fish). Each captured fish was identified to species, and fork length was measured to the nearest cm. For cameras, two replicate, randomized, 15-minute deployments were conducted within a 500 x 500 m sample unit. In-situ footage was analyzed to generate species-level counts by the MaxN method (Cappo et al., 2006), and to measure fork lengths to the nearest mm. Replicate counts were averaged for a given sample unit.

Cameras have a depth limitation (300 m) and fishing is not allowed in certain areas; thus, deploying both gears was necessary for sampling the full bottomfish survey domain. As described in Richards et al. (2016), Robson's (1966) relative fishing power method was used to convert species counts for the hook-line gear to camera species counts based on comparative gear experiments. These experiments also found that the camera did not observe smaller or larger fishes than those captured by hook-line. Consequently, there was no need to correct for length selectivity between the two gears. The hook-line gear-standardized sample unit observations were combined with the camera sample unit observations, and analyzed as for a single gear survey.

Estimation of Deep7 population metrics followed standard procedures for stratified random sampling (Cochran, 1977; Ault et al., 1999; Lohr, 2010; Smith et al., 2011). The number of fish per sample unit U_N was the principal metric used to develop the statistical sampling design. Computational formulae for estimating the mean number of fish $\overline{U}_N$, a relative index of population abundance, and associated variance at both the stratum and survey frame levels are provided in Table 2. Survey design estimation was carried out using the SAS (SAS Institute, v 9.4) and R (R Development Core Team, v 3.1.3) software packages.

2.2. Biomass estimation

Estimation of total population biomass B entailed expanding the mean biomass per unit $\overline{U}_B$ to the full survey frame,

$$B = \overline{U}_B \frac{A_i}{a_i} G \quad , \tag{1}$$

where A_i is the area of a grid cell sample unit, a_i is the effective sampling area of the camera gear, and G is the number of grid cells in the survey domain. Mean biomass per sample unit (Table 2, eq. T-2) was obtained by converting length to weight of each individual fish via an allometric weight-length function (Table 2, eq. T-1), and then summing the weights for all observed fish by species. Allometric functions were developed for each Deep7 species using paired weight-length observations collected in the Main Hawaiian Islands by scientists at the PIFSC. Allometric model parameters were estimated using the nonlinear least-squares procedure from the R (R Development Core Team, v 3.1.3) software package.

The number of sample units G in the Main Hawaiian Islands survey frame was determined from the habitat maps (Fig. 1, Table 1). However, the effective sampling area of a standard camera sample, a_i, likely did not cover the entire area of an individual grid cell ($A_i = 250{,}000$ m^2). Analogous to a two-stage design (Smith et al., 2011), the ratio A_i/a_i in eq. (1) is the scaling factor for estimating total biomass at the level of an individual grid cell, and G further scales total biomass to the full sampling domain.

2.3. Feasible range for camera sampled area

A principal uncertainty in the fishery-independent survey estimation of population biomass (eq. 1) for Deep7 bottomfish species was that the exact value for a_i, the camera sampled area, was unknown. Similar to diver stationary point counts for reef fish (Smith et al., 2011), the sampling area for a stationary camera can be considered as a two-dimensional circle with radius r,

$$a_i = \pi r^2 \quad . \tag{2}$$

At a particular moment of time, the stationary stereo-video camera observes fish within an 82^o field of view to a distance (radius) of 7.5 m (Amin et al., 2017). However, given that the camera is baited and the sampling period is 15 min, it is likely that fish are attracted from outside the defined radius during a standard camera sample.

A population modeling approach was developed to estimate the feasible range for effective area sampled by the camera in terms of radius distance. This approach entailed: (i) estimating a feasible range for opakapaka population biomass that corresponded with fishery catches and observed population length structure in the exploitable phase of the population; (ii) using eq. (1) to solve for a_i; and (iii) using eq. (2) to solve for radius distance r.

2.4 Numerical Length-based Population Model

A length-based numerical cohort-structured model (Ault et al., 1998, 2018) was parameterized for opakapaka using empirical information from life history demographic studies, the fishery-independent survey, and the commercial fishery. The numerical model, adapted for data-limited fisheries, tracked cohort numbers-at-size (length and weight) over age and time. Simplifying assumptions were: (i) average annual constant recruitment; and (ii) knife-edged gear selectivity at length L_c.

Demographic data for opakapaka, the dominant species caught, were used for model parameterization as requisite life-history data were not available for the other Deep7 species. Parameters for the von Bertalanffy growth function (length-age), maximum lifespan, and length-at-maturity were obtained from Andrews et al. (2012) and Luers et al. (2017). Estimates of opakapaka total catch (commercial and recreational) for recent years were obtained from Langseth et al. (2018).

