Fisheries Research 270 (2024) 106897

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

To trawl or not to trawl: Questioning core assumptions of trawl placement choice in fisheries acoustics surveys

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ARTICLE INFO

Handled by A.E. Punt

Keywords:
Biomass estimate
Trawl selection
Stock assessment
Abundance survey
Acoustics

ABSTRACT

In acoustic-trawl surveys, acoustic echosign needs to be biologically characterized, and if done correctly, will lead to accurate biomass estimates, robust stock assessments, and ensuing healthy fish stocks. However, methods for validating the core assumption that trawl placement choice yields a representative sample of the associated echosign (given an ideal net) are rarely described. Therefore we detail several such methods, using Pacific hake as a case study, exploiting both historic survey data as well as additional field experimental data. Specific methods focused on validation of (1) trawl effort spatially matching backscatter distributions, (2) trawled-location backscatter amounts matching all-location backscatter amounts, (3) trawled depth matching backscatter depth, and (4) spatial homogeneity of fish length within an aggregation. Application of the methods to the adult Pacific hake survey generally validated the assumption that trawl placement choice yielded a representative sample of the associated echosign, except for two instances. The backscatter from fished aggregations was greater than that from general aggregations in one of the two survey years analyzed. In addition, experimental field data detected a slight but significant trend of longer fish in the offshore portion of an aggregation. Neither of these occurrences are expected to yield a bias in the biomass estimate of Pacific hake.

1. Introduction

Acoustic-trawl surveys, which combine acoustic technologies with trawl sampling, are globally used in the estimation and enumeration of fish stocks, such as herring (*Clupea harengus)* and sprat (*Sprattus sprattus)* in the Baltic Sea (Baltic International Fish Survey Working Group, 2014), anchovy (*Engraulis encrasicolus*) and sardine (*Sardina pilchardus*) in the Mediterranean sea (Tsagarakis et al., 2015; Tugores et al., 2016), and spawning hoki (*Macruronus novaezelandiae)* off New Zealand (Coombs and Cordue, 1995). The primary use of acoustic-trawl surveys is to obtain estimates of biomass for stock assessment and fishery management; other desired information may include distribution, habitat, and life history parameters.

Trawling is an integral component of acoustic-trawl surveys and the concomitant estimates of fish biomass and distribution. The fundamental role of trawls in an acoustic-trawl survey is to accurately assign biological characteristics (e.g. species, length, age, sex) to echosigns. Lengths of target species may be used for the calculation of target strength and conversion to biomass, while age or sex information may be necessary for stock assessment.

An important assumption behind trawling is that trawl results are representative of the composition of the underlying backscatter of interest. We define "trawl representativeness" in this paper to denote that the trawl is representative of the acoustic sign the trawl is assigned to (in terms of species and length, and for some surveys, age and sex). Although the selectivity of the net may affect the result of the catch (Bethke et al., 2010; De Robertis et al., 2015; Williams et al., 2010), "trawl representativeness" is further defined to refer to how the *choice* of trawl location and duration affects whether the trawl results are representative of the acoustic data. This representativeness applies both at the scales of individual aggregations and at the larger scales of the full survey. Lack of trawl representativeness could be a source of important potential bias; sampling strategy of hauls can be as important as acoustic sampling strategy (Massé and Retière, 1995; Simmonds, 1995;

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https://doi.org/10.1016/j.fishres.2023.106897
Received 3 August 2023; Received in revised form 26 October 2023; Accepted 26 October 2023
Available online 19 November 2023

Simmonds et al., 2009). Lack of trawl representativeness is a recognized issue that is more likely to occur when there is a structure in the distribution of the species of interest; this could be the case for many surveys that have demonstrated size segregations in distribution (e.g. Alaska Pollock (*Theragra chalcogramma*) (Bailey et al., 1999; Honkalehto et al., 2009; Parker-Stetter et al., 2015) and Chilean hake (San Martín et al., 2013). Lack of trawl representativeness could lead to a bias in biomass estimates and ensuing stock assessments. However, in spite of large potential effects, there have been no studies to directly address this issue.

The issue of trawl representativeness was raised for the Joint U.S.-Canada Integrated Ecosystem and Pacific hake (*Merluccius productus)* Acoustic-Trawl Survey ("Pacific hake survey") during a 2010 expert panel review (STAR, 2010). This survey estimates the biomass-at-age of age-2+ Pacific hake along the Pacific coasts of the United States and Canada. Pacific hake cover a broad geographic range, with length and age generally increasing with latitude (Ressler et al., 2007; Smith et al., 1990). Trawl strata, clusters of hauls used for target-strength length calculations, are determined post-hoc by clustering hauls with similar length-frequency data together. While it is known that age-1's and adults often aggregate separately, it is assumed that there is no age or length structure within single adult aggregations of hake. Yet if this structure exists, trawling without understanding or accounting for this structure could lead to bias. Pacific hake, with a broad range but an unknown small-scale population structure, make an ideal case study for trawl representativeness.

The purpose of this study was to describe and use explicit methods for assessing trawl representativeness in the Pacific hake acoustic-trawl survey by analyzing historical data and additional experimental data. Specific objectives were to determine if (1) trawl effort spatially matched backscatter distributions, if (2) trawled-location backscatter amounts matched all-location backscatter amounts, if (3) trawled depth matched backscatter depth, and if there was (4) spatial homogeneity of fish length within an aggregation.

2. Methods

2.1. Survey details

Pacific hake are generally found between 50 and 500 m water depth and distributed between 25° and 55° N, with a summer northward feeding migration. Although the distribution varies from year to year, Pacific hake concentrations in the summer are greatest around the shelf break area (200 m bottom depth) and at daytime water column depths of 150 – 250 m (Hamel et al., 2015). However, Pacific hake aggregations, which may span several tens of kilometers (Dorn, 1997), can also extend considerably offshore.

The Pacific hake survey used by stock assessment spans from 1995 to 2021. The survey was conducted triennially from 1995 to 2001, then biennially from 2003 to 2021, with an extra survey in 2012. The NOAA Ship *Miller Freeman* and/or the C.C.G.S. *W. E. Ricker* conducted the survey from 1995 to 2009. The *W.E. Ricker* continued surveying until 2015, but in 2011 the NOAA Ship *Bell M. Shimada* replaced the *Miller Freeman* as the U.S. vessel in the survey. The fishing vessel *Nordic Pearl* was chartered for the Canadian effort in 2017–2021. The survey occurred from mid-June to mid-September, covering the continental slope and shelf (~50 m to 1500 m bottom depths) from south of Monterey Bay, CA to northern British Columbia, Canada or southern Alaska. The nominal transect spacing was 10 nmi (e.g. Fig. 1), with greater transect spacing in situations that involved a compressed time schedule (such as mechanical breakdowns or additional collaborations). The early years of the survey (e.g. 1995) involved considerable bottom trawling as well as midwater trawling; the current incarnation of the survey fishes only with a midwater trawl.

