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In-season monitoring of harvest and effort from a large-scale subsistence salmon fishery in western Alaska

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Abstract

In-season management of salmon harvest requires real-time data. Specifically, following a brief period of open fishing, knowledge of harvest outcomes is useful when deciding the nature of subsequent fishing periods. This in-season management strategy is relatively new to the lower Kuskokwim River of western Alaska, where depressed salmon runs have caused restrictions to the subsistence fishery. We have developed an in-season monitoring program to rapidly inform managers about fishery outcomes from short-duration (6–24 h) fishery openings. Completed trip information and one or more aerial surveys are combined to estimate daily effort and harvest from drift gillnet fishers spanning 11 communities and ∼130 river kilometers. We present a re-analysis of the 40 monitored openers in June–July 2016–2023, and validate harvest estimates of Chinook, chum, and sockeye salmon by comparing them to post-season estimates derived from an independent long-term monitoring program. Our results indicate that the program has produced estimates of sufficient quality to inform in-season managers, although it will likely need alterations to be successful in years with less restricted fishing.

Key words: subsistence fisheries, Pacific salmon, monitoring, in-season management

1. Introduction

In the fast-paced setting that is in-river, in-season management of Pacific salmon (*Oncorhynchus* spp.) harvest by "emergency order", in-season data are needed rapidly to inform decisions about where, when, and with what gear type(s) to allow fishing (Minard and Meacham 1987). These fisheries are "sequential gauntlets" in which fish are harvested as they pass communities on their upstream migration to natal tributaries to spawn. Fishery managers are guided by multiple objectives during in-season deliberations, perhaps chief of which is ensuring enough prospective spawners survive the fishery to sustain the population (termed "escapement"). Simultaneously, managers must ensure that fishery harvests are not limited unnecessarily and that sufficient access to the surplus is provided. These two already conflicting objectives are often complicated by additional objectives or considerations, such as a need to preferentially target or avoid harvesting certain stocks (e.g., different species, or subpopulations of the same same species, which may have overlapping migrations) or distributing harvest temporally throughout the run for the sake of conserving genetic structure and diversity. Managers use a wide variety of information to aid in this decision-making effort, often combined using statistical models to facilitate inference (Hyun et al. 2005; Michielsens and Cave 2018); however, available information is rarely as precise or timely as would be desired for high certainty in the success of any given decision (Staton and Catalano 2019). Still, waiting too long—even by a week or less—can lead to missed harvest opportunities, but aggressive harvesting can negatively affect escapement, its composition, and fishing opportunities upstream.

KManagement by emergency order refers to the case in which the run is anticipated to be of insufficient size to support unrestricted harvest and the fishery is closed to certain types of harvest (e.g., species, areas, gears) until announced open for a period (Adkison and Cunningham 2015). Data needs arising from these short-duration openers are different than those for many fisheries open for entire seasons at a time (Bernard et al. 1998)—because the nature of this management strategy benefits from timely information about cumulative harvest to date when deciding the remaining fishing opportunities for the season. Further, many fisheries are spatially constricted, whereas others may be spatially dispersed, such as in the Arctic–Yukon–Kuskokwim region of western Alaska where the bulk of harvest occurs by communities spanning dozens or hundreds of river kilometers (rkm). Subsistence fishery harvest in these larger and more remote systems has historically (i.e., pre-2010s) been largely unrestricted (Brown et al. 2023) and monitored exclusively by post-season data collection. However, declining and lower-than-average salmon productivity and returns throughout the late-2000s and 2010s (Dorner et al. 2018; Larson 2024) brought the implementation of the emergency order management strategy to subsistence fisheries in the region.

The spatial size, remoteness, and short temporal nature of these kinds of fisheries present unique challenges to developing a monitoring program that can rapidly and accurately estimate harvest in-season. Since a complete census is unachievable in such conditions, estimates require information on the number of trips, the attributes of an average trip (e.g., catch rate, species composition, and active fishing time), and the heterogeneity in attributes among trips. A roving creel program would likely be unsuccessful because fishers are widely distributed (or locally very compressed, depending on river morphology and fishing conditions), trips can be quite long, and fishers would prefer to not be interrupted when actively fishing (the primary harvest method is drift gillnet fishing; Bembenic and Koster 2024). These features suggest that an access point creel program would better provide completed trip information on a spatially explicit and less intrusive basis; however, access points are numerous and spatially diverse, potentially making them difficult to representatively sample without many personnel. Additionally, some fishers may be reluctant or unwilling to provide completed trip information. Without interviewing every fisher, completed trip interviews alone do not allow expansion of trip-level attributes to area- and opener-wide harvest. These challenges were highlighted by pilot projects evaluating the feasibility of in-season harvest monitoring in the Kuskokwim (Runfola and Koster 2019) and Yukon (Brown and Jallen 2019) rivers, where insufficient sample sizes (and thus representation) of fisher reports documenting trip-level fishing outcomes were cited as a primary barrier to the feasibility of in-season harvest estimates.