Total instantaneous mortality rate (Z) in the exploited phase of the population was estimated using the length-based model of Ehrhardt and Ault (1992),

$$\left[\frac{L_\infty - L_\lambda}{L_\infty - L_c}\right]^{\frac{\hat{Z}(t)}{K}} = \left[\frac{\hat{Z}(t)\left(L_c - \bar{L}(t)\right) + K\left(L_\infty - \bar{L}(t)\right)}{\hat{Z}(t)\left(L_\lambda - \bar{L}(t)\right) + K\left(L_\infty - \bar{L}(t)\right)}\right] \tag{3}$$

where, L_c is length at first capture, L_λ is average length at the oldest age a_λ, $\bar{L}(t)$ is the average length in the exploited phase (i.e., between L_c and L_λ) at time t (i.e., year), and K and L_∞ are parameters of the von Bertalanffy growth equation. Estimates of $\bar{L}(t)$ from both the fishery-independent survey and commercial catch were used to develop a feasible range of Z estimates. A stratified random design ratio-of-means procedure (Lohr, 2010) was used to estimate $\bar{L}(t)$ for opakapaka from survey observations of numbers-at-length (Table 2, eqs. T-3 and T-4). For fishery data, estimates of mean fish weight from reported commercial data over the 2016 state fiscal year (July 1, 2015 – June 30, 2016) were converted to a distribution of mean lengths using the allometric function for opakapaka, and $\bar{L}(t)$ was subsequently estimated as the average of this distribution. Natural mortality rate M was estimated from lifespan (Alagaraga, 1984; Hoenig, 1983) assuming that 5% of a cohort survives to the maximum age/length, and fishing mortality rate F was estimated by subtracting M from Z (Ault et al., 1998).

The estimated total annual catch from the numerical population model was matched to the total fishery catch (reported and unreported combined) for opakapaka by adjusting annual recruitment to the population. A calibration check for the numerical estimation-simulation model compared model-predicted length frequencies in the exploited phase with observed length frequencies from the survey using Akaike information criteria (AIC). The final calibrated model was then used to produce a feasible range of estimates of average population biomass. These opakapaka biomass estimates were in turn used to derive a feasible range of estimates of effective area sampled by the camera. A range of biomass values was then computed for Deep 7 species in the survey frame.

3. Results

The 2016 Deep7 bottomfish survey sampled 559 grid cell units (n=461 fishing gear, n=90 camera gear, n=8 both gears). For the principal design metric, mean number per unit $\overline{U}_N$, CVs ranged from 14.7% to 21.9% for more abundant species (ehu, opakapaka, kalekale) and from 23.2% to 42.1% for less abundant species (lehi, onaga, hapu’upu’u, gindai) (Table 3).

Estimated allometric weight-length functions (Table 4; Fig. 3) were used to compute survey mean biomass per unit $\overline{U}_B$, the relative index of abundance needed for total population biomass estimates. The procedure for estimating $\overline{U}_B$ and its standard error for the survey frame from stratum-level estimates is illustrated for opakapaka for the exploited phase (length > 37 cm) in Table 5. The slight difference in sample size between the exploited phase estimates (n=549) and the full life-stage estimates (n=559) is due to the exclusion of observations with missing length values.

Demographic parameters for opakapaka synthesized from empirical studies and used as inputs for the numerical cohort-structured population model are provided in Table 6. The estimated total catches for opakapaka for state fiscal years 2015 and 2016 are given in Table 7. Mortality rates Z were estimated from two length frequency distributions for opakapaka: (1) fishery-independent survey; and, (2) commercial fishery catches derived from a distribution of mean weight per fish (Fig. 4). The mortality rates were used in separate runs of the population model to estimate the expected population biomass (Table 8) that produced the total catch for opakapaka for fiscal year 2016 (Table 7). The resulting estimated radius distance for camera sampled area ranged from 27.6 m to 60.6 m (Table 8).

As a verification, the model-simulated population length structure in the exploited phase was compared to the observed length structure from the survey (Fig. 5). Model 1 provided a better match between model-predicted and observed length frequencies for smaller length classes (<44 cm) compared to Model 2, and had an overall better correspondence (lower AIC). Model 2, however, provided a better match for larger length classes > 50 cm compared to Model 1. The estimated radii for effective camera sampled area from both models (Table 8) were used to estimate population biomass B for Deep7 species from the survey (Table 9) following eq. (1).