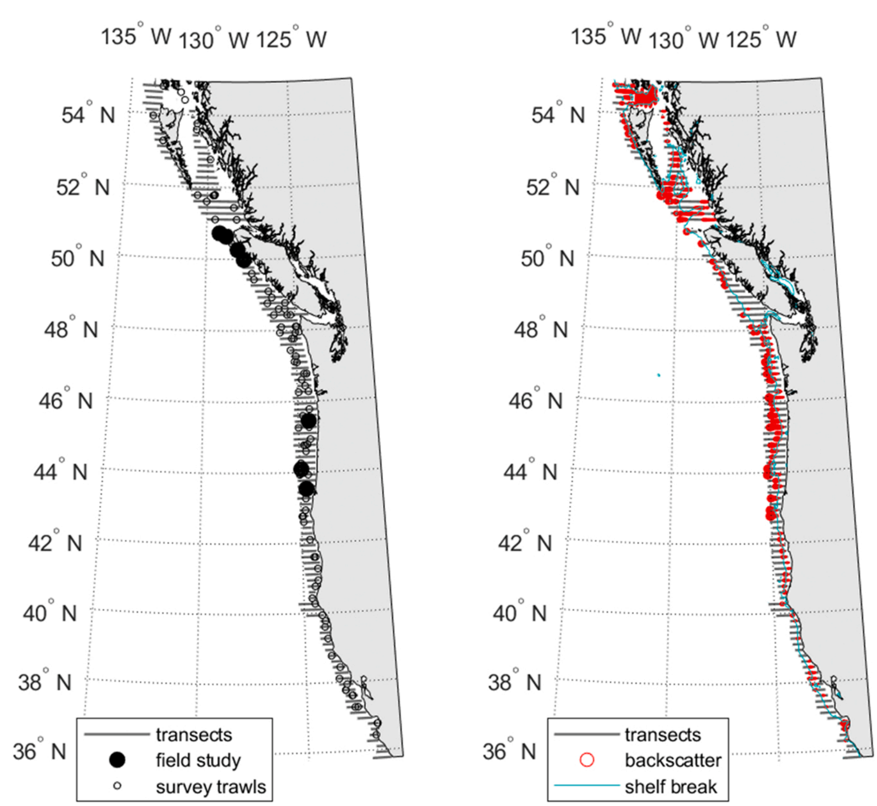

Fig. 1. Map showing survey area with 2007 survey transects for reference. The filled circles are the aggregations for the experimental field study in 2010 and 2014. The open circles are trawls for 2007.

2.2. Acoustic sampling + processing

All survey ships used 38-kHz acoustic transducers as the primary frequency for the biomass estimate (Table 1). Transducers on each ship were calibrated using standard sphere methods (Demer et al., 2015; Foote et al., 1987) at the beginning and/or end of the survey.

Echoview (Echoview Software Pty Ltd, Hobart, Australia) was used for acoustic data processing. Given time and resource constraints, two surveys were selected from the time series for survey-based analysis as being representative of a "standard survey." Surveys in 2007 and 2013 were chosen as they had standard survey design and minimal large-scale biological contaminants (e.g. 2009 *Dosidicus gigas* range extension). Aggregations were visually identified in the echogram by an analyst and manually drawn as polygonal analysis "regions" around the aggregation. Trawls were performed opportunistically during the survey for species identification as well as to obtain hake biological data. Regions of hake backscatter were assigned to a single trawl, and by extension to the trawl's associated length-frequency stratum, consisting of a grouping of trawls with similar length-frequencies. These trawl groupings were automatically calculated using hierarchical cluster analysis on Kolmogorov-Smirnov goodness-of-fit values calculated for every pair of trawls in a survey. Area acoustic backscatter data (reflected acoustic energy s_A; m^2/nmi^2) were exported in 0.5-nmi (horizontal) by 10-m (vertical) bins and was the fundamental sampling unit of backscatter used in this paper.

2.3. Biological sampling

Trawl locations were determined ad hoc during the survey to verify the composition of the aggregation and to obtain biological samples. Midwater trawls, conducted to within 5 m of the bottom, and bottom trawls, conducted directly on the bottom, have both been used by the survey. However, use of the midwater trawl was predominant. Headrope sensors (e.g. SIMRAD FS70) were used to monitor success of the tow in targeting marks of interest. Trawl duration at target depth varied from < 1 to > 40 min, depending on the relative density of targets observed from the headrope sensor during trawling. The characteristics of the nets and echsounders used in the survey are given in Table 1. The number of trawls in the survey has varied considerably (63−141) over the years. As the length for strong spatial correlations for summer hake distributions has been estimated to be roughly 25–35 km (11–19 nm) (Dorn, 1997), trawls on the target species are performed at a maximum N/S spacing of 74.1 km (40 nm), preferably less, to reduce the chances of missing local changes in length-frequency distributions. Standard catch sorting and enumeration methods were used to process catches (Hughes, 1976; Weir and Station, 1978). Catches were sorted completely when feasible (< ~ 1000–1500 kg) or subsampled. Pacific hake were sampled to obtain length (to the nearest centimeter) and sex data (~300 fish/trawl), and to collect otoliths to determine age and individual weights (~50 fish/trawl). Additional collection such as gonads, stomachs, blood, and other samples have varied by year and ship.

Table 1
Characteristics of transducers and nets used in the Pacific Hake acoustic survey.