In this article, we describe a somewhat unique in-season monitoring program (ISMP) for the subsistence fishery that spans ~130 rkm of the lower Kuskokwim River, where management by emergency order has been used primarily to limit the harvest of Chinook salmon (*Oncorhynchus tshawytscha*) during recent periods of reduced run sizes. A pilot ISMP began in 2015 and the current ISMP has operated each year since 2016 and has evolved with greater spatial coverage in data collection and refinement of analytical methods over the years. By combining completed trip interview data, collected largely by local residents of these remote communities (Inman et al. 2021) to bolster sample sizes and ensure spatial representation, and one or more aerial surveys, the program estimates harvest by species for the day in which fishing was open. Our objectives with this article are to (1) document the methods of data collection and estimation; (2) present a complete re-analysis of all drift gillnet harvest data collected since 2016 with consistent analytical methods; and (3) validate the ISMP by (*a*) comparing harvest estimates to empirical information gathered by a post-season monitoring program (PSMP)[1] and (*b*) stochastic simulation. We conclude by discussing our reasoning for believing that the ISMP has produced sufficiently reliable estimates for informing in-season management in the years it has operated thus far and by presenting recommendations and caveats for its broader application.

[1] Abbreviations "PSMP" and "ISMP" are used here for convenience and are not the official names of these programs.