4. Discussion

This study developed a survey and modeling methodology for estimating biomass for the Deep7 bottomfish complex in the Main Hawaiian Islands. The first island-wide fishery-independent survey was conducted to generate estimates of relative abundance- and biomass-at-length. A length-based modeling approach was applied using survey and fishery size-structured abundance data, life history demography, and total fishery catch to estimate a feasible range of effective sampling area for the reference gear. These sampling area estimates were then used to expand survey estimates of relative biomass to population total biomass.

The approach for estimating total biomass for Deep 7 species from the fishery-independent survey is not yet fully “independent” in that it relied on total fishery catches for a principal species (opakapaka). The key uncertainty was the effective area sampled by the stereo-video camera system. Here we used length-based modeling to define a feasible range of effective radius of 27.6 to 60.6 meters. For diver-based surveys of reef fishes (Bohnsack and Bannerot, 1986; Smith et al., 2011) the effective area sampled by a buddy team of two divers, each sampling 7.5 m radius cylinders in a five to eight minute time period, is 354 m^2, which equates to a single cylinder with radius of 10.6 m. Given that our camera was baited and the sampling period was 15 minutes (i.e., two to three times longer than a diver sample), it seems reasonable that the radius of the effective area sampled would be larger than 10 to 11 m. Modeling results based on comparisons of predicted and observed length distributions suggested that the true value for camera effective radius in our survey was somewhere between 27.6 and 60.6 m.

The longer-term focus of this effort is to improve stock assessments of the Deep7 complex. The survey and modeling methods developed in this study provide the underpinnings of an integrated information and modeling system for assessment that enables multiple levels of comparison and validation with respect to data sources (fishery-dependent and fishery-independent) and modeling approaches (biomass-dynamic and cohort-structured). Previous Deep7 bottomfish stock assessments have used biomass-dynamic models to infer stock dynamics based on fishery-dependent catch-effort indices (Brodziak et al., 2014). The most recent stock assessment included the 2016 fishery-independent survey biomass estimate, fitting to the relative abundance estimate, and a Bayesian prior based on the range of the radius of the reference gear as presented herein to incorporate uncertainty in effective area sampled (Langseth et al. 2018). The fishery-independent survey can now provide complementary population indices to enhance these modeling efforts, especially as the time-series of survey estimates develops in the coming years, and may help to ameliorate potential problems common to fishery-dependent indices, e.g., fishing effort may not be proportional to resource abundance (Hilborn and Walters, 1992; Walters and Martell, 2004). Abundance-at-size data, obtained from the fishery-independent survey or from the fishery, are primary inputs for cohort-structured stock assessment models, which can provide cross-checks for results from biomass-dynamic models (Ault et al., 2014). Two pressing needs to bring this integrated information-assessment system to fruition are: (i) fully independent biomass estimates from the survey; or in the absence of (i) then (ii) improved data for cohort-structured assessments.

Direct estimation of population biomass from the fishery-independent survey will require a sampling method that obtains species counts and length composition within a consistent, known area (i.e., density-at-length). From our perspective, modifications to the camera system seem the most expedient route for achieving this. Uncertainties in the effective area sampled by the reference gear (this study) and in the MaxN method for estimating density from video footage (Cappo et al., 2006; Schobernd et al., 2014) could both be assuaged by technology that provides a clear 360^{o} field of view of known area (Campbell et al., 2018). This would eliminate the need for bait, but may increase required sampling effort due to the likely smaller sampling area compared to the current baited system. A potential wrinkle is the assumption that the Deep 7 species are primarily demersal, occupying an area in close proximity to the seafloor that is within viewing range of the camera system. However, over the course of the pilot experiments (2011-2015) and the 2016 full-scale survey, both the fishers and camera analysts have observed a few instances where Deep 7 fishes were higher in the water column and may have been out of range of the camera gear after it settled on the bottom. Hydroacoustics could provide a more synoptic way to estimate the length-structured density of target fishes within a known area, but have their own challenge of species identification when multi-species aggregations exist (Richards et al., 2016).

Basic information needs for cohort-structured assessment models are size-structured abundance data (e.g., Fig. 4) and life history demography (e.g., Table 6). The fishery-independent survey provides abundance-at-size data. However, mean length in the exploited phase from fishery catches was derived from the distribution of average fish weights per commercial reporting day. Future cohort-structured modeling would benefit from records of individual length composition, possibly obtained by sampling of catch or changing reporting requirements. In this study, life history demographic data were only available for the dominant (opakapaka) Deep7 species. As a result, the radius estimation was determined for opakapaka, which was extrapolated to the other Deep7 species. Obtaining the full spectrum of life history demographics for the entire Deep7 complex would allow for more complete cohort-structured population and community modeling, and these can serve as validation checks for biomass-dynamic assessments and for fishery-independent biomass estimates.