Ship		*Miller Freeman, Bell M. Shimada*	*W. E. Ricker*
Midwater Trawl	Type	Aleutian Wing Trawl 24/20	CanTrawl 250
	Vertical Opening (m)	18	20
	Liner (cm)	3.2	0.7 cm
	Doors	4-m², 884.5-kg, 'Fishbuster'	5-m², 1135 kg, 'USA JET' (Model P)
Bottom Trawl	Type	Poly Nor'eastern trawl 89/121	Poly-Yankee 36 modified with roller gear
	Vertical Opening(m)	3	4–5
	Liner (cm)	3.2	2.5
	Doors	4-m², 884.5-kg, 'Fishbuster'	5-m², 1135 kg, 'USA JET' (Model P)
Echsounder	Transceiver	EK500: 1995 – 2001* EK60: 2005–2019	EK500: 1995 – 2003 EK60: 2003 – 2019(+)
	Transducer	38 kHz (Simrad 38B)	38 kHz (Simrad 38B)
	Ping rate	≤ 4 s/ping	≤ 4 s/ping
	Power	2000 W	2000 W
	3 dB beam angle	Along: 6.8 Athwart: 6.9 (offsets=0)	Along: 7.1 Athwart: 7.1 (offsets=0)
	Collection depth	9.15 m	5.2 m
	Vessel speed	5.6–6.1 m/sec (11–12 knots)	4.6–5.1 m/sec (9–10 knots)

* no US vessel in 2003

Additional experimental fieldwork was conducted on hake aggregations in the (non-survey) summers of 2010 and 2014 to explore length structure within individual aggregations. Large aggregations of at least 1.0 nm length and 50 m depth thickness were scouted. Trawling locations along a transect through the aggregation were selected, and as many locations as possible were sampled before the fish dispersed overnight. In 2010, the core of the aggregation (location "A" in Fig. 2(c)) was always fished first. The order of the rest of the fishing locations was chosen randomly. In 2014, fishing order was completely random. Locations across the aggregation but at the same trawling depth (C1, C2, and C3 in Fig. 2(c)) were spread throughout the length of the aggregation, and locations at different depths depended on the thickness of the aggregation (locations B1 and B3 in Fig. 2(c)). Some aggregations did not have enough depth for separate trawls, so only the "C" locations were fished.

2.4. Data analysis

Two types of data were analyzed: historical survey data and additional experimental field data. Survey data were used to evaluate large-scale representativeness of trawls across a survey. Experimental field data were used to evaluate smaller-scale representativeness of trawls within an aggregation using repeated hauls.

2.4.1. Validating if trawl effort spatially matched the backscatter distribution

For the 2007 and 2013 surveys, the number of hake regions that were trawled was calculated as a percentage of the number of total acoustic regions classified as hake. In addition, the location of survey trawls relative to transects and hake backscatter (s_A, units m^2/nm^2) was mapped and the acoustically weighted distance to the associated trawl was calculated as

$\sum_{ij} \frac{s_{Ai} d_{ij}}{\sum_i s_{Ai}}$, where s_{Ai} was the area backscatter in cell i, and d_{ij} was the distance (nm) from cell i to trawl j.

The weighted (by backscatter) distance to the associated trawl was used as a measure of the spatial relationship between acoustic regions and trawls. This distance would ideally be within the spatial correlation distance of the fish distribution (local patchiness). We also compared trawl effort against acoustic backscatter as the survey progressed, by plotting the cumulative distribution function (CDF) of the survey backscatter and completed trawls by latitude. The cumulative distribution of trawls by latitude is the proportion of total trawls that have been completed by that line of latitude. The cumulative distribution of backscatter by latitude is the proportion of total backscatter that has been accumulated by that line of latitude. These distributions were compared using a Kolmogorov-Smirnov test.

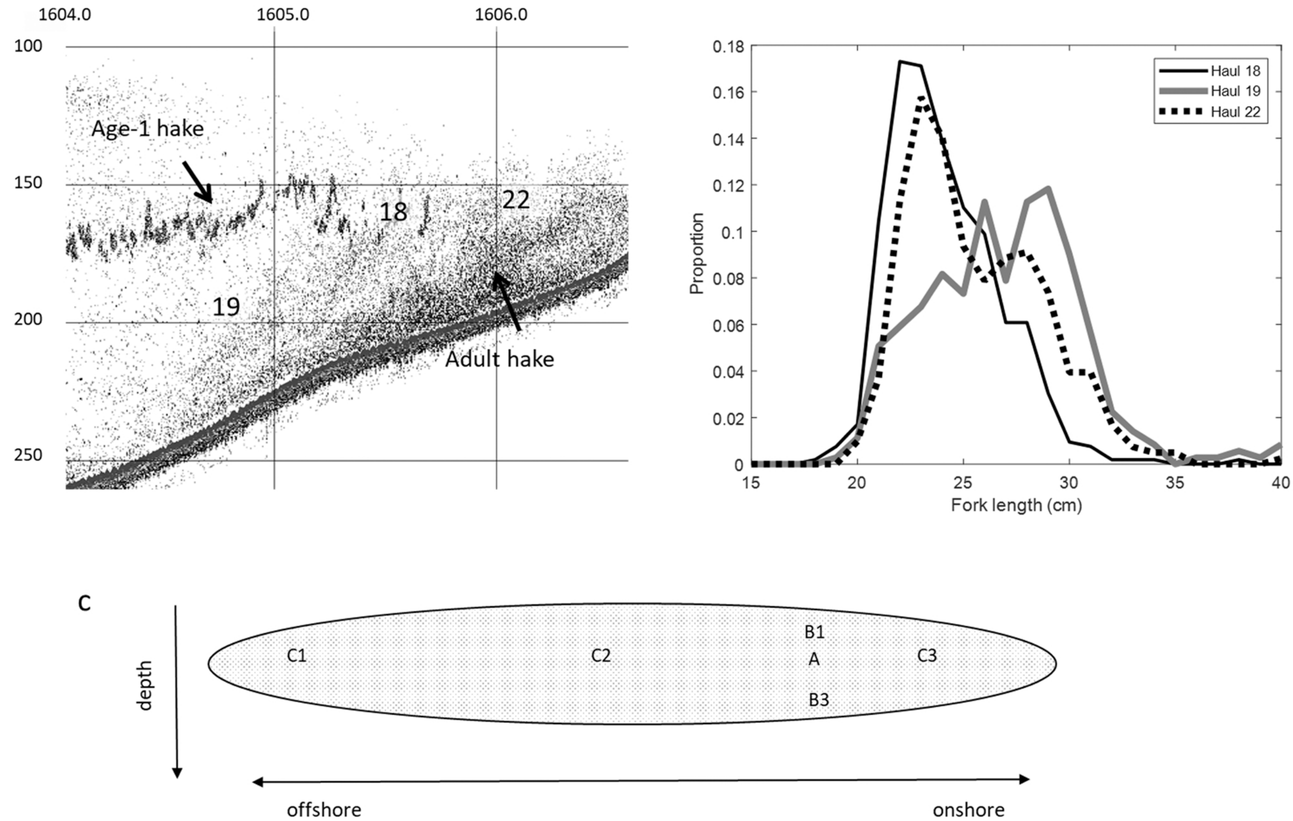

Fig. 2. (a) Example echogram of an area of layered age-1 and adult hake aggregations. Depth (m) is on the y-axis, and vessel log (corresponding roughly to distance in nmi along the transect) is on the x-axis. The dark grey line is the bottom. The numbers are the hauls in that location. (b) Length-frequency of hake from the three trawls through the area of the age-1 and adult aggregations. (c) Trawl placement sampling scheme for trawl representativeness field work. The shaded area represents a hypothetical aggregation of hake. "A" designates the trawl performed as would be done on a survey. The "B" trawls are those done at approximately the same latitude/longitude as the "A" trawl, but at different depths. The "C" trawls are done at different locations within the aggregation, but at the same depth as the "A" trawl.