2. Methods

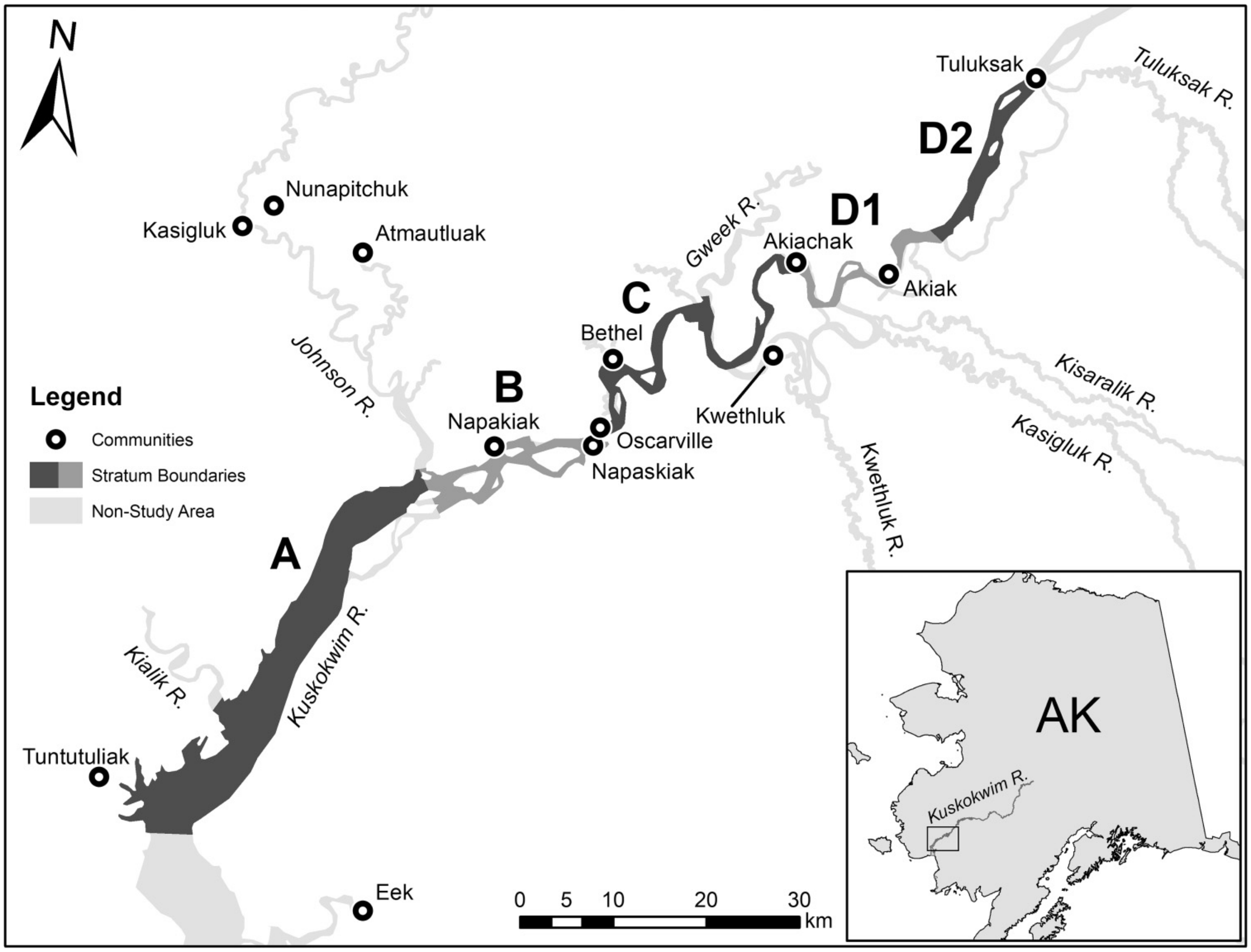
2.1. Study area, species, and timeframe

The Kuskokwim River is a large (watershed area ~130 000 km^2, mainstem ~1500 rkm) and remote river system in western Alaska that supports returns of all five anadromous species of Pacific salmon: Chinook, chum (*Oncorhynchus keta*), sockeye (*Oncorhynchus nerka*), pink (*Oncorhynchus gorbuscha*), and coho (*Oncorhynchus kisutch*). Chinook salmon begin the upriver spawning migration each year in late May, with chum and sockeye salmon returning somewhat later in the season but certainly intermixed with at least the second half of the Chinook salmon run, making June–July the primary time to harvest these three species. Migrating salmon are harvested by local residents who are primarily Yup'ik Alaska Natives and for whom subsistence salmon fishing is an essential aspect of the culture, lifestyle, and food security (Wolfe and Spaeder 2009; Brown et al. 2023; Esquible et al. 2024). With respect to Chinook salmon, the Kuskokwim River constitutes one of the largest subsistence fisheries in the state of Alaska, comprising approximately half of all state-wide Chinook salmon subsistence harvests (Fall et al. 2018; Carothers et al. 2021; Brown et al. 2023). Based on historical harvests in the region (community-specific estimates dating back to 1990 presented in Hamazaki 2011; basin-wide estimates for 1976–1989 presented in Larson 2024), the Alaska Board of Fisheries has designated the amounts reasonably necessary for subsistence (ANS; salmon per year) in the Kuskokwim River as 67 200–109 800 for Chinook salmon, 41 200–116 400 for chum salmon, and 32 200–58 700 for sockeye salmon—these three species account for the majority of subsistence salmon harvests in the region. Although Chinook salmon are preferred by most Kuskokwim River residents (Hamazaki 2008; Brown et al. 2023), restrictions caused by low run sizes have prevented ANS achievement since 2011 (Smith et al. 2022).

Fishing pressure is not homogeneously distributed throughout the Kuskokwim River basin. There are 26 communities that have been monitored long term for harvest (Bembenic and Koster 2024), although 11 communities in the lower Kuskokwim River and within the ISMP study area (Fig. 1) have accounted for an average 81%, 78%, and 79% of all subsistence-caught Chinook, chum, and sockeye salmon in the basin, respectively, between 2010 and 2022. Over this period, annual basin-wide subsistence harvest of these species averaged 32 900, 42 900, and 43 600 (Bembenic and Koster 2024). These 11 communities include (in approximate order moving upstream from the river mouth): Tuntutuliak, Atmautluak, Kasigluk, Nunapitchuk, Napakiak, Napaskiak, Oscarville, Bethel, Kwethluk, Akiachak, and Akiak (Fig. 1).