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Table 1. The total number of mapped 500 x 500 m grid cells (primary sample units, G) by substrate-slope-depth strata within the Main Hawaiian Islands bottomfish sampling survey domain.

Substrate	**Slope**	**Depth**	**Strata Code**	$\boldsymbol{G_h}$
SB (softbottom)	A (high & low slope)	Shallow (S, 75 to <200 m)	SB_A_S	1,863
HB (hardbottom)	L (low slope)	Shallow	HB_L_S	4,562
HB	H (high slope)	Shallow	HB_H_S	4,777
SB	A	Medium (M, ≥200 to <300 m)	SB_A_M	1,449
HB	L	Medium	HB_L_M	2,688
HB	H	Medium	HB_H_M	2,412
SB	A	Deep (D, ≥300 to 400 m)	SB_A_D	1,591
HB	L	Deep	HB_L_D	3,801
HB	H	Deep	HB_H_D	2,749
			$\boldsymbol{G = \sum_h G_h =}$	**25,892**

Table 2.- Computational formulae for the Deep7 bottomfish survey stratified random sampling design. Numbered equations are referred to in the text.

Symbol	Definition	Computational Formula	Equation Number
i	Sample unit (500 x 500 m map grid cell)		
j	Individual fish		
h	Stratum		
G	Number of mapped grid cells in sampling frame	$G = \sum_h G_h$	
G_h	Number of sample units *i* in stratum *h*		
ω_h	Stratum *h* weighting factor	$\omega_h = \frac{G_h}{\sum_h G_h}$	
$\overline{U}_{N_h}$	Mean number of fish per sample unit *i* in stratum *h*	$\overline{U}_{N_h} = \frac{1}{n_h} \sum_i U_{N_{hi}}$	
n_h	Number of units *i* sampled in stratum *h*		
$U_{N_{hi}}$	Number of fish in sample unit *i* in stratum *h*		
$\overline{U}_{B_h}$	Mean biomass of fish per sample unit in stratum *h*	$\overline{U}_{B_h} = \frac{1}{n_h} \sum_i U_{B_{hi}}$	
$U_{B_{hi}}$	Biomass in sample unit *i* in stratum *h*	$U_{B_{hi}} = \sum_j W_{hij}$	
W_{hij}	Weight of fish *j* in sample unit *i* in stratum *h*	$W_{hij} = \alpha \left(L_{hij} \right)^{\beta}$	T-1
L_{hij}	Length of fish *j* in sample unit *i* in stratum *h*		
α, β	Parameters of allometric weight-length function		
$var[\overline{U}_h]$	Variance of mean number or biomass per unit in stratum *h*	$var[\overline{U}_h] = \left(1 - \frac{n_h}{G_h}\right) \frac{s_h^2}{n_h}$	
s_h^2	Sample variance of number or biomass in stratum *h*	$s_h^2 = \frac{\sum_i (U_{hi} - \overline{U}_h)^2}{n_h - 1}$	

$\bar{U}_N$	Mean number per unit for the full survey frame	$\bar{U}_N = \sum_h \omega_h \bar{U}_{N_h}$	
$\bar{U}_B$	Mean biomass per unit for the full survey frame	$\bar{U}_B = \sum_h \omega_h \bar{U}_{B_h}$	T-2
$var[\bar{U}]$	Variance of survey frame mean number or biomass per unit	$var[\bar{U}] = \sum_h \omega_h^2\, var[\bar{U}_h]$	
$SE[\bar{U}]$	Standard error of survey frame mean number or biomass per unit	$SE[\bar{U}] = \sqrt{var[\bar{U}_h]}$	
$CV[\bar{U}]$	Coefficient of variation of mean number or biomass per unit	$CV[\bar{U}] = \frac{SE[\bar{U}]}{\bar{U}}$	
B	Total population biomass in survey frame	$B = \bar{U}_B \frac{A_i}{a_i} G$	
A_i	Area of sample unit *i*		
a_i	Effective sampling area of camera gear in sample unit *i*		
$SE[B]$	Standard error of population biomass	$SE[B] = \sqrt{var[\bar{U}_B] \left(\frac{A_i}{a_i} G\right)^2}$	
$\bar{L}$	Mean length in exploited phase in survey frame	$\bar{L} = \frac{\bar{Y}}{\bar{X}}$	T-3
$\bar{X}$	Per unit mean number in exploited phase in survey frame	$\bar{X} = \sum_h \omega_h\, \bar{X}_h$	
$\bar{Y}$	Per unit mean sum of lengths in exploited phase in survey frame	$\bar{Y} = \sum_h \omega_h\, \bar{Y}_h$	
$\bar{X}_h$	Per unit mean number in exploited phase in stratum *h*	$\bar{X}_h = \frac{1}{n_h} \sum_i X_{hi}$	
X_{hi}	Number in exploited phase in sample unit *i* in stratum *h*		
$\bar{Y}_h$	Per unit mean sum of lengths in exploited phase in stratum *h*	$\bar{Y}_h = \frac{1}{n_h} \sum_i Y_{hi}$	
Y_{hi}	Sum of lengths in exploited phase in sample unit *i* in		

