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RESEARCH ARTICLE

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Estimating spatiotemporal availability of transboundary fishes to fishery-independent surveys

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Abstract

1. Taxa can expand beyond historical scientific survey footprints and into new areas with different survey protocols as they move to track their preferred climate. In global groundfish fisheries, for example, scientists estimate population dynamics within the spatial extent of a fishery-independent survey using an index known as a design-based estimator. Observed changes in species distribution in recent years suggest that some groundfish are moving beyond the spatial extent of single surveys. We must intercalibrate disparate data that cover a larger spatial extent to maintain our ability to accurately index populations as their availability to historical surveys changes.
2. We combine US and Russian data from the northern, eastern and western Bering Sea to understand the proportion of fish biomass within the extent of the eastern survey ('availability'). Surveys are within close proximity to each other, but with different sampling protocols (hence catch a different proportion of local densities, termed 'sampling efficiency ratio'). We use Alaska pollock *Gadus chalcogrammus*, Pacific cod *Gadus macrocephalus* and Alaska plaice *Pleuronectes quadrituberculatus* as case studies to calculate survey efficiency ratios and two area-swept estimators, termed local and conventional, to summarize groundfish biomass over various spatial scales across the Bering Sea.
3. We estimated variation in spatial availability of transboundary stocks to the eastern Bering Sea (EBS) survey. In 2017, the most recent available year of survey coverage that included all three Bering Sea regions, estimated availability in the EBS of pollock biomass was ~33%, cod biomass was ~27% and plaice biomass was ~26%, down from ~58%, ~71% and ~30%, respectively, in 2010.
4. *Synthesis and applications*. This is the first study to provide an empirical way to combine Russian and US data in the Bering Sea to assess changes in the availability of groundfish biomass, which, in turn, will alter the interpretations and values of population indices used in regional management. We recommend leveraging this approach using existing global fishery-independent datasets that span different spatiotemporal footprints to monitor transboundary stocks, and as a template to initiate international cooperation on the assessment of spatial availability of stocks common to multiple countries.

KEYWORDS
Bering Sea, design-based estimator, fisheries-independent survey, groundfish, index of biomass, sampling efficiency ratio, spatiotemporal availability, transboundary stocks

1 | INTRODUCTION

Many terrestrial and marine taxa are moving as they track their preferred climate across the landscape, following both the speed and direction that climate shifts (Chen et al. 2011; Pinsky et al. 2013). This can create a problem for the assessment of mobile taxa because they often move outside of their historical survey extent (Currie et al. 2019) to areas that are surveyed using different protocols. In global groundfish fisheries, for example, scientists summarize the fish biomass within the spatial extent of a fishery-independent survey using an index known as a design-based estimator, to then estimate population dynamics (Hilborn & Walters, 1992). However, stock movements between two or more survey areas complicate these estimates and require combining biomass estimates from multiple survey areas.

Because design-based estimators can only be applied within one survey sampling region, we need to intercalibrate disparate data that cover a larger spatial extent to maintain the data necessary for resource management, known as stock assessments in fisheries, as populations move. Apparent temporal trends in design-based indices may be due to fish movement beyond a survey region rather than population size changes, for example due to ontogenetic migration, density-dependent effects and climate-related movement (Kotwicki et al. 2014). Combining multiple fishery-independent surveys that

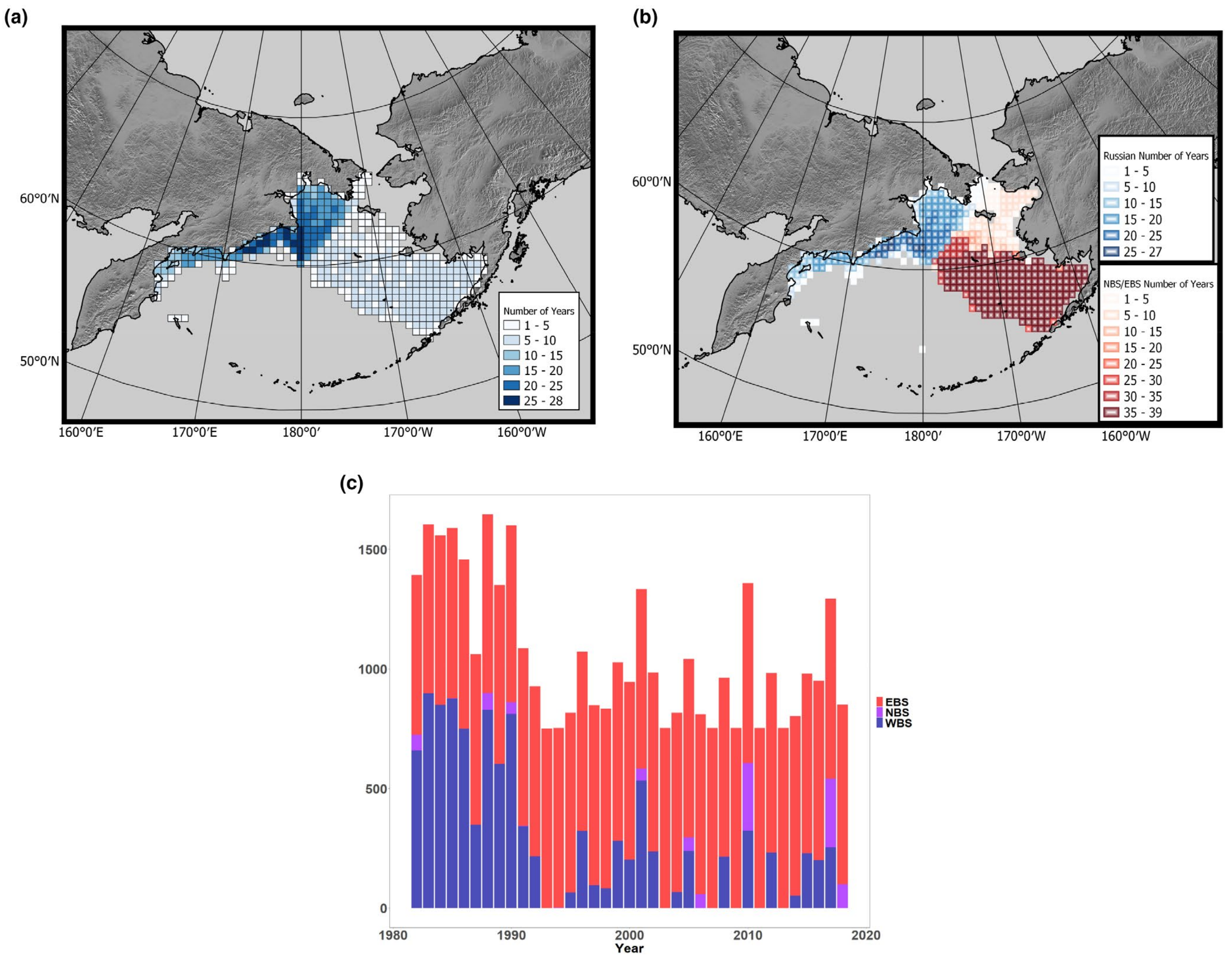

FIGURE 1 (a) TINRO survey spatial extent (1982–2017), darker blue represents a larger number of years with observations. (b) TINRO survey footprint (blue) in the WBS and NOAA AFSC footprint (red) in the EBS (1982–2018) and NBS (1985–2018), darker blue or red represents more observations. (c) The total number of observations for each year and region of the Bering Sea (EBS, eastern Bering Sea; NBS, northern Bering Sea; WBS, western Bering Sea)

span different spatial regions will help to understand the spatial extent, spatial variation and changes in the proportion of stock biomass to each survey, and hence improve the estimated relationship between survey indices and population biomass (Ono et al. 2018).