Within the Yukon Delta National Wildlife Refuge, which encompasses the entire ISMP study area, in-season subsistence salmon harvest has, since 2015, been managed by co-operative agreement between the U.S. Fish and Wildlife Service (USFWS) and the Kuskokwim River Inter-Tribal Fisheries Commission (KRITFC), with authority delegated by the Federal Subsistence Board; the Alaska Department of Fish and Game (ADF&G) has maintained management primacy for fisheries occurring upstream of the Refuge boundaries (Smith and Gray 2022). Beginning around 1 June each year, salmon

Fig. 1. Lower Kuskokwim River showing the geographic strata of the study area for the in-season subsistence salmon harvest monitoring program. Strata A, B, C, and D1 boundaries are marked with alternating dark and light gray portions of the mainstem, whereas the lightest gray areas are not included in the study area. Communities of Eek and Tuluksak are shown only for completeness but are not included in analyses because most harvest from those communities tends to occur outside strata A–D1; stratum D2 was sampled in 2016 and 2023 only and is not included in the current analyses. Map was created using ESRI ArcMap with data from the Alaska Department of Natural Resources (mainstem and state boundary) and the Alaska Department of Fish and Game (tributaries).



harvest using gillnets is closed in the mainstem Kuskokwim River, with short-duration periods of subsistence harvest opportunities (hereafter, "openers") announced by Federal Special Action (non-salmon spawning tributaries and non-gillnet harvest methods have generally remained open all season). Prior to 12 June, openers have allowed set gillnets (i.e., fixed to the riverbank) in the mainstem Kuskokwim River with ≤4 inch stretched mesh, and ≤6 inch starting in 2019, to target non-salmon species, though small numbers of Chinook salmon have been caught in these openers (Decossas 2019*b*, 2020; Russell et al. 2021; Bechtol and Schomogyi 2022; Bechtol et al. 2024). Beginning on 12 June each year, openers allowing ≤6 inch stretched mesh gillnets in the mainstem have been implemented, and drift gillnets have been allowed in many of these openers. Openers are typically 12 h in duration, though have ranged from 6 to 24 h (Table SC1). Although the ISMP samples both set and drift gillnet fishers during these openers, drift gillnets are the primary method (reported by ∼90% of fishers in the ISMP study area as the primary harvest method; McDevitt et al. 2020, 2021*a*, 2021*b*; McDevitt and Koster 2022; Bembenic and Koster 2024) and have accounted for ∼95% of all harvest estimated by the ISMP (e.g., Staton 2018; Decossas 2019*b*, 2020; Russell et al. 2021; Bechtol and Schomogyi 2022; Bechtol et al. 2024). Thus, we have focused this article on exclusively subsistence harvest of Chinook, chum, and sockeye salmon using drift gillnets in the mainstem Kuskokwim River between the communities of Tuntutuliak and Akiak (Fig. 1) during June and July 2016–2023.

2.2. Data collection

The ISMP estimates harvest on a daily basis by combining aerial surveys with access point completed trip interviews. The aerial surveys give instantaneous estimates of fishery participation (i.e., effort) and its spatial distribution throughout the study area, whereas interviews provide information about trip characteristics, such as the times the trip was active, how many salmon of each species were harvested, and the broad geographic area in which the trip occurred.

2.2.1. Aerial effort surveys

For each monitored opener and for which weather conditions allowed, one or more aerial survey flights were flown to count the number of drift boats and set nets fishing within the study area (Fig. 1). Flights were generally scheduled to capture boat counts during anticipated times of peak participation and the often-abbreviated opener duration (generally 12 h), resulted in flights that were spaced relatively equally throughout the opener with approximately 3–4 h between the end of one flight and the start of the next flight (Fig. 2). Flight missions involved fixed wing aircraft staffed usually by USFWS employees (at least one pilot and one observer) flying at a target altitude of 1000 feet (but no lower than 500 feet) using predominantly the aircraft Cessna 185 N714 or Cessna 206 N740; a smaller number of surveys were flown with a Cub Crafters Top Cub N278CC. In several cases necessitated by USFWS staff unavailability (generally later in the season, and in more recent years), KRITFC or Orutsararmiut Traditional Native Council (ONC) staff served as observers on a USFWS flight or a chartered flight was used.

Flights departed Bethel Airport (PABE) downstream and southwest toward Kuskokwim Bay to the community of Tuntutuliak, then turned upstream and northeast to the community of Akiak, and then back to land in Bethel (Fig. 1). The flight path took approximately 1.5–2 h and involved flying past all points twice longitudinally. Counts were made separated into sections that were demarcated by major landmarks, such as tributaries or communities, which allowed them to be stratified for analysis later. River sections for which both banks could be viewed clearly were assigned the maximum of the two counts, sections that were too wide to be seen flying one direction were counted bilaterally (one side counted flying each direction) and the counts were summed—this bilateral counting applied primarily to set gillnets observed downstream of Bethel and especially downstream of the Johnson River confluence with the Kuskokwim River (Fig. 1).