	stratum *h*		
$var[\bar{L}_h]$	Variance of mean length in exploited phase in stratum *h*	$var[\bar{L}_h] = \left(1 - \frac{n_h}{G_h}\right)\frac{s^2_{h(Y\mid X)}}{n_h \bar{X}^2_h}$	
$s^2_h(Y\mid X)$	Sample variance of Y conditioned on X in stratum *h*	$s^2_h(Y\mid X) = \frac{\sum_i (Y_{hi} - \bar{L}X_{hi})^2}{n_h - 1}$	
$SE[\bar{L}]$	Standard error of mean length in exploited phase in survey frame	$SE[\bar{L}] = \sqrt{\sum_h \omega^2_h var[\bar{L}_h]}$	T-4

Table 3. Estimates of Main Hawaiian Islands-wide mean number per unit $\bar{U}_N$, standard error, and CV (%) for Deep 7 bottomfishes (all sampled life stages) for the 2016 survey (n=559).

Species	$\boldsymbol{\bar{U}_N}$	$\boldsymbol{SE(\bar{U}_N)}$	$\boldsymbol{CV(\bar{U}_N)}$
Onaga	0.0725	0.0225	31.1
Ehu	0.4546	0.0667	14.7
Kalekale	0.3123	0.0684	21.9
Opakapaka	0.9512	0.1965	20.7
Gindai	0.0326	0.0076	23.2
Hapuupuu	0.0135	0.0046	34.0
Lehi	0.0255	0.0107	42.1

Table 4. Bottomfish allometric relationships $W=\alpha L^{\beta}$ for Hawaiian Deep7 bottomfish species. Units for L in cm and W in kilograms. Letters for each species correspond to Figure.

Species		$\boldsymbol{\alpha}$	**SE($\boldsymbol{\alpha}$)**	$\boldsymbol{\beta}$	**SE($\boldsymbol{\beta}$)**	**df**
Onaga	(A)	6.005E-05	3.365e-06	2.673	1.321e-02	1,436
Ehu	(B)	1.551E-05	7.251e-07	3.026	1.231e-02	1,164
Kalekale	(C)	2.243E-05	3.112e-06	2.932	3.870e-02	556
Opakapaka	(D)	2.311E-05	1.189e-07	2.928	1.275e-02	1,442
Gindai	(E)	3.526E-05	1.062e-06	2.859	8.278e-02	144
Hapu’upu’u	(F)	3.065E-05	3.786e-06	2.884	2.797e-02	857
Lehi	(G)	1.298E-04	3.206e-05	2.458	5.711e-02	128

Table 5. Strata estimates of opakapaka mean number $\overline{U}_{N_h}$ and biomass (kg) $\overline{U}_{B_h}$ per unit and associated variances, and illustration of estimation of survey frame biomass (kg) per unit $\overline{U}_B$ and standard error from strata-level estimates. Strata codes are defined in Table 1.

Strata Code	$\boldsymbol{n_h}$	$\boldsymbol{\omega_h}$	$\boldsymbol{\overline{U}_{N_h}}$	$\boldsymbol{var(\overline{U}_{N_h})}$	$\boldsymbol{\overline{U}_{B_h}}$	$\boldsymbol{var(\overline{U}_{B_h})}$
SB_A_S	16	0.0720	0.9034	0.3949	3.5604	6.2078
HB_L_S	73	0.1762	0.1188	0.0139	0.3277	0.1057
HB_H_S	154	0.1845	2.0789	0.5758	4.2760	1.8326
SB_A_M	16	0.0560	0.0000	0.0000	0.0000	0.0000
HB_L_M	47	0.1038	0.3691	0.0655	0.5559	0.1485
HB_H_M	106	0.0932	0.1384	0.0076	0.3554	0.0404
SB_A_D	21	0.0614	0.0000	0.0000	0.0000	0.0000
HB_L_D	54	0.1468	0.0000	0.0000	0.0000	0.0000
HB_H_D	62	0.1062	0.0000	0.0000	0.0000	0.0000
$n =$	549			$\overline{U}_B = \sum_h \omega_h \overline{U}_{B_h} =$	1.1936	
					$var(\overline{U}_B) = \sum_h \omega_h^2 var(\overline{U}_{B_h}) =$	0.0998
					$SE(\overline{U}_B) = \sqrt{var(\overline{U}_B)} =$	0.3158