2.4.2. Validating if trawled-location backscatter amounts matched all-location backscatter amounts

To determine whether trawl effort matched backscatter distributions over the survey area, the median backscatter from all hake aggregations was compared to the median backscatter from hake aggregations that were trawled for each of the two survey years. As the distribution of backscatter is skewed – backscatter data are all positive, but contain many values near zero—a logarithmic transform was applied and a non-parametric analysis of variance (ANOVA, Kruskal-Wallis) was used to compare the two distributions.

2.4.3. Validating if trawled depth matched backscatter depth

Using 2007 and 2013 survey data, we compared the empirical cumulative distribution function (CDF) of trawl depth to the CDF of backscatter depth to determine if the depth of trawls was representative of the backscatter. The CDF for trawls (or backscatter) by depth was calculated as the proportion of trawls (or backscatter) at or less than that depth in the water column. Trawl mean depth (headrope depth) was compared to the mean depth of the weighted backscatter using a t-test.

2.4.4. Validating lack of spatial variation of fish length within an aggregation

We employed two methods to assess trawl representativeness of the distribution of fish length with respect to potential structure within an aggregation. Fish may differ in size throughout the aggregation, but the same methods that are used to fish pelagic parts of the aggregation may not be appropriate for near/on-bottom parts of the aggregation. The first method compared fish length from deep parts of aggregations (that were on the bottom) vs. off-bottom, and the second method looked at differences in fish length throughout off-bottom portions of aggregations.

First, the mean length of fish was compared between bottom trawls and midwater trawls in the 1995 survey to assess potential disparity in fish length close to the bottom. A non-parametric ANOVA (Kruskal-Wallis) was used to compare the medians of the two groups. The 1995 survey was chosen as bottom trawls have been only sparingly deployed in more recent years; the current incarnation of the survey does not deploy a bottom trawl.

Second, comparisons of fish length throughout different parts of off-bottom portions of an aggregation were performed. As aggregations may have different length distributions, the mean fish length in each trawl was standardized by the overall mean fish length of the targeted aggregation to generate a fish "length anomaly" for each trawl. A one-way ANOVA using the experimental data collected in 2010 and 2014 was performed to determine if trawl position in the aggregation affected the mean length of the fish in the trawl, and a subsequent Tukey-Cramer multiple comparisons test used to determine which locations differed in length. In addition, a linear mixed effect model relating length anomaly to location in the aggregation and year was constructed and tested.

3. Results

3.1. Trawling representative of distribution of fish over the survey area

In the 2007 survey, we trawled in 27.6% of the hake regions identified on the echogram. The mean weighted distance to trawl was 29.1 km (15.7 nm). In 2013, we trawled in 14.5% of the hake regions, and the mean weighted distance to trawl was 27.2 km (14.7 nm). For both survey years, trawling effort was distributed over the course of the survey in a similar manner to the backscatter (Fig. 3) (Kolmogorov-Smirnov test, 2007: p = 0.707, 2013: p = 0.2823).

3.2. Trawl effort matched backscatter distributions over the survey area

The median area backscatter in hake aggregations in 2013 was not significantly different (Kruskal-Wallis nonparametric one-way analysis of variance, p = 0.153, df=1) between trawled regions (78.2 m^2/nm^2) and untrawled regions (70.9 m^2/nm^2) (Fig. 4(a) and (b)). In 2007, the median backscatter in trawled (28.9 m^2/nm^2) vs. untrawled (8.6 m^2/nm^2) aggregations was found to be significantly different ($p < <.01$, df=1) (Fig. 4, (c) and (d)).

3.3. Trawling representative of the distribution of the depths of aggregations

For both 2007 and 2013, the mean depth of trawling vs. the weighted mean backscatter was not significantly different (Fig. 5, Table 3). The shapes of the curves do appear to have minor differences between 2007 and 2013. For 2007, at shallow depths (<150 m), there was a slightly higher proportion of backscatter vs. trawls. In 2007, 75% of the backscatter and trawls were at less than 300 m water depth, but in 2013, it was less than 50%. However, for each year, the mean depth of trawling and the mean backscatter followed a similar cumulative distribution to each other.

3.4. Trawling representative of the distribution of fish length within an aggregation

Survey: Data from 1995 indicated that the mean lengths of hake close to the bottom (40.0 cm, from bottom trawls) were quite similar to those in the water column (40.9 cm, from midwater trawls) (Kruskal-Wallis nonparametric one-way analysis of variance, p = .385, df=1).

Experimental field data: The *W.E. Ricker* performed 15 trawls on four separate aggregations in 2010, and 16 trawls on three aggregations in 2014 (Table 2). In addition, in 2010, the *Miller Freeman* performed 16 trawls on three areas that contained layered age-1 and adult aggregations, with age-1 hake forming a denser layer above the deeper adult hake. These layers are considered separate aggregations, but given their proximity, could be trawled at the same time. The results of one such area are shown in Fig. 2a) and (b). In this area, a shallow trawl sampled the further offshore age-1 hake, another trawl sampled a mixed area, and yet another trawl, while attempting to sample the deeper adult hake, also caught the shallower age-1 hake on the way up and down. In all three fishing locations, the trawls sampled across both age-1 and adult aggregations, rendering the trawls unsuitable for single-aggregation analysis, but added valuable insights into the importance of fishing age-1 and adult aggregations separately (or separating age-1 from age-2+ in the trawl). These unsuitable trawls are not used in the analysis.