There are many challenges associated with combining fishery-independent surveys conducted by different groups. One challenge is to estimate the sampling efficiency ratio (Gulland, 1956), that is, the ratio of efficiency of gears used in different surveys. This is synonymous with 'detectability' as defined in many wildlife models and will influence the precision of the design-based index. Differences in sampling efficiency among surveys can be dealt with by calibrating one survey relative to the others, classically done using side-by-side experimental trawls at the same time and place (Thygesen et al. 2019). However, side-by-side trawling experiments are uncommon due to logistical constraints such as operating costs, limited time for additional projects during surveys and occasionally the need for international coordination of surveys. Thus, there is a need to calibrate surveys using an approach that can extract information from existing datasets.

We combine multiple bottom trawl surveys that span various spatiotemporal extents in the Bering Sea to empirically understand the spatial availability of groundfish to an eastern Bering Sea survey. These surveys separately collect bottom-trawl observations of major groundfish species in the northern (NBS), eastern (EBS) and western (WBS) portions of the Bering Sea (Figure 1). We use samples at similar locations and times of year within alternative estimators to identify the sampling-efficiency ratio between surveys while also propagating uncertainty about this ratio into the combined abundance estimate. We used Alaska pollock *Gadus chalcogrammus*, Pacific cod *Gadus macrocephalus* and Alaska plaice *Pleuronectes quadrituberculatus* as case studies. These fish represent a spectrum of body sizes and life histories from the Bering Sea region where there are documented distribution shifts in recent years of some fish species, suspected to be due to warming conditions (Stevenson & Lauth, 2019). We use these data to estimate the spatial availability of these groundfish to the EBS survey using area-swept estimators of biomass indices to understand the accuracy and precision of EBS indices of groundfish biomass. We refer to our index estimators in this study as area-swept estimators, defined as an estimator that applies the same formulae as a design-based estimator (Cochran, 1977), but the underlying survey does not necessarily follow a probabilistic design. We use these case studies as an example of leveraging existing datasets that span different spatiotemporal footprints to monitor transboundary stocks, a characteristic common to many fish stocks managed around the world.

2 | MATERIALS AND METHODS

The proportion of groundfish biomass in the EBS relative to the WBS and NBS was determined by (1) calibrating the EBS and WBS surveys (the NBS did not need to be calibrated because it used the same gear, personnel and deployment procedure as the EBS survey) using observed catches from nearby samples, (2) calculating an area-swept index of stock biomass (mean catch per unit effort or CPUE in kg/ha) for all three regions using two approaches (conventional and local, defined below) that differed in how spatial observations were aggregated and variance estimated and (3) determining the proportion of biomass in the EBS relative to the other regions for each species, and how this changed over time. We first summarize the data, then describe the methods involved in steps 1–3.

2.1 | Data

2.1.1 | Alaska Fisheries Science Center (AFSC) fishery-independent data

We analysed the standardized fishery-independent bottom trawl data from the EBS and NBS. These stratified fixed station gear-standardized surveys have been conducted by the Alaska Fisheries Science Center (NOAA) annually from 1982 to 2018 (Stauffer, 2004). See Supporting Information Section A for more information on all data sources.

2.1.2 | Eastern Bering Sea (EBS) survey

The EBS survey, defined as the southern standard survey area, occurs during daylight from approximately late May to early August and extends from Bristol Bay north to just north of Nunivak and St. Matthew Islands and west to the 200 m depth contour (Figure 1; Armistead & Nichol, 1993).

2.1.3 | Northern Bering Sea (NBS) survey

The full NBS survey occurs in US territorial waters during daylight from August to mid-September from north of St. Matthew and Nunivak Islands to the Bering Strait, including Norton Sound and Bristol Bay (Figure 1; Figure A1). The vessels, gear and sampling strategy match the EBS survey as an extension of that survey, but has been conducted irregularly (in time and spatial extent). A partial NBS survey (i.e. only portions of the total area were sampled) occurred during 1982, 1985, 1988, 1991, 1994, 2001, 2005, 2006 and 2018. Two full region NBS surveys occurred during 2010 and 2017.

2.1.4 | Pacific branch of the Russian Federal Research Institute of Fisheries and Oceanography (TINRO) fishery-independent data

Western Bering Sea (WBS) survey

The TINRO survey extends west of the international maritime boundary between the US and Russian Federation on the WBS shelf. The survey conducted from 1982 to 2017 during May to September does not follow a probabilistic survey design and does not have a fixed temporal schedule (Figure 1). We included TINRO observations from spatial areas that were consistently surveyed throughout the time series to compensate for applying area-swept index calculations to the unbalanced TINRO survey (strata 2–7, Figure 2). A subset of TINRO data collected on the EBS shelf in 1982–1991 was included in the sampling efficiency ratio calculation (Volvenko et al. 2018; Figure 1a,b). See Supporting Information Section A for more TINRO data details.

2.2 | Sampling efficiency ratio

To calibrate the TINRO survey relative to the EBS survey, we calculated the sampling efficiency as the ratio of the TINRO survey index of biomass in the EBS relative to that for the AFSC bottom trawl survey. All samples compared occurred during the same year and were close in time and space. Our index of biomass was CPUE (kg/ha) at each haul or station, where we divide by area for each gear deployment to standardize for the area swept (Alverson & Pereyra, 1969). We located the TINRO hauls that occurred closest to the AFSC hauls in the EBS using a k-nearest neighbour centroid approach (Fix & Hodges, 1951). The TINRO data were from the 1980s and 1990s, when the TINRO survey sampled in the EBS (Figure B1; see Supporting Information for more details). We estimated the ratio of the index of biomass of the two surveys using observations that: (a) were within 6.4 km of each other and (b) were within 1 month of each other in the same year between May to September.

The sampling efficiency for TINRO station k, f_k, was the ratio of the CPUE at that station to that of the nearest AFSC station. Sampling efficiencies were reported as the median values for all years and vessel comparisons combined that includes all observations up to a distance of 6.4 km (4 miles; based on asymptotic characteristics of the sampling efficiency ratio estimate; the value of sampling-efficiency ratios did not change when the distance increased past 6.4 km; Figure B2). The sampling distribution for the estimates of sampling efficiency ratio was obtained using nonparametric bootstrapping based on 1,000 samples with replacement (Elvarsson et al. 2014), each of which had the same number of hauls as the original dataset. The median sampling efficiency ratio at a maximum distance of 6.4 km was the estimate for that species. Eight Russian trawling vessels were included in the calibration.

Studies have transformed the sampling efficiency ratio to a proportion, defined below, because the sampling efficiency ratio cannot be computed with zero fish in the denominator and may be potentially biased towards smaller values (Kotwicki et al. 2017). The number of AFSC pollock (<2%) and cod (0%) hauls that were zero was a small enough fraction to be ignored. However, 92 out of 337 plaice observations (27% of the data) closest to a TINRO hauls were zero. Consequently, for plaice, the sampling efficiency at station j in stratum i for the pair of gears compared with d, was calculated as a proportion $p_d = \frac{CPUE_{j,d,1}}{CPUE_{j,d,2} + CPUE_{j,d,1}}$ and then rearranged to obtain the sampling efficiency ratio $\frac{CPUE_{j,d,2}}{CPUE_{j,d,1}} = \frac{1}{p_d} - 1$ (Kotwicki et al. 2017).

2.3 | Catch per unit effort

Following the calibration of the TINRO survey to the AFSC surveys, we calculated the CPUE for each survey, or our area-swept estimators for biomass as a measure of density by weight in kg/ha. The CPUE was estimated using the area-swept method (Wakabayashi, 1985). We calculated the standardized sample at each station ($CPUE_{i,j}$), calculated the area-weighted average CPUE across each stratum ($CPUE_i$) and then summed them to get the area-swept estimator for biomass across all strata ($CPUE_T$).