Table 6. Values for demographic parameters of Hawaiian opakapaka (*Pristipomoides filamentosus*) used in the numerical cohort-structured model.

Parameter	**Definition**	**Units**	**Value**	**Source**
a_{λ}	Maximum observed age	yrs	43	Andrews et al. (2012)
M	Natural mortality rate	yr^{-1}	0.0697	Ault et al. (1998)
L_{∞}	Ultimate length	cm	67.5	Andrews et al. (2012)
K	Brody growth coefficient	yr^{-1}	0.2420	Andrews et al. (2012)
a_0	Age at which length equals zero	yrs	-0.2900	Andrews et al. (2012)
α	Weight-length scalar	kg	2.311E-05	Table 4, this paper
β	Weight-length power coefficient	dimensionless	2.928	Table 4, this paper
L_c	Minimum length at first capture	cm	37.050	Langseth et al. (2018)
L_m	Minimum length at first maturity	cm	39.1	Luers et al. (2017)

Table 7. Estimated catch of Deep7 bottomfish species for Hawaii state fiscal years 2015 (July 1, 2014 – June 30, 2015) and 2016 (July 1, 2015 – June 30, 2016). Estimates were calculated from Hawaii Department of Aquatic Resources Fisherman Reporting System data for commercial catch (Langseth et al., 2018).

	Total Catch (kg)	
Species	**2015**	**2016**
Onaga	38,056	49,759
Ehu	18,189	100,561
Kalekale	10,251	17,509
Opakapaka	208,289	205,160
Gindai	2,041	136
Hapu'upu'u	6,713	27,760
Lehi	6,214	17,509
TOTAL	289,755	403,606

Table 8. Estimates of opakapaka total mortality rate (Z), abundance (*N*), biomass (*B*), recruitment (R), and the radius of camera sampled area using two different length frequency distributions: Model 1, fishery-independent survey (**Fig. 5**); Model 2, fishery catches (**Fig. 4**, right panel).

	$\bar{L}(t)$	Z	N	B	R	**radius (m)**
Model 1	49.0	0.376	301,496	669,386	138,838	60.6
Model 2	56.6	0.134	960,239	3,227,790	158,330	27.6

Table 9. 2016 survey estimates of Deep 7 species exploited phase mean biomass per unit $\bar{U}_B$, and total population biomass B for two estimates of radius of camera sampled area.

				radius = 60.6 m		**radius = 27.6 m**	
Species	n	$\bar{U}_B$	$SE(\bar{U}_B)$	$B(kg)$	$SE(B)$	$B(kg)$	$SE(B)$
Onaga	554	0.1289	0.0637	72,268	35,720	348,479	172,242
Ehu	547	0.2832	0.0549	158,791	30,774	765,691	148,392
Kalekale	548	0.0777	0.0273	43,576	15,312	210,123	73,834
Opakapaka	549	1.1936	0.3158	669,386	177,119	3,227,790	854,069
Gindai	556	0.0112	0.0048	6,260	2,719	30,186	13,111
Hapu'upu'u	557	0.0922	0.0354	51,699	19,835	249,295	95,644
Lehi	555	0.0449	0.0258	25,206	14,451	121,541	69,682
Total				1,027,186	185,575	4,953,106	894,846