3.5. Trawling representative of the distribution of fish length within an aggregation

Comparisons of length distributions between the trawls in different parts of a single aggregation in 2010 and 2014 (Fig. 6) indicated that mean fish lengths differed by less than 4 cm between trawls in an aggregation (not including separate age-1 aggregations noted above). The variances in fish raw length for 2010 and 2014 were 11.5 and 7.8 cm^2, respectively. An ANOVA on fish length anomalies found a significant difference ($p < 0.04$, df=5) between length anomalies within an aggregation. A Tukey-Cramer multiple comparison test found a significant difference ($p < 0.05$) between C1 and C3 locations, but no significant difference was found between other locations in the aggregation. The C1

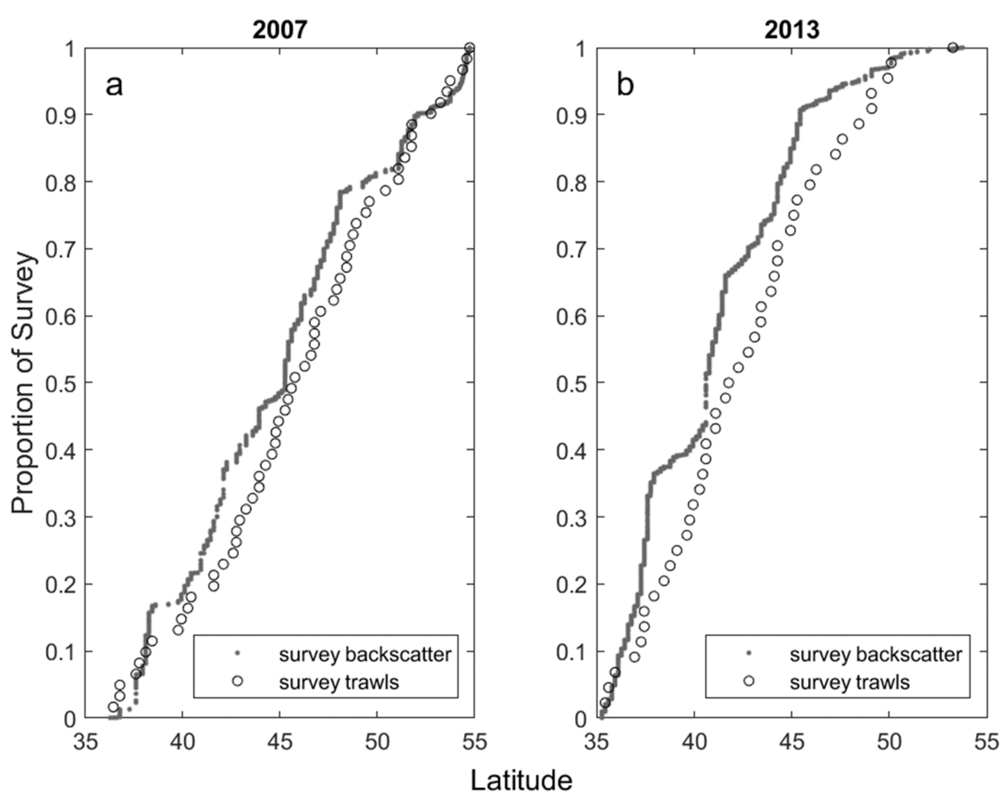

Fig. 3. Plot of (a) 2007 and (b) 2013 survey hake backscatter (m^2/nm^2) and allocation of survey trawls with respect to degrees of North latitude (x-axis) and proportion of total amount of trawls or backscatter over the survey (y-axis). If trawls and backscatter were evenly spaced along latitude, the lines would be diagonally straight.

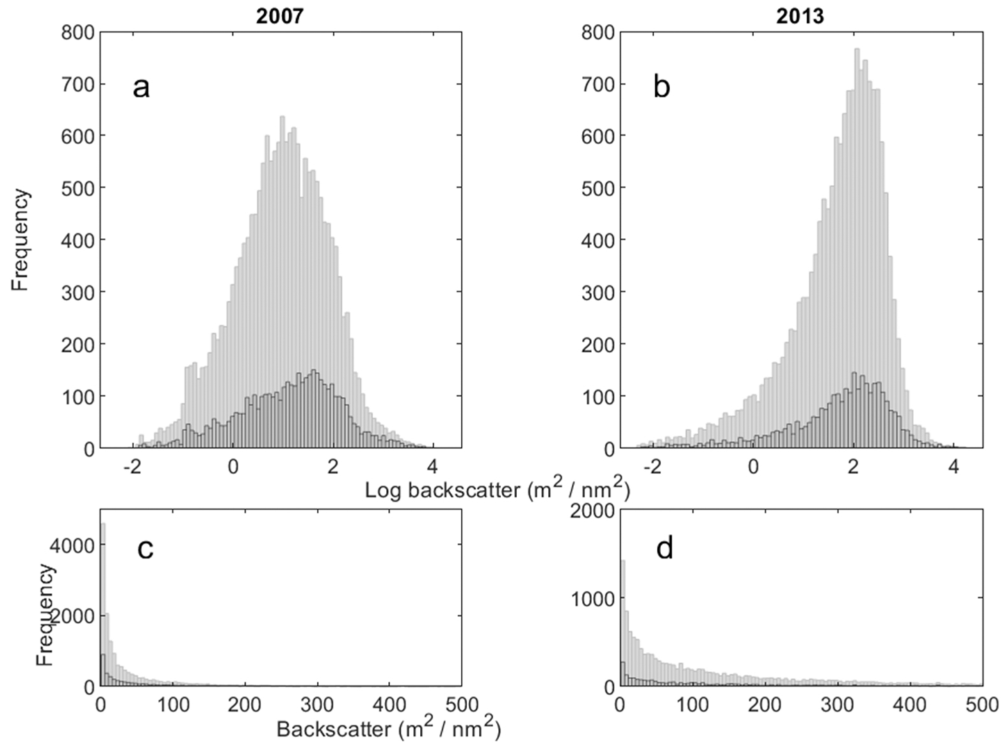

Fig. 4. Log area backscatter (a, b) and untransformed area backscatter (c, d) from all hake regions (light grey) and from hake regions actually trawled (dark grey). Data are from the 2007 (a, c) and 2013 surveys (b, d). For plots c and d, the data extend further to the right, but the plots were truncated for ease of viewing.