We used two area-swept estimators for the CPUE calculations based on different spatial groupings of observations: (a) conventional area-swept and (b) local area-swept. The conventional area-swept estimator is a standard area-weighted average CPUE, where the average CPUE is weighted using the default stratum area (Figure 2; Wakabayashi, 1985). The local area-swept estimator uses k-nearest neighbours to group hauls from the whole dataset based

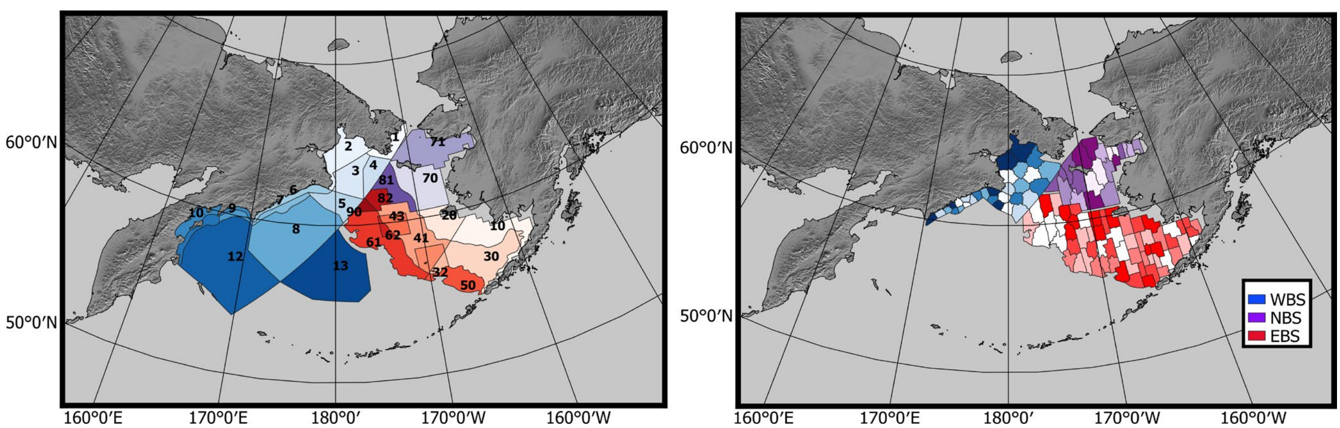

FIGURE 2 The eastern (EBS; red), northern (NBS; purple) and western (WBS; blue) Bering Sea (left) biostatistical strata for the Pacific branch of the Russian Federal Research Institute of Fisheries and Oceanography (TINRO) and NOAA Alaska Fisheries Science Center bottom trawl surveys, where TINRO strata 2–7 were used in the analyses, and (right) clusters used in local area-swept estimators for the EBS (k = 60), NBS (k = 20) and WBS (k = 30)

on nearest neighbour, with a target cluster size of four observations (Strand, 2017; Figure 2). The biostatistical strata and nearest-neighbour clusters used in each of these approaches cover the same total region and area of the Bering Sea (Figure 2). All data (EBS, NBS and WBS) used in the area-swept estimators, area-swept estimator precision and associated coefficient of variation (CVs) were subset to only include strata or clusters that had at least two tows per stratum/cluster.

The variance of the biomass sampling efficiency ratio was propagated through into the TINRO area-swept estimator calculations using nonparametric bootstrapping. We sampled the sampling efficiency ratio with replacement (Figure B2), calculated CPUE and variance for each sample using the equations in the section below and reported the mean estimate of the samples. This was done for all area-swept estimators across the Russian survey extent within the WBS. For all stratum and area-swept estimator calculations, we included only data from locations where two or more hauls per year occurred.

2.3.1 | Conventional area-swept estimator

In this approach, the distance fished was multiplied by the distance between wingtips, or net width, to determine the area swept (Weinberg & Kotwicki, 2008). The weight of catch in each haul was then divided by the area swept to get a standardized index per haul. Any TINRO hauls were then divided again by the sampling efficiency value to standardize them to the AFSC survey. These were then summarized within strata based on the number m_i of successfully trawled stations j in stratum i, $\mathrm{CPUE}_i = \frac{\sum_{j=1}^{m_i} \mathrm{CPUE}_{i,j}}{m_i}$, for each species (see strata in Figure 2). The stratum CPUEs were further summarized across all strata as an area-weighted average CPUE, that is, $\mathrm{CPUE}_T = \frac{\sum_{i=1}^{n} \mathrm{CPUE}_i \times A_i}{A_T}$ to estimate the conventional area-swept estimator for the entire survey area T for each species (CPUE_T) where A_i is the area of each stratum i, A_T is the total survey area and n is the total number of strata. The standard deviation of the conventional area-swept estimators was calculated as $\sigma_i = \sqrt{\frac{1}{m_i - 1} \sum_{j=1}^{m_i} \left(\mathrm{CPUE}_{i,j} - \mathrm{CPUE}_i\right)^2}$ for each stratum and then summarized across all strata i as $\sigma_T = \sqrt{\sum_{i=1}^{n} \left[\left(\frac{A_i}{A_T}\right)^2 \times \sigma_i^2\right]}$.

2.3.2 | Local area-swept estimator

A nearest neighbour cluster analysis was used to develop groupings of hauls located nearest to each other in the same total area as the biostatistical strata across all years (Figure 2). The number of clusters for all years and surveys was determined by dividing the number of stations in any year for a survey type by four (for target group size as close to four stations as the nearest neighbour analysis allows). The final number of clusters for each survey was selected to maximize the number of years where stations were grouped into clusters of 4 or greater. Data were then grouped into clusters using 'KMEANS' from the 'STATS' base package in R version 3.6.0 (R Core Team, 2020). Total clusters for each of the surveys were 30 for WBS, 60 for EBS and 20 for NBS (Table D1; Figure 2).

The cluster and area-swept estimator indexes of biomass were computed as for the conventional area-swept estimator with cluster replacing stratum. The standard deviation of the local area-swept estimator σ_l for each species accounted for the number of clusters b, the number of hauls q in each cluster l, the total area A_l of cluster l, the total area A_T, the area swept n_l in cluster l and the variance within each cluster l (s_l^2) and was calculated as

$$\sigma_l = \sqrt{\sum_{l=1}^{b} w_l^2 \frac{s_l^2}{q_l} \frac{(A_l - n_l)}{A_l}} \text{ where } s_l^2 = \frac{1}{q_l} \sum_{i=1}^{q_l} (x_i - \hat{x}_l)^2 \text{ and } w_j = \frac{A_l}{A_T},$$

(Strand, 2017).

2.4 | Available biomass

The 'availability' of each species in the EBS relative to the WBS or NBS was the proportion of stock biomass within the spatial extent of the EBS survey relative to the total extent of all surveys in the analysis that included the WBS or the NBS. The proportion of stock biomass within the extent of the EBS when only the WBS or NBS was surveyed is also reported as 'proportion of fish biomass'. We used mean area-swept estimator values calculated for all three regions to calculate the proportion of fish biomass in the EBS. The proportion of biomass in the EBS relative to the WBS ($P_{W,t}$) for each year t was calculated as $P_{W,t} = \frac{\mathrm{CPUE}_{T(E)}}{\mathrm{CPUE}_{T(W)} + \mathrm{CPUE}_{T(E)}}$, where $\mathrm{CPUE}_{T(E)}$ is the area-swept estimate for the EBS and $\mathrm{CPUE}_{T(W)}$ is the area-swept estimate for the WBS. The proportion of biomass in EBS relative to the NBS ($P_{N,t}$) was calculated analogously to $P_{W,t}$, as was the availability of species in the EBS relative to the total Bering Sea ($P_{T,t}$).