Weather conditions that were amenable to flying also resulted in good survey visibility and although boats could be seen clearly, no attempt was made to differentiate boats in transit from those actively fishing—all boats and set nets were counted and all boats were presumed to be drift fishing. For each flight of the day, counts were totaled within each of the four study geographic strata (indexed by j and labeled A, B, C, and D1; Fig. 1)—the total count for flight f that occurred on day d is denoted $n(X_{f,d})$ and the geographically stratified version is denoted $n(X_{f,j,d})$ (see Table 1 for symbology used throughout). The spatial distribution of effort at the time of the flight was summarized by

$$p_{f,j,d} = \frac{n\left(X_{f,j,d}\right)}{n\left(X_{f,d}\right)} \quad (1)$$

The resulting $p_{f,j,d}$ values for day d were averaged across flights to obtain $p^N_{j,d}$, which was assumed to represent the overall spatial distribution of effort throughout the entire day and was used to weight the interview data outcomes in harvest estimation (eq. 5).

2.2.2. Access point completed trip interviews

Interviews were designed to be minimally intrusive while simultaneously gathering the most pertinent information to obtain quantitative estimates of fishing conditions (e.g., standardized catch rates). Participation was entirely voluntary and no personally identifiable information of any kind, such as names, the number of persons in the boat, or boat licenses was gathered at any point.

Interviews were conducted by three organizations with different spatial coverage: (*a*) ONC has collected data at the Bethel boat harbor (55% of all interviews) and at fish camps in the Bethel area and near the communities of Oscarville, Napaskiak, and Napakiak (12%), (*b*) KRITFC has conducted interviews in a variety of communities outside of Bethel as part of the Community-Based Harvest Monitoring program (33%; Russell et al. 2021), and (*c*) ADF&G Division of Subsistence conducted interviews in the tundra communities of Atmautluak and Kasigluk (1%; 2018 only).

Pertinent information gathered during interview i that occurred on day d included the (*a*) interview location, (*b*) trip start and end time ($T^{\text{start}}_{i,d}$ and $T^{\text{end}}_{i,d}$), (*c*) total amount of time the gillnet was actively fished (i.e., soak time; $t_{i,d}$), (*d*) geographic stratum j where the majority of soak time was spent (Fig. 1), (*e*) type (drift vs. set) and length ($L_{i,d}$) of the net, and (*f*) number of salmon harvested by species ($h_{i,s,d}$). Other interview questions may have been asked depending on the organization collecting the data; however, responses to these six questions were the only data used to inform harvest and effort estimates.

With most openers lasting 12 h or less, it was feasible to have near-continuous interview coverage at most surveyed access points. Interviewers were instructed to begin interviewing approximately 2 h after the start of the opener (as trips this short should be exceedingly rare) and up to 2 h after its conclusion. Shifts were scheduled such that interviewers rarely worked more than 8 h at a time to prevent fatigue. The pace at which fishers returned to the access points allowed most fishers to be approached for an interview, but interviewers were instructed to select fishers at random if they could not interview every returning fisher. An “interviewed trip” constituted one interview per returning boat for which most of the pertinent information was deemed reliable.[2] For example, an interview that has all information except the trip start time could be used for informing catch rate (eq. 4) but not the effort estimator (e.g., eq. 3); see eq. SA1 and surrounding text for details.

[2] Quality assurance checks performed prior to analysis described at: https://htmlpreview.github.io/?https://github.com/bstaton1/KuskoHarvEst/blob/main/inst/rstudio/templates/04-docs/06-data-checks.html.

Fig. 2. Timing of various elements of ISMP-monitored drift gillnet openers, June–July 2016–2023. Elements on each panel include: (*a*) background light gray distributions show the percent of interviewed trips active at a given time of the day; (*b*) overlapping dark gray stripes show timing of aerial survey flight(s); (*c*) points show the estimated probability that a trip was active/counted during a given flight ($\widehat{\pi}_f = n\left(X_f\right)/\widehat{N}$); and (*d*) dashed lines show the portion of the day the fishery was open. Active trip times may extend beyond the fishery open period because of transit to and from the fishing grounds before and after the fishery is open. Points that track the shape of light gray distributions indicate agreement between interview and flight data with respect to the proportion of all trips active at a given time, making each panel an assessment of model fit.