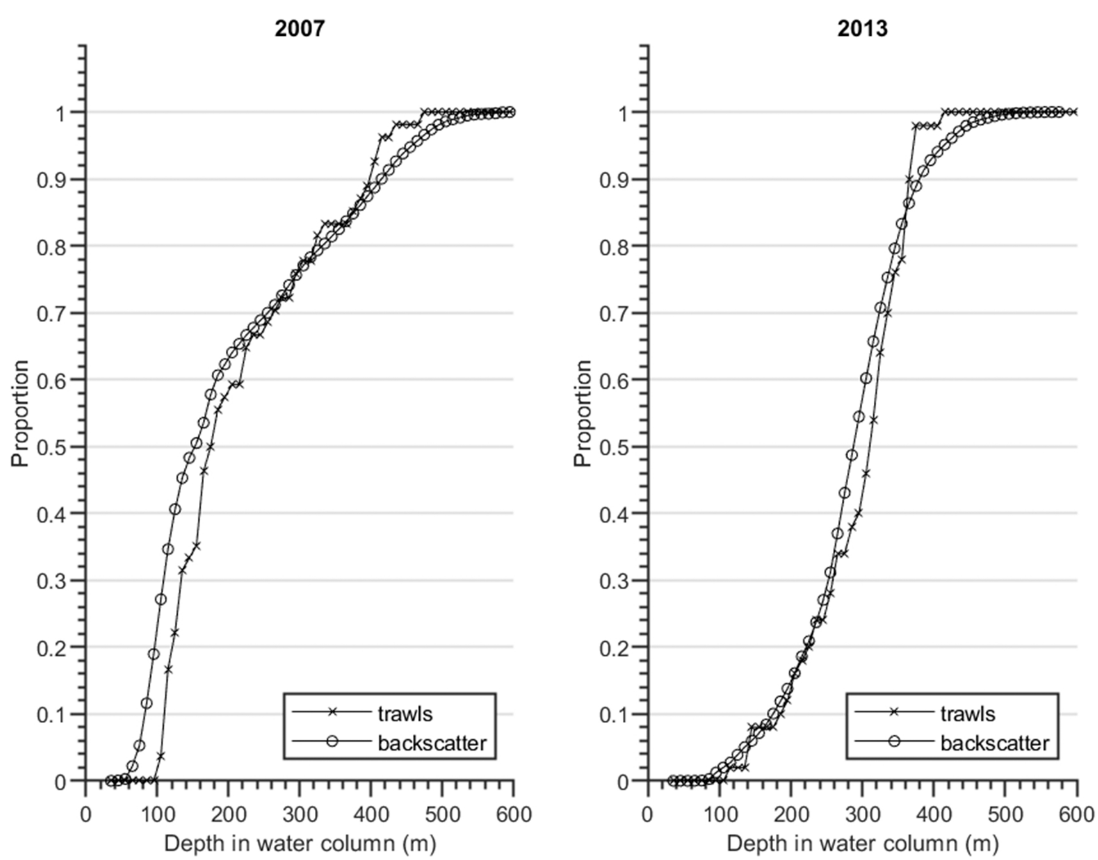

Fig. 5. The empirical cumulative distribution function of the depth of the haul and the backscatter at depth for hake over the survey for 2007 and 2013. Each circle is the proportion at a haul, and each x is the proportion of backscatter at a haul. If hauls were done proportionally at the same depths as backscatter of hake, the curves would lie completely on top of each other.

Table 2
Year, aggregation, haul number, latitude, longitude, haul duration (at target depth), and haul depth of trawls for 2010 and 2014 experimental work.

Year	Aggregation	Location in Aggregation	Haul Number	Latitude (N)	Longitude (W)	Haul Duration (min:s)	Haul Depth (m)
2010 adults							
	T	A	28	50.72	129.25	19:00	310
		C1	29	50.72	129.24	29:00	310
		C2	30	50.72	129.24	15:00	310
	U	A	32	50.63	128.85	24:00	300
		C2	33	50.63	128.87	19:00	300
		C3	34	50.62	128.86	30:00	300
		C1	35	50.63	128.85	30:00	300
	V	A	37	50.25	128.19	11:00	300
		C2	38	50.26	128.19	07:00	315
		C3	39	50.25	128.20	16:00	305
		C1	40	50.26	128.18	12:13	290
	W	A	41	49.98	127.84	09:00	255
		C1	42	49.98	127.81	16:00	235
		C3	43	49.98	127.84	19:00	300
		C2	44	49.98	127.83	09:00	255
2014 adults							
	X	C1	8	44.093	124.928	03:06	130
		B1	9	44.096	124.921	14:34	100
		A	10	44.097	124.924	01:06	128
		B3	11	44.087	124.924	09:15	161
		C2	12	44.094	124.925	00:56	135
		C3	13	44.093	124.923	01:50	130
	Y	C2	20	43.15	124.74	02:19	252
		B1	21	43.145	124.739	01:09	224
		C1	22	43.146	124.746	04:47	250
		B3	23	43.164	124.75	03:48	275
		C3	24	43.156	124.74	01:45	255
	Z	C2	25	45.452	124.462	05:58	304
		C3	26	45.454	124.472	07:58	297
		C1	27	45.445	124.448	08:22	275
		B3	28	45.445	124.462	05:48	325
		B1	29	45.438	124.44	32:10	256

Table 3
Comparisons between trawling mean depth and weighted backscatter mean depth for 2007 and 2013. The p and df statistics are given for the comparison between depths within each year (student's t-test). (These p-values indicate no significant differences between trawling mean depth and backscatter mean depth).

Year	2007	2013
Trawling mean depth (m)	196	270
Weighted backscatter mean depth (m)	198	279
p	0.8779	0.3899
df	53	49

location (offshore) had fish that were on average 1.2 cm longer than C3 (onshore location). A linear mixed effect model found no significant year effect ($p < 0.16$).

4. Discussion

Study results suggest that the Pacific hake survey trawled representatively on the spatial scales of the survey area and within individual aggregations, and to a more limited extent trawled representatively on the range of backscatter distributions. The trawling effort was relatively even over the northern progress direction of the survey with relation to the integrated backscatter (Fig. 3). Visual inspection of the plots indicates that, despite not being significantly different, the survey backscatter curve is slightly to the left of the survey trawls curve for the intermediate portion of the survey, but not at the survey start and end. The trawls may also more evenly spaced than backscatter throughout the survey extent. These differences likely stem from three processes: (1) the need of the survey to regularly sample the length distribution of fish for target strength calculations, (2) uncertainty about where trawls will be needed later in the survey, and the desire not to over-sample a spot at the cost of later under-sampling, and (3) the effort put into trawling at the beginning and end of the survey where there is little fish, and a single haul is necessary to obtain samples of small aggregations and. This extra effort serves to accurately determine the northern and southern extent of the fish population. On a more local scale, the mean weighted distance to an associated haul of ~29 km (~15 nm) was within the 25–35 km correlation distance computed by Dorn (1997). This means that, in general, trawling on hake was frequent enough to be representative of backscatter within correlation distances. Some length stratification within aggregations of Pacific hake was found, with offshore hake being potentially smaller than onshore hake.

For both the 2007 and 2013 survey years, the depth of trawls was not significantly different than depth of the backscatter (Fig. 5). Despite the non-significance, for 2007 there appears to be a slightly greater proportion of backscatter than trawls at shallower depths. This is likely related to increased shallow hake in that year. Hake have a tendency to dive when targeted by trawls, and when fished they are often caught by driving them toward the bottom. Midwater trawls are also difficult to deploy in less than 75 m of water, so backscatter in shallow depths is quite challenging to verify with a trawl. Both of these factors could result in trawls being done deeper than the observed backscatter, especially in shallow waters. Comparing on-bottom and off-bottom trawls in 1995, fish lengths were similar for both, suggesting that a sampling strategy using midwater gear near the bottom should not introduce a bias.