The sampling distribution for the available biomass in the EBS was obtained using nonparametric bootstrapping. Each of the 1,000 bootstrap samples involved selecting (with replacement) sampling efficiency ratios and the same number of hauls (for each of the TINRO and AFSC surveys) as the original dataset. We then applied the area-swept estimators to each of the bootstrapped surveys, with the median sampling efficiency ratio by bootstrap replicate draw incorporated into the TINRO area-swept estimator for each bootstrap. Finally, the proportions of fish biomass in the EBS was calculated for each bootstrap replicate.

3 | RESULTS

3.1 | Sampling efficiency ratio

The ratio of expected catches for the Russian survey to those for the US survey ('sampling efficiency ratio') was largest for the largest fish, cod, and smallest for the smallest fish, plaice, included in the analyses. The sampling efficiency ratio was based on 337 observations (8 TINRO vessels, 6 AFSC vessels and 8 years—1982, 1983, 1985–1990; Figure B3). The median sampling efficiency ratio ±1 standard deviation for pollock biomass was 0.7 ± 0.16, 1.5 ± 0.14 for cod biomass and 0.2 ± 0.003 for plaice biomass (Table B1). The sampling efficiency ratio estimate for plaice biomass was 0.19 ± 0.003 when no corrections were made for the large number of zero observations. The median sampling efficiency ratio values were robust to a spatial cut-off distance of roughly 2–5 km (Figure B2).

3.2 | Trends in area-swept estimators by region

Indices of pollock biomass increased slightly overall in the WBS during 2010–2017. In the EBS, indices of pollock biomass increased from 2009 to 2014 and then decreased from 2015 to 2018 (Figure 3). The NBS index of biomass increased from 2010 to 2018, but this includes only three data points.

The trend in the index of cod biomass is more apparent than for pollock. The index of cod biomass in the WBS from 2010 to 2017 and NBS from 2010 to 2018 increased overall for both estimators (Figure 3). The final year of cod biomass index in the NBS is above the historical range (but the historical data are more limited and there was not always full spatial coverage of the NBS). The cod biomass index decreased in the EBS from 2014 to 2018.

The index of plaice biomass in the WBS is variable in the final years of data. The plaice biomass index in the final 2 years of NBS data in this study, 2017 and 2018, are estimated to be above the EBS plaice biomass index for the conventional and local design-based biomass estimator. The plaice biomass index in the EBS remained fairly consistent across the entire time period of the study, including the final few years.

The conventional and local area-swept estimator values were very similar for each species, as expected for a systematic survey design (Figure 3). The post-stratified local-based estimator had lower standard errors than the conventional-based estimator for all regions (Figure 4).

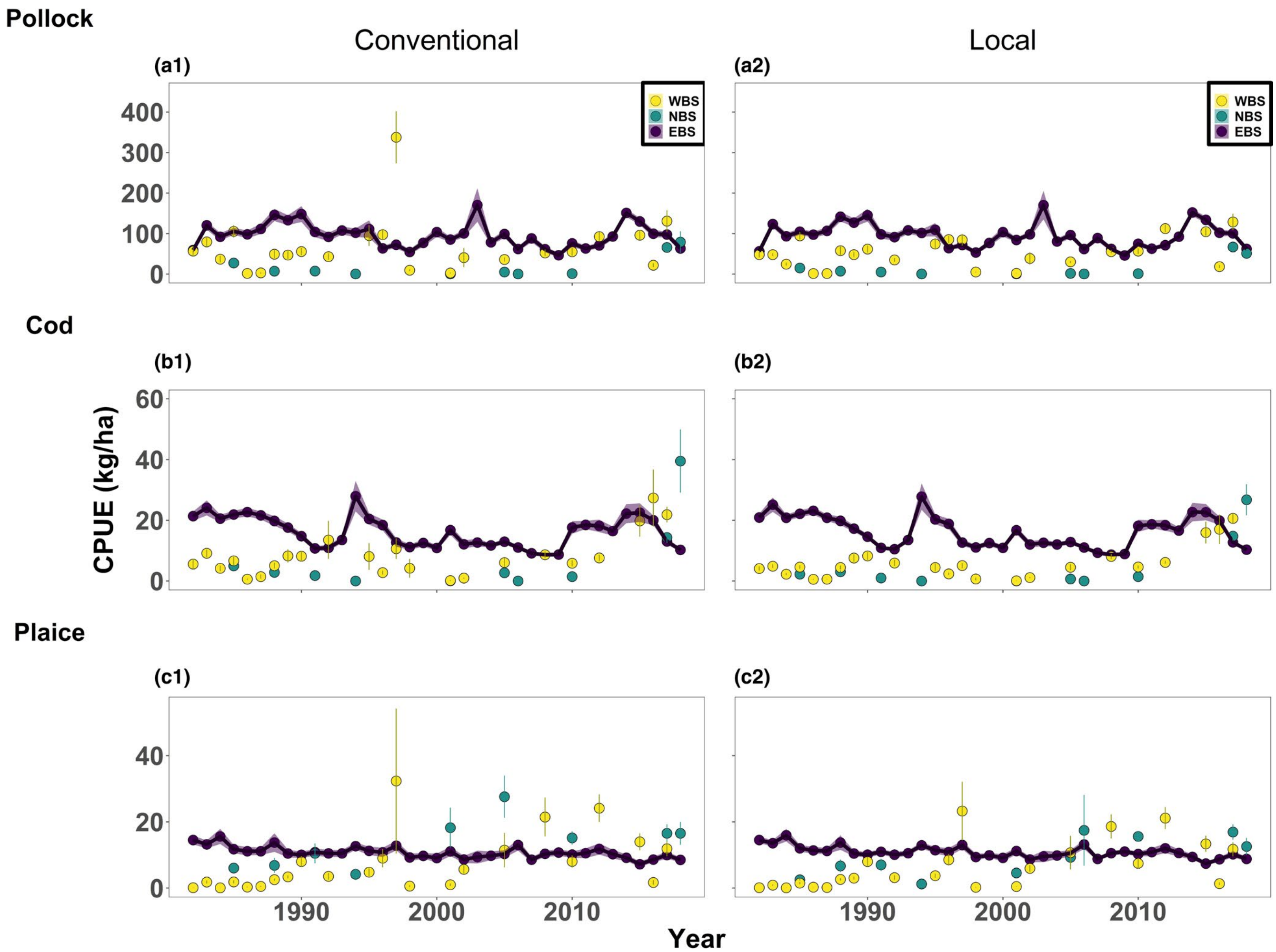

FIGURE 3 Mean standardized biomass catch per unit effort in kg/ha (CPUE; solid line and points) surrounded by one standard deviation (shaded area and vertical bars) for pollock, cod and plaice in the eastern Bering Sea (EBS; purple), western Bering Sea (WBS; yellow) and northern Bering Sea (NBS; aqua), respectively, for the conventional (left) and local (right) and approaches from 1982 to 2018. One outlier NBS plaice conventional CPUE from 2006 (with value 81 ± 58) was removed from the figure so that the plaice temporal CPUE trend was visible