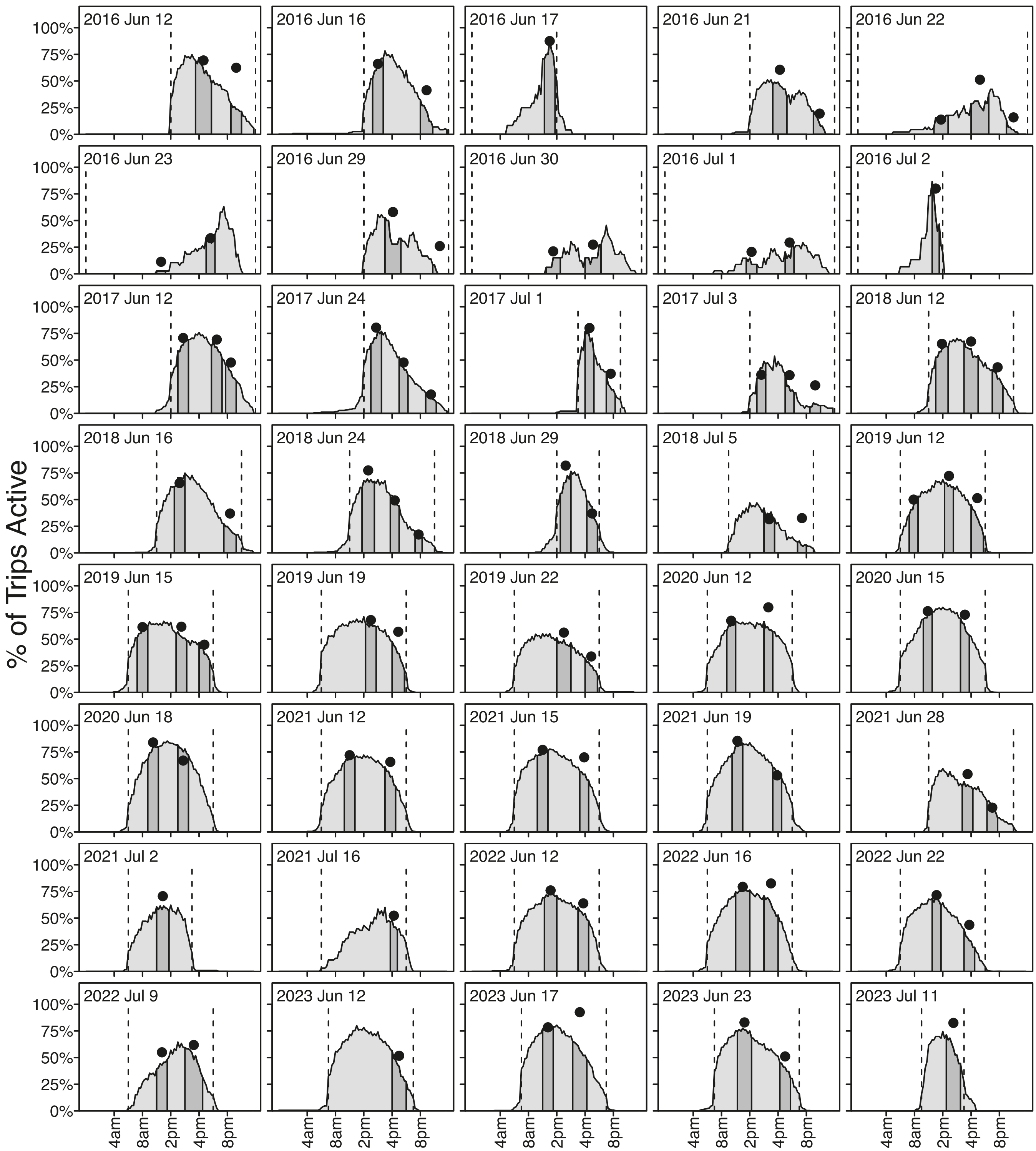


Table 1. Symbols used in the descriptions and derivations of the estimators for harvest and effort, and the development of correction factors for performing the validation analysis comparing estimates generated by the in-season (ISMP) and post-season (PSMP) monitoring programs.