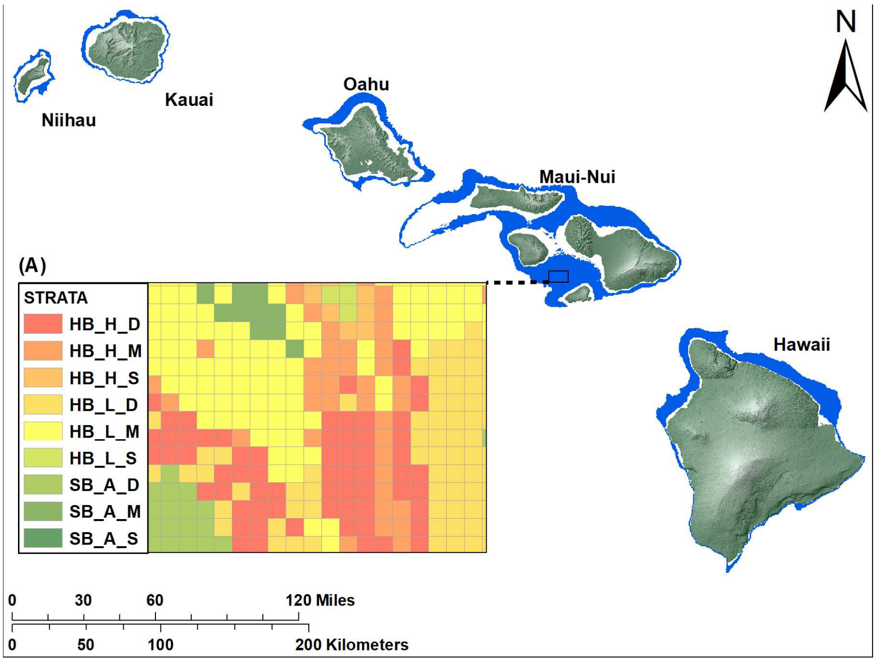

Figure 1 The spatial frame of the Deep7 bottomfish survey domain (blue shaded region) extending from Niihau in the northwest to the island of Hawaii in the southeast. Inset shows a section of the survey frame in the Maui-Nui region (islands of Maui, Moloka'i, Lana'I, Kaho'olawe) showing the 500 x 500 m mapped grid cells classified by habitat-depth strata. Definitions of substrate-slope-depth strata in panel (A) are given in Table 1.

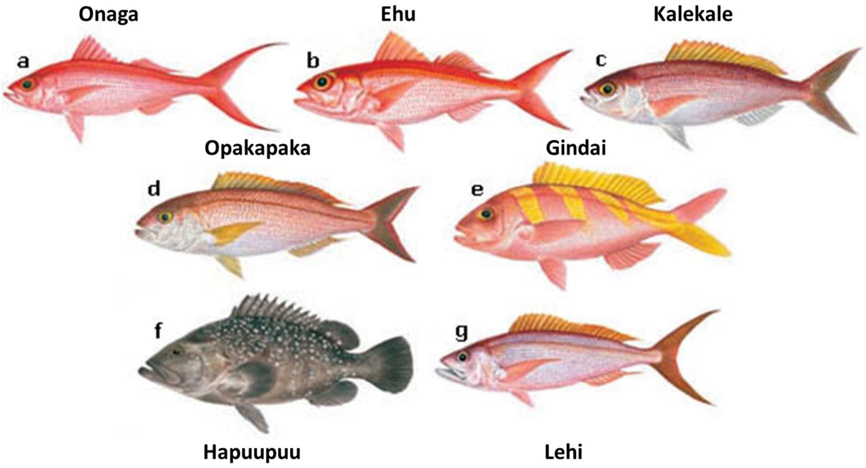

Figure 2. Members of the Hawaiian Deep7 bottomfish (i.e., deepwater snappers and grouper) complex: (A) onaga (*Etelis coruscans*); (B) ehu (*E. carbunculus*); (C) kalekale (*Pristipomoides sieboldii*); (D) opakapaka (*P. filamentosus*); (E) gindai (*P. zonatus*); (F) hapu'upu'u (*Hyporthodus quernus*); and, (G) lehi (*Aphareus rutilans*). Artwork by Les Hata (Hawaii Department of Aquatic Resources/Department of Land and Natural Resources).