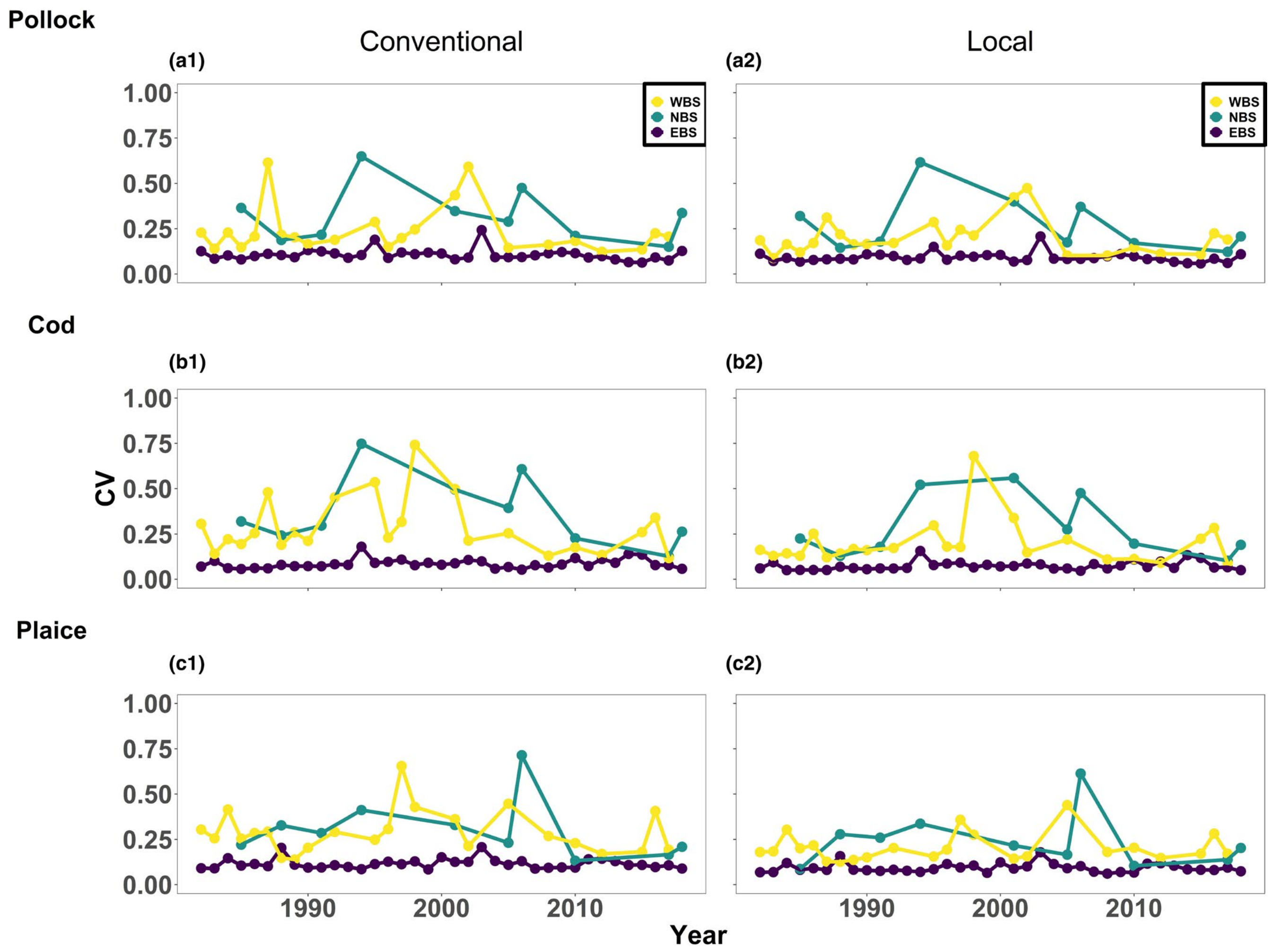

FIGURE 4 Coefficient of variation (CV) of the conventional and local area-swept estimators based on weight for pollock, cod and plaice in the eastern (EBS; purple), western (WBS; yellow) and northern (NBS; aqua) Bering Sea, respectively, from 1982 to 2018

3.3 | Biomass availability

Overall, much of the pollock biomass was in the EBS (67% for conventional area-swept method; 70% for local). Both the conventional and local pollock area-swept biomass indices indicate an increase in pollock in the NBS from 2010 to 2018 relative to the EBS (Figure 5; Tables C1a, C1b), although not all of the NBS was surveyed during all years. In 2017, on average about 60% of the pollock stock was in the EBS relative to the NBS and during 2018 about 44% or 55%, depending on whether the conventional or local area-swept estimator are used, respectively. The proportion of pollock biomass in the EBS relative to the NBS ranged from 44% to 99% from 2010 to 2018. The EBS pollock biomass relative to NBS fell below 50% only in 2018 and only for the conventional area-swept estimator, while the majority of the stock was in the EBS for the other 7 years of data. In 2010 (full NBS survey), the pollock biomass was near 100% in the EBS; during 2017 (full NBS survey), 60% of the pollock biomass was in the EBS; and during 2018 (partial NBS survey), the proportion of pollock biomass was 44% or 55% in the EBS (depending on if based on the conventional or local based estimator, respectively) in the final year. The availability trends in the EBS compared to the entire Bering Sea (i.e. WBS and NBS together) are similar (Figure 5).

The biomass of cod was greater in the EBS relative to the WBS and NBS for the majority of years except 2016–2018 (and 1992, 2008 for the conventional estimator; Figures 2 and 4). From 2015 to 2017, on average about 44%–50% of the stock was in the EBS relative to the WBS. The biomass proportion in the EBS during this time ranged from 37% to 59% for the conventional and local area-swept estimators (Figure 5; Tables C2a, C2b). Cod biomass in the NBS increased over time, and biomass in the NBS in the final 2 years of the study (2017 and 2018) was greater than the cod biomass in the EBS for both area-swept indices. From 2010 to 2018, on average about 54%–56% of the cod stock was in the EBS relative to the NBS, and the proportion of cod biomass ranged from 21% to 93% depending on the area-swept estimator used. EBS cod biomass relative to the NBS fell below 50% during 2017 and 2018 for both area-swept estimators while the majority of the stock was in the EBS for the other 6 years of data (Figure 5). The total availability of cod in the EBS during the final 2 years of data that includes both the NBS and WBS fell further below 30% for both area-swept estimators (Figure 5).