Group	Symbol	Description
	i	Individual trip, some of which are interviewed[a]
	j	Geographic stratum: A, B, C, D1 (Fig. 1)
	k	Spatial group for aggregating subsistence calendar data
	s	Salmon species
	c	Community
	y	Year
	g	Gear type
	f	Flight
Indices	d	Day
	N_d	Number of trips that occurred in opener d
	$\widehat{N}_d$	Estimated number of trips that occurred in opener d
	$\pi_{f,d}$	Probability any trip was counted on flight f
	ψ_d	Probability any trip was interviewed
	$n(Y_d)$	Number of trips interviewed (or not, $n(Y'_d)$)
	$n(X_{f,d})$	Number of trips counted (or not, $n\left(X'_{f,d}\right)$) on flight f
	$n(X_{f,d} \cap Y_d)$	Number of interviewed trips counted on flight f
	$n(X_{f-1,d} \cap X_{f,d} \cap Y_d)$	Number of interviewed trips counted on both flights f and $f-1$
	$n\left(X'_{\text{any},d} \cap Y_d\right)$	Number of interviewed trips not counted on any flight
	$[X_{f,d}]$	Marginal probability that any trip is counted on flight f (equal to $\pi_{f,d}$)
	$[X_{f-1,d} \cap X_{f,d}]$	Joint probability that any trip is counted on both flights f and $f-1$
	$[X_{f-1,d} \mid X_{f,d}]$	Conditional probability that any trip counted on flight f is counted on $f-1$
	$T^{\text{start}}_{i,d}$; $T^{\text{end}}_{i,d}$	Reported start and end times for trip i
Effort estimator	$F^{\text{start}}_{f,d}$; $F^{\text{end}}_{f,d}$	Start and end times for flight f
	$p^{N}_{j,d}$	Proportion of all trips ($\widehat{N}_d$) estimated to have occurred in each spatial stratum
	$h_{i,s,d}$	Number of salmon harvested by species for trip i
	$L_{i,d}$	Gillnet length for trip i; $\bar{L}_{j,d}$ is average across trips
	$t_{i,d}$	Gillnet soak time for trip i; $\bar{t}_{j,d}$ is average across trips
	$r_{i,s,d}$	Catch rate by species for trip i; $\bar{r}_{j,s,d}$ is average across trips
	$\widehat{H}^{\text{IS}}_{s,j,d}$	ISMP daily harvest estimate by species and stratum
Harvest estimator	$\widehat{H}^{\text{IS}}_{s,d}$	ISMP daily harvest estimate by species
	$\widehat{H}^{\text{IS}}_{s,y}$	ISMP season-wide harvest estimate by species
	$\widehat{H}^{\text{PS}}_{s,y}$	PSMP harvest estimate by species; corrected to scale of ISMP
	$H^{\text{PS}}_{y,s,c}$	PSMP annual estimate of harvest for species s and community c
	$C_{y,d,s,c}$	Harvest reported in harvest calendars by community
	$C_{y,d,s,k}$	Harvest reported in harvest calendars by spatial group
	D^{PS}	Last day included for subsistence harvest calendars; set to 30 September
	D^{IS}_{y}	Last day of ISMP sampling in year y
	$p^{\text{Time}}_{y,s,k}$	Proportion of entire season (PSMP) monitored by the ISMP
	$R_{y,g,c}$	Number of fishers reporting using gear g in year y and community c
	$p^{\text{Gear}}_{y,c}$	Proportion of PSMP-estimated harvest specific to drift gill nets only
	$S_{c,j}$	Number of interviews conducted in a community that reported fishing in stratum j
Validation analysis	$p^{\text{Space}}_{c,j}$	Proportion of PSMP-estimated harvest specific to ISMP stratum j

[a]In Supplement A, i is used to refer to any trip, whether interviewed or not. In the main text, i is used to index interviewed trips.

2.3. Estimators

2.3.1. Effort estimator

The role of the effort estimator is to estimate the number of trips (N_d) that occurred on day d of fishing within the study area. The quantity N_d is the critical value that allows expanding trip-level catch and effort data to the scale of the entire study area for estimating harvest (eq. 5). Acknowledging this, accuracy in the estimation of N_d is crucial—since it serves as a direct expansion factor, errors in harvest estimates will be proportional to errors in N_d, all else equal.