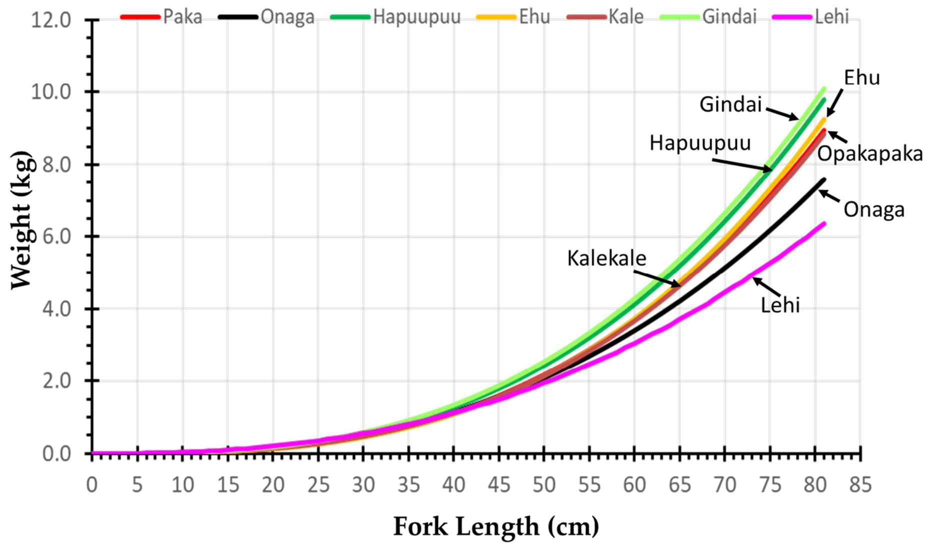

Figure 1. Comparison of allometric curves for Hawaiian Deep7 bottomfish species.

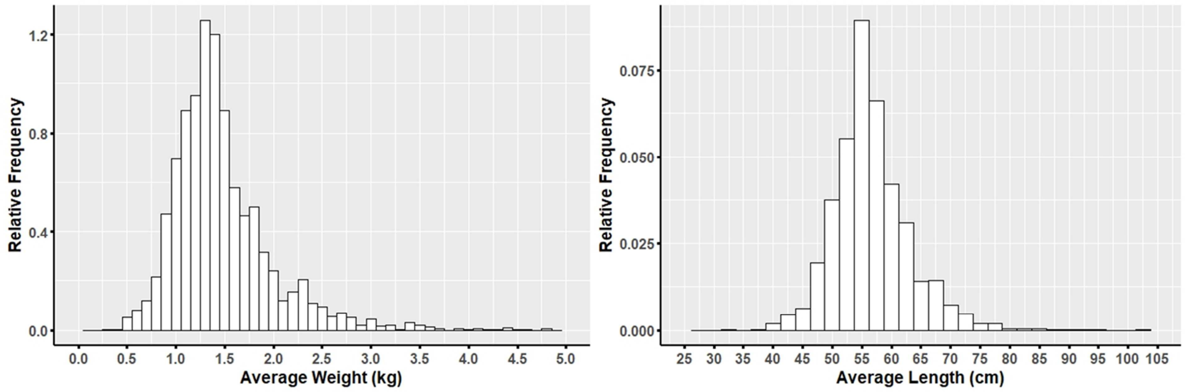

Figure 2. Frequency distribution of opakapaka mean weight per fish for reported commercial records (left panel), and the resulting distribution of mean length per fish after conversion using the allometric weight-length function (right panel).

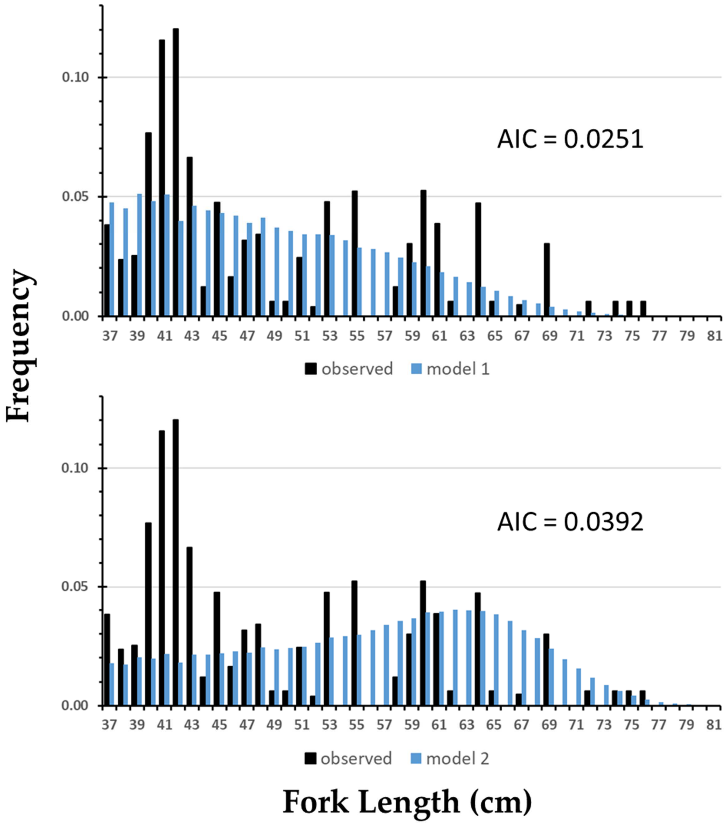

Figure 3. Comparison of survey-observed (black bars) and numerical population model-predicted (Model 1 & 2, **Table 8**) length frequency distributions for opakapaka.