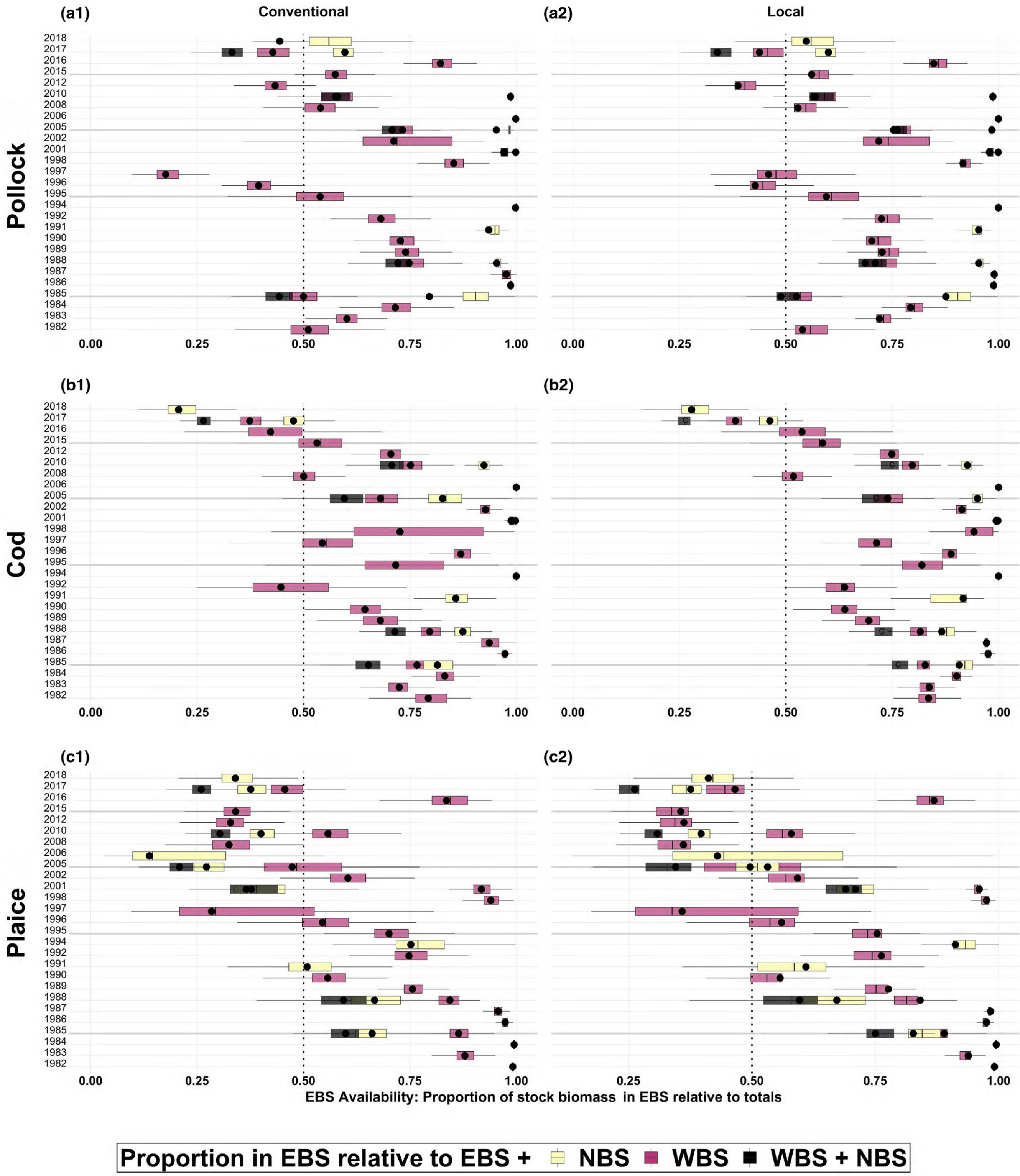

FIGURE 5 Proportion of pollock (a1–2), cod (b1–2), and plaice (c1–2) biomass in EBS relative to the 'total' that includes EBS + NBS (yellow), EBS + WBS (purple) or EBS + both WBS and NBS (grey) for the conventional (left column) and local (right column) area-swept estimators. Mean (crosses) proportions of biomass are surrounded by a boxplot of upper (75th percentile) and lower quartiles (25th percentile; shaded regions) with a vertical line representing the median created from the bootstrap samples. The upper and lower whiskers represent ±1.5 × IQR. A vertical dotted line marks 50% availability. Note that we do not include a blue or purple shape for any year that is missing data in the WBS or NBS, respectively (e.g. there is no purple NBS in 2011–2016)

The proportion of plaice biomass was highly variable between the EBS and WBS (Figures 2 and 4). From 2012 to 2017, the majority of the plaice biomass fluctuated between the EBS and WBS, with the average proportion in the EBS 54%–56% (Figure 5; Tables C3a, C3b). The majority of plaice in the EBS relative to the NBS was in the NBS from 2006 to 2018 for both the conventional and local area-swept estimator (Figures 2 and 4). From 2010 to 2018, on average about 37%–40% of the plaice stock was in the EBS relative to the NBS, and the proportion of plaice biomass in the EBS ranged from 34% to 41% across that time period. The total availability of plaice in the EBS in the final year of data that includes both the NBS and WBS fell further below 50%, down to 26% for both area-swept estimators (Figure 5).

4 | DISCUSSION

Our study illustrates that datasets used to manage transboundary stocks that have different spatial and temporal footprints, as well as different protocols, can be used to provide an overview of fish population biomass availability. We used region-specific, calibrated conventional and local area-swept estimators to demonstrate this. Fisheries scientists and managers can use these methods to combine fishery-independent datasets to incorporate into stock assessment and management, and alternative model-based estimators were used to incorporate NBS (but not WBS) data during recent assessments for pollock and cod (O'Leary et al. 2020). Side-by-side trawling experimentation is not necessary to estimate the relative sampling efficiency of fish to each survey.

Estimation of the sampling efficiency ratio is integral to the method of combining datasets with different protocols. We demonstrated that the sampling efficiency ratio can be estimated using the ratio of CPUEs between hauls selected using a k-nearest neighbours algorithm when research surveys use different survey protocols and vessels, and there are no regular side-by-side trawling experiments available to compare the surveys (Supplementary Info section A). The TINRO bottom trawl vessels are estimated to be less effective than the AFSC vessels at catching pollock and plaice, but more efficient for cod. Possible reasons for the lower efficiency in catching pollock and plaice include (a) escapement of fish below the TINRO bottom trawl net as there is no direct measure of bottom contact (Main, 1981), which can lead to overestimation of effort (Zimmermann et al. 2003), (b) the TINRO survey vessels trawl faster and so may retain fewer fish due to lighter bottom contact and more vessel noise (Somerton & Weinberg, 2001), (c) differences in trawl geometry and consequent variation in net width while towing (the height of the standard TINRO net is smaller, but net width is larger, potentially resulting in smaller catch weight; Weinberg & Kotwicki, 2008), (d) the duration of TINRO hauls was longer on average, ranging from 0.25 to 1 hr (as compared to 0.5 hr for the AFSC survey), potentially leading to net saturation and escapement (Godø et al. 1990) and (e) the smaller body and finer codend mesh size for the TINRO net may retain smaller individuals, reducing the overall biomass of TINRO catch and consequently fishing different sizes in the population (Suuronen & Millar, 1992). More generally, the TINRO survey has a different protocol for determining the location of survey tows, resulting in different gear performance if the Russian survey targeted (cod) or avoided (plaice, pollock) quality habitats for each species arising at fine spatial scales.

4.1 | Application to North Pacific pollock, cod and plaice availability

In recent years (2010–2018), groundfish movement northward and westward, or biomass increases beyond the EBS survey extent and decreases in the EBS, likely impacted the availability of groundfish species to the EBS shelf survey. Decrease in availability of EBS plaice and cod relative to the WBS and NBS, combined with the reduced proportion of pollock biomass in the EBS in the final few years of the study, is consistent with observations of northward shifts in density and range reported by other studies (Spies et al. 2019; Stevenson & Lauth, 2019). The proportion of stock biomass of all three fish species in the EBS relative to the WBS fell below 50% in 2017.

These trends suggest that there are not only changes in regional biomass but also shifts in spatial range due to changing oceanographic and feeding conditions. The cold pool, a subsurface feature defined by temperatures below 2°C and one of the main physical barriers preventing northward movement of groundfish, has reached a historically reduced spatial extent in recent years (Thoman & Walsh, 2019) owing to low winter ice formation and warmer air temperatures. The increase in groundfish in the NBS is possible because this physical barrier between the NBS and EBS was reduced or removed (Grebmeier et al. 2006). However, northward movement or northern biomass increase is a difficult effect to quantify due to the lack of a long-term NBS time series. Our results underscore the importance of continuing the NBS and WBS surveys to monitor changes in groundfish availability to the EBS surveys.