Results of tests looking at representativeness of trawling over the range of backscatter distributions showed mixed results, and merit further discussion, but do not necessarily indicate bias. Backscatter in the hake survey is heavily right-skewed with many areas of low backscatter and fewer areas of high backscatter (log backscatter is somewhat left-skewed). In general, if fish are patchy, then in order to have trawl effort match backscatter distribution along the survey (objective 1), the survey will need to trawl more often in zones of high backscatter. This may lead to an inability to meet the second objective (having the backscatter in the trawls match the overall backscatter). Given the

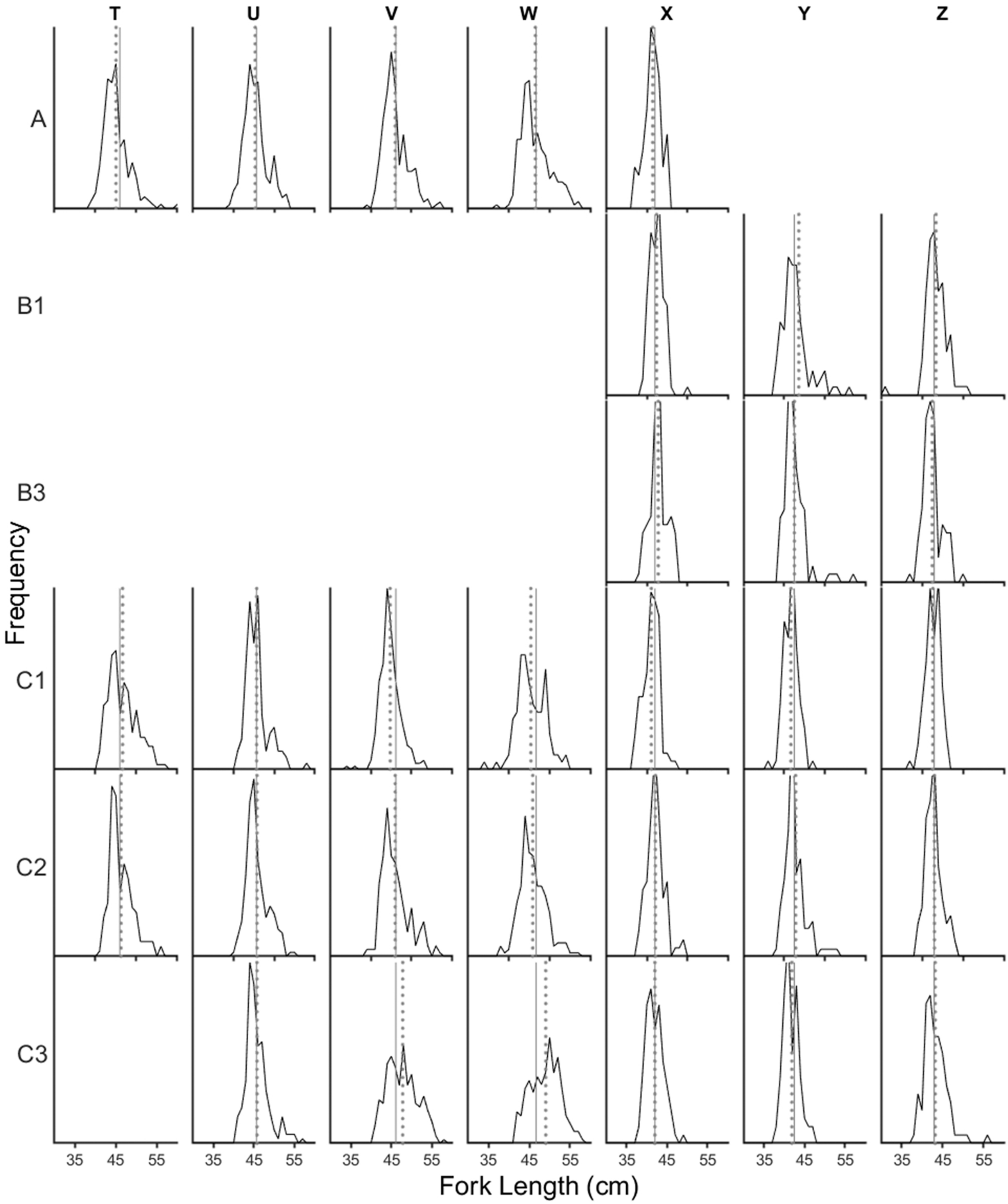

Fig. 6. Length-frequency plots from individual trawls on seven different hake aggregations (T-Z) in 2010 and 2014. Each box displays the length-frequency of the fish in the trawl at the sampling location denoted by each row and in the aggregation denoted in each column. The dotted line is the mean length of hake in that trawl, and the solid line is the mean length of hake in the aggregation. The length and frequency axes for each graph are consistent, and are displayed in row C3.

importance of correctly assigning species and length composition to high backscatter areas, this may actually be a preferred outcome, especially in years of very patchy high and low backscatter areas.

In 2007, the lower backscatter in untrawled vs. trawled regions could be due to the relatively low biomass in that year (3rd lowest in the time series) and patchiness. In addition, the trawl location needs to be selected to ensure a large enough sample in a reasonable amount of time. If, due to lower biomass in 2007, there was an increase in the number of hake regions too sparse to fish on, this could also lead to the effect of the trawled regions having higher backscatter than untrawled regions.

Results from two studies provide context for our findings. Massé and Retière (1995) demonstrated that bias in a biomass estimate can be introduced by using hauls in just one part of the study area, when those hauls are not representative of the overall study area. Routinely plotting survey backscatter and allocation of survey trawls with respect to latitude (and/or longitude) and proportion of the survey completed (Fig. 3), as well as simple mapping of location of backscatter and hauls, would help avoid this type of bias. The analysis by Simmonds (1995) of variance of proportions-at-age using bootstrap techniques concluded that additional criteria [other than opportunistically sampling acoustically detected regions] might need to be considered when choosing when and where to carry out hauls. A trawl sample is used to characterize the mark seen by the echosounder and, if classified as hake, to provide length observations for further analysis. If the hake from untrawled regions (e.g. less dense backscatter) is actually hake and of similar size to the hake in nearby trawled regions, then there is not likely to be a bias. Additional work in this area may include sampling regions that are typically not trawled and comparing them to regions that would normally be trawled and used to characterize the untrawled regions.