The inter-annual variability in the proportion of biomass found in the WBS and NBS for all three species suggests that it is worth considering TINRO and NBS fish biomass from year to year when evaluating the status of the Bering Sea groundfish stocks as well as a threshold of biomass availability to any survey that impacts stock assessment results and management reference points. This has now been done in pollock and cod assessments for the northern Bering Sea survey, but not for all northward moving species. We recommend incorporating availability information into conservation and management decisions for transboundary stocks to consider the sustainability of the entire Bering Sea shelf stocks by adjusting the catchability of the fisheries-independent survey (such as a time-varying catchability) and altering the standard deviations around the index of biomass in the stock assessment, with the caveat that there is a need to understand the implications of this change given movement and stock structure assumptions. The former approach is conventionally done for some flatfish assessments (flathead, yellowfin; McGilliard et al. 2016; Spies et al. 2020) to account for climate-driven changes in the timing of onshore-offshore movement and resulting seasonal availability to surveys; these same assessments are likely affected by northward shifts into the NBS but this component of availability has not been addressed for these species.

4.2 | Caveats and additional work

This work does not explicitly control or correct for spatial autocorrelation, and so further work is ongoing to explore the use of spatiotemporal models that explicitly account for spatial autocorrelation in the biomass index standardization and their variances (Grüss et al. 2019). This is particularly important to account for survey data arising from a spatially unbalanced design (e.g. NBS in all years except 2010 and 2017); the area-swept estimator in these cases will calculate zero biomass in areas without any survey data, and this is somewhat mitigated by conditioning upon information from other years using a spatiotemporal estimator (O'Leary et al. 2020). The area-swept estimators assume the survey follows a probability sampling design, samples randomly within a survey region, crosses biological gradients (thus providing a representative sample of the region) and covers all potential fish habitat (Kimura & Somerton, 2006). The TINRO survey violates the first of those assumptions (Volvenko, 2014).

This work also does not consider stock structure. There is evidence for cod and pollock stock separation from older genetic studies as well as stock mixing from more recent work (Eisner et al. 2020; Spies et al. 2019; Thompson et al. 2020). For example, Eisner et al. (2020) suggest that in warm years, pollock populations from the WBS and EBS are mixing in the NBS, and ongoing cod tagging work suggests that there is seasonal movement between EBS, NBS, WBS and Gulf of Alaska (J. Nielsen, personal comm., 2021). Different subpopulations and differing exploitation of those could lead to changes in available biomass independently or in conjunction with a moving population. Follow-up work should consider stock structure, particularly as the ocean climate warms and the likelihood of subpopulation mixing increases based on tagging studies evidence.

Several possible follow-up studies, in addition to spatiotemporal model-based approaches, include (a) determining the threshold of availability that will impact stock assessment results to understand the management implications of changes in groundfish availability to each survey and (b) simulation studies to confirm the sampling efficiency ratio precision that results from the approach used in this study to understand how urgent it is to pursue collaborative side-by-side trawl surveys in the Bering Sea. Future work could also include the collection of additional size- and age-class information as well as tagging and movement studies to help corroborate estimates of changing availability from our analysis and differentiate between movement outside of the survey area or changes in population local mortality rates or recruitment due to changes in local conditions.

Future survey cooperation between the Russian Federation, the United States and other neighbouring countries is necessary for stocks that move across the border because failing to monitor this can lead to biases in assessments. The precision in the estimated sampling efficiencies when using nearest neighbour techniques contributes to the uncertainty in the proportion and availability estimates, and demonstrates that it is worth planning overlap between surveys in neighbouring regions. Sampling efficiencies were estimated from data collected during the 1980s and 1990s, when it was common for Russia to sample in the EBS, but this sampling has not occurred during the last two decades. Closer cooperation between the United States and Russia is necessary to continue analyses such as presented here to provide successful and effective management advice. Such international cooperation of bottom trawl survey effort and data sharing occurs between seven countries in the North Sea and Northeast Atlantic from 1970 to present, including Norway, Denmark, Germany, Sweden, Scotland, France, England and the Netherlands via the ICES International Bottom Trawl Survey (ICES, 2020).

5 | CONCLUSIONS

Overall, the methods described here can provide estimates of species availability that can be applied wherever there are multiple surveys with some spatial overlap, including regions such as the North Atlantic, as well as North, Celtic and Mediterranean Seas. These results can guide further research questions to investigate overall change in population biomass and movement of fish stocks between survey regions. Information on the changes in fish stock availability from year to year can apprise managers to look beyond the extent of the current survey area to understand observed population abundance and biomass changes. This approach can provide a general overview of spatial trends in fish stocks over time, but we advise direct consideration of uncertainty and the suggested improvements (Mets et al. 2017). As work on groundfish continues, scientists and managers can consider incorporating this availability information into stock assessments through adjustments of the catchability of fisheries-independent surveys, or altering the standard deviations around fisheries-independent data inputs. As we begin to understand large-scale trends in groundfish movement both northward and westward in the Bering Sea, it sheds light on the need to consider fish movement beyond the extent of the standard survey region in the EBS to help guide future stock assessments as fish stocks respond to our warming oceans.

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AUTHORS' CONTRIBUTIONS

S.K., G.R.H., J.T.T., R.R.L., A.E.P., V.V.K. and J.N.I. conceived the ideas; C.A.O., S.K., G.R.H., J.T.T. and R.R.L. designed methodology; S.K., G.R.H., V.V.K., R.R.L., D.G.N. and J.C. collected and/or contributed pre-processed subsets of data; C.A.O. wrote code, adjusted contributed JC code, and analysed the data; C.A.O. led the writing of the manuscript and all authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

NOAA data are available via https://www.fisheries.noaa.gov/alaska/commercial-fishing/alaska-groundfish-bottom-trawl-survey-data#northern-bering-sea-shelf. All TINRO data are property of the Russian Federation and should be requested through the Federal Agency for Fishery http://government.ru/en/department/243/ and VNIRO http://vniro.ru/en/home/root/about-vniro/contacts.

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REFERENCES

Alverson, D. L., & Pereyra, W. T. (1969). Demersal fish explorations in the northeastern Pacific Ocean-an evaluation of exploratory fishing methods and analytical approaches to stock size and yield forecasts. *Journal of the Fisheries Research Board of Canada*, *26*(8), 1985–2001.

Armistead, C. E., & Nichol, D. G. (1993). *1990 bottom trawl survey of the eastern Bering Sea continental shelf*. Retrieved from https://repository.library.noaa.gov/view/noaa/6096/noaa_6096_DS1.pdf

Chen, I. C., Hill, J. K., Ohlemüller, R., Roy, D. B., & Thomas, C. D. (2011). Rapid range shifts of species associated with high levels of climate warming. *Science*, *333*(6045), 1024–1026.

Cochran, W. G. (1977). *Sampling techniques*. John Wiley & Sons.

Currie, J. C., Thorson, J. T., Sink, K. J., Atkinson, L. J., Fairweather, T. P., & Winker, H. (2019). A novel approach to assess distribution trends from fisheries survey data. *Fisheries Research*, *214*(June), 98–109.

Eisner, L. B., Zuenko, Y. I., Basyuk, E. O., Britt, L. L., Duffy-Anderson, J. T., Kotwicki, S., Ladd, C., & Cheng, W. (2020). Environmental impacts on walleye pollock (*Gadus chalcogrammus*) distribution across the Bering Sea shelf. *Deep Sea Research Part II: Topical Studies in Oceanography*, *181–182*, 104881.

Elvarsson, B., Taylor, L., Trenkel, V. M., Kupca, V., & Stefansson, G. (2014). A bootstrap method for estimating bias and variance in statistical fisheries modelling frameworks using highly disparate datasets. *African Journal of Marine Science*, *36*(1), 99–110.

Fix, E., & Hodges, J. L. (1951). Discriminatory analysis: Nonparametric discrimination: Consistency properties. *PsycEXTRA Dataset*, https://doi.org/10.1037/e471672008-001

Godø, O. R., Pennington, M., & Vølstad, J. H. (1990). Effect of tow duration on length composition of trawl catches. *Fisheries Research*, *9*(2), 165–179.

Grebmeier, J. M., Overland, J. E., Moore, S. E., Farley, E. V., Carmack, E. C., Cooper, L. W., Frey, K. E., Helle, J. H., McLaughlin, F. A., & Lyn McNutt, S. (2006). A major ecosystem shift in the northern Bering Sea. *Science*, *311*(5766), 1461–1464.

Grüss, A., Walter, J. F., Babcock, E. A., Forrestal, F. C., Thorson, J. T., Lauretta, M. V., & Schirripa, M. J. (2019). Evaluation of the impacts of different treatments of spatio-temporal variation in catch-per-unit-effort standardization models. *Fisheries Research*, *213*(May), 75–93.

Gulland, J. A. (1956). The study of fish populations by the analysis of commercial catches. *Rapports Et Procès-Verbaux Des Réunions Du Conseil Permanent International Pour L'exploration De La Mer*, *140*(1), 21.

Hilborn, R., & Walters, C. J. (1992). Quantitative fisheries stock assessment: Choice, dynamics and uncertainty. *Reviews in Fish Biology and Fisheries*, *2*(2), 177–178.

ICES. (2020). *Manual for the North Sea International Bottom Trawl Surveys*. Series of ICES Survey Protocols SISP 10-IBTS 10, Revision 11, 102 pp.

Kimura, D. K., & Somerton, D. A. (2006). Review of statistical aspects of survey sampling for marine fisheries. *Reviews in Fisheries Science*, *14*(3), 245–283.

Kotwicki, S., Ianelli, J. N., & Punt, A. E. (2014). Correcting density-dependent effects in abundance estimates from bottom-trawl surveys. *ICES Journal of Marine Science: Journal Du Conseil*, *71*(5), 1107–1116.

Kotwicki, S., Lauth, R. R., Williams, K., & Goodman, S. E. (2017). Selectivity ratio: A useful tool for comparing size selectivity of multiple survey gears. *Fisheries Research*, *191*(July), 76–86.

Main, J. (1981). *A study of the fish capture process in a bottom trawl by direct observations from a towed underwater vehicle*. Department of Agriculture and Fisheries for Scotland.

McGilliard, C. R., Stockhausen, W., Nichol, D., & Palsson, W. (2016). 9. Assessment of the flathead sole-bering flounder stock in the Bering Sea and Aleutian Islands. In *Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands Region* (pp. 1229–1318). North Pacific Fishery Management Council.

Mets, K. D., Armenteras, D., & Dávalos, L. M. (2017). Spatial autocorrelation reduces model precision and predictive power in deforestation analyses. *Ecosphere*, *8*(5), e01824.

O'Leary, C. A., Thorson, J. T., Ianelli, J. N., & Kotwicki, S. (2020). Adapting to climate-driven distribution shifts using model-based indices and age composition from multiple surveys in the walleye pollock (*Gadus chalcogrammus*) stock assessment. *Fisheries Ocenanography*, *29*(6), 541–557. https://doi.org/10.1111/fog.12494

Ono, K., Ianelli, J. N., McGilliard, C. R., & Punt, A. E. (2018). Integrating data from multiple surveys and accounting for spatio-temporal correlation to index the abundance of juvenile Pacific halibut in Alaska. *ICES Journal of Marine Science: Journal Du Conseil*, *75*(2), 572–584.

Pinsky, M. L., Worm, B., Fogarty, M. J., Sarmiento, J. L., & Levin, S. A. (2013). Marine taxa track local climate velocities. *Science*, *341*(6151), 1239–1242.

R Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. Retrieved from https://www.R-project.org/

Somerton, D. A., & Weinberg, K. L. (2001). The affect of speed through the water on footrope contact of a survey trawl. *Fisheries Research*, *53*(1), 17–24.

Spies, I., Gruenthal, K. M., Drinan, D. P., Hollowed, A. B., Stevenson, D. E., Tarpey, C. M., & Hauser, L. (2019). Genetic evidence of a northward range expansion in the eastern Bering Sea stock of Pacific cod. *Evolutionary Applications*, *13*(2), 362–375. https://doi.org/10.1111/eva.12874

Spies, I., Haehn, R., Siddon, E., Conner, J., Britt, L., & Ianelli, J. (2020). Assessment of the Yellowfin Sole Stock in the Bering Sea and Aleutian Islands. In *Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands Region* (pp. 1–97). North Pacific Fishery Management Council.

Stauffer, G. (2004). *NOAA protocols for groundfish bottom trawl surveys of the nation's fishery resources*. NOAA Tech. Memo. NMFS-F/SPO-65. Retrieved from https://spo.nmfs.noaa.gov/sites/default/files/tm65.pdf

Stevenson, D. E., & Lauth, R. R. (2019). Bottom trawl surveys in the northern Bering Sea indicate recent shifts in the distribution of marine species. *Polar Biology*, *42*(2), 407–421. https://doi.org/10.1007/s00300-018-2431-1

Strand, G.-H. (2017). A study of variance estimation methods for systematic spatial sampling. *Spatial Statistics*, *21*(August), 226–240.

Suuronen, P., & Millar, R. B. (1992). Size selectivity of diamond and square mesh codends in pelagic herring trawls: Only small herring will notice the difference. *Canadian Journal of Fisheries and Aquatic Sciences. Journal Canadien Des Sciences Halieutiques Et Aquatiques*, *49*(10), 2104–2117.

Thoman, R., & Walsh, J. E. (2019). *Alaska's changing environment: Documenting Alaska's physical and biological changes through observations*. International Arctic Research Center, University of Alaska Fairbanks.

Thompson, G. G., Conner, J. S., Shotwell, K., Fissel, B., Hurst, T., Laurel, B., Rogers, L., & Siddon, E. (2020). Assessment of the Pacific cod stock in the eastern Bering Sea. In *Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands Region* (pp. 1–344). North Pacific Fishery Management Council.

Thygesen, U. H., Kristensen, K., Jansen, T., & Beyer, J. E. (2019). Intercalibration of survey methods using paired fishing operations and log-gaussian cox processes. *ICES Journal of Marine Science: Journal Du Conseil*, *76*(4), 1189–1199.

Volvenko, I. V. (2014). The new large database of the Russian bottom trawl surveys in the Far Eastern Seas and the North Pacific Ocean in 1977–2010. *International Journal of Environmental Monitoring and Analysis*, *2*(6), 302–312.

Volvenko, I. V., Orlov, A. M., Gebruk, A. V., Katugin, O. N., Vinogradov, G. M., & Maznikova, O. A. (2018). Species richness and taxonomic composition of trawl macrofauna of the North Pacific and its adjacent seas. *Scientific Reports*, *8*(1), 16604.

Wakabayashi, K. (1985). Methods of the US–Japan demersal trawl surveys. In R. G. Bakkala & K. Wakabayashi (Eds.), *Results of cooperative US–Japan groundfish investigations in the Bering Sea during May–August 1979. International North Pacific Fishery Management*, *12*, 7–26.

Weinberg, K. L., & Kotwicki, S. (2008). Factors influencing net width and sea floor contact of a survey bottom trawl. *Fisheries Research*, *93*(3), 265–279.

Zimmermann, M., Wilkins, M. E., Weinberg, K. L., Lauth, R. R., & Shaw, F. R. (2003). Influence of improved performance monitoring on the consistency of a bottom trawl survey. *ICES Journal of Marine Science: Journal Du Conseil*, *60*(4), 818–826.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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