Limitations to this study include sample size, not examining the issue of net selectivity, and a consideration of similarities with closely spaced aggregations. Choosing survey and experimental field data years/areas with a single year class and not much length variation could yield similar findings to those in this paper. For instance, if there were a single dominating year class in 1995 when the bottom/midwater gear were collected and compared, we might not see a difference between results from the two gear types. However, that survey observed several strong year classes, including 2, 5, 8, and 11 year olds, which will generate considerable variation in length. Similar homogeneity in year classes could cause similar problems in the experimental field data. In 2010, variation in lengths was over 11 cm, which indicates a significant variation in lengths and age class, although in 2014 this variation was only ~8 cm. Hake do tend to move north along the coast depending on how big they are (Smith et al., 1990), so mixed age/length groups are not always easy to find, even in years that show extensive variations in the population. The difficulty of finding mixed age groups may indicate that bias from the location trawled within such aggregations may not be a significant issue in practice, but it is more important to sample spatially across the stock.

The sample size of the experimental field data (31 trawls over seven isolated aggregations) may not be large enough to apply to all conditions, and not all combinations of trawl locations were sampled in each year. The results from the ANOVA (Fig. 7) indicated that there may be systematic variation on fish length within hake aggregations. Using standard fisheries acoustic calculations (Maclennan et al., 2002) and the hake target strength-length equation of $TS = 20 \log (\text{fork length}) - 68$ (Traynor, 1996), an increase in length of 1.2 cm applied to all fish in a survey would result in a decrease in estimated abundance of − 2.76%. Given this small percentage, and the fact that in the survey there is no systematic targeting of only an offshore or onshore end of an aggregation, this effect is unlikely to significantly affect a biomass estimate for hake, as long as potential age-1, which may aggregate separately, are accounted for. This study was also limited to a couple of years, and it is possible that in other years the length difference may be larger, so it would be prudent to ensure that the survey continues to not target specific ends of aggregations (or that it samples from multiple parts of aggregations).

Anecdotal reports from fishermen trawling on night-time hake during non-summer months (when hake may stay more aggregated at night), indicate that fishermen may target the bottom of an aggregation to get larger fish. This study had low sample size in the upper vs. lower parts of the aggregation (B1 vs B3), but no significant difference between the upper and lower parts of the aggregation was found.

However, Pacific hake juveniles sometimes aggregate close to adults (Fig. 2 as an example), and care is necessary to separate the two on the echogram. Although there are historic instances of what appear to have been truly mixed juvenile-adult aggregations, none were found during the experimental field study. Issues with haul representativeness will

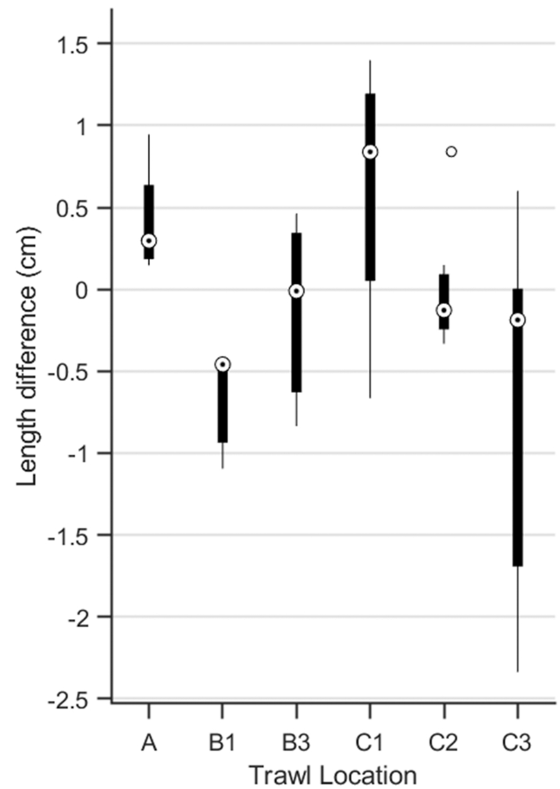

Fig. 7. Boxplot of experimental field data. The difference of the mean hake length (cm) from each trawl from the total mean length (cm) of the aggregation was calculated. The central circle with a dot is the median, the solid line the interval between the 25th and 75th percentiles, the thin lines extend to the most extreme points not considered outliers, and the unfilled circle is an outlier.

compound any existing bias from selectivity and escapement from the trawl. Net selectivity for hake is not known, but it may be similar to that of Alaska Pollock (*Gadus chalcogrammus*) (Williams et al., 2010), which shows significant selectivity for juvenile fish (length-at-50% retention of 14–27 cm). Although the hake survey focused on fish 2 + years old (generally 30 + cm), there may still be selectivity at shorter lengths. Regardless, the presence of age-1 Pacific hake in a trawl indicates that additional scrutiny of the echogram is necessary.

Understanding how bias from non-representative trawling might be propagated through to the survey and stock assessment results as well as to management processes is an important and complex issue. As is standard practice, the observations from trawls in this acoustic-trawl survey are not specifically used to quantify the abundance, but are used to classify the backscatter in terms of the presence and length of a species in an aggregation, which is then used to appropriately quantify what is seen on the echogram (Simmonds and MacLennan, 2005). It is important to adequately sample the aggregations to characterize the backscatter across the range of the survey. Given that, this study demonstrated that trawling is representative of the distribution of Pacific Hake over the survey area, including the ends of the hake distribution where hake abundance is typically less dense than in the core areas. Trawl effort from past acoustic-trawl surveys for Pacific hake covered the full extent of the Pacific hake population and with some caveats, was generally representative of the distribution of fish length.

CRediT authorship contribution statement

Thomas: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Gauthier:** Project administration, Editing. **Grandin**: Investigation, Resources, Data curation. **Hicks:** Methodology, Writing – review & editing. **Parker-Stetter:** Project administration, Writing –

review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The raw acoustic data for the 2007 and 2013 surveys can be accessed through the National Centers for Environmental Information (https://www.ncei.noaa.gov/maps/water-column-sonar/).

Acknowledgments

The authors gratefully acknowledge the edits from Julia Clemons and Steve de Blois and their improvements to the paper as well as thanking the crew and scientists staffing the NOAA Ship *Bell M. Shimada*, the NOAA Ship *Miller Freeman,* and the CCGS *W.E. Ricker* for their hard work and long hours. We also thank Patrick Cordue for initially raising the issue of haul representativeness.

Supplementary material

The catch data for the experimental field work in 2010 and 2014 is available by request from the author.

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