The quantity N_d cannot be estimated with aerial survey data alone because fishing activity during unflown times is unknown, as is the frequency with which trips are counted more than once in the case of multiple aerial surveys. Likewise, estimation of N_d with interview data alone is impossible because the number trips that were not interviewed is unknown. However, by combining information from the two data sources, and through several assumptions regarding random and independent sampling, we have derived estimators for N_d ($\widehat{N}_d$; see Supplement A for complete details) in the case of one survey flight:

$$\widehat{N}_d = \frac{n\left(X_d\right) n\left(Y_d\right)}{n\left(X_d \cap Y_d\right)} \tag{2}$$

where $n(X_d)$ is the number of active trips counted during the flight, $n(Y_d)$ is the number of interviews that were conducted, and $n(X_d \cap Y_d)$ is the number of interviews that documented trips active during the flight—we assumed that a trip was counted via aerial survey if the reported times ($T^{\mathrm{start}}_{i,d}$ and $T^{\mathrm{end}}_{i,d}$) overlapped with the times of the flight ($F^{\mathrm{start}}_{f,d}$ and $F^{\mathrm{end}}_{f,d}$; eqs. SA1 and SA6). Readers may notice the similarity with the two-sample mark–recapture estimator for closed populations (e.g., Seber 1986)—we discuss this and its relevance to sampling and estimator performance in Supplement A.

In the case of two or more aerial surveys conducted in one day (three flights has been the maximum to date), the estimator must be altered to account for the fraction of trips counted on consecutive flights:

$$\widehat{N}_d = \frac{n\left(X_{1,d}\right) + \sum_{f=2} n\left(X_{f,d}\right)\left(1 - \frac{n\left(X_{f-1,d} \cap X_{f,d} \cap Y_d\right)}{n\left(X_{f,d} \cap Y_d\right)}\right)}{1 - \frac{n\left(X'_{\mathrm{any},d} \cap Y_d\right)}{n(Y_d)}} \tag{3}$$

where $n(X_{f,d})$ is the count on flight f, $n(X_{f-1,d} \cap X_{f,d} \cap Y_d)$ is the number of interviews reporting trips that were active during two consecutive flights, and $n\left(X'_{\mathrm{any},d} \cap Y_d\right)$ is the number of interviews reporting trips that were inactive during all flights. According to eq. 3, the total number of trips in day d is equal to all trips counted on the first flight, plus the portion of each subsequent flight f that was not counted on the previous flight $f-1$, with the result expanded to include trips that occurred during unflown times.

2.3.2. Harvest estimator

Harvest estimation based on in-season access point interviews characterized features of the average trip (e.g., net length, soak time, salmon harvest by species) and expanded them by the estimated number of trips ($\widehat{N}_d$). “Average trip” calculations were spatially stratified to account for geographic differences in fishing conditions, weighted by the number of trips in that stratum (i.e., $\widehat{N}_d p^N_{j,d}$). The catch rate of species s for interviewed trip i was standardized to the number of salmon harvested per unit length of gillnet soaked per hour:

$$r_{i,s,d} = \frac{h_{i,s,d}}{L_{i,d} t_{i,d}} \tag{4}$$

The quantities $L_{i,d}$, $t_{i,d}$, and $r_{i,s,d}$ were grouped spatially and averaged ($\bar{L}_{j,d}$, $\bar{t}_{j,d}$, and $\bar{r}_{j,s,d}$) to characterize local differences in trip outcomes. For strata with fewer than 10 interviews (often stratum D1; Fig. 1), interview data were pooled with the nearest stratum for the calculation of stratum-specific averages. In-season harvest estimates by stratum, species, and day ($\widehat{H}^{\mathrm{IS}}_{s,j,d}$) were obtained as

$$\widehat{H}^{\mathrm{IS}}_{s,j,d} = \bar{L}_{j,d} \bar{t}_{j,d} \bar{r}_{j,s,d} \times p^N_{j,d} \widehat{N}_d \tag{5}$$

where the first term is expected salmon catch by species for the average drift gillnet trip occurring in stratum j on day d and the second term is the estimated number of trips that occurred in stratum j on day d. Total harvest by species estimated by the ISMP for day d was obtained as the sum across strata ($\widehat{H}^{\mathrm{IS}}_{s,d} = \sum_j \widehat{H}^{\mathrm{IS}}_{s,j,d}$).

2.3.3. Uncertainty estimation

A non-parametric bootstrap was used to derive estimates of uncertainty in $\widehat{H}^{\mathrm{IS}}_{s,j,d}$ based on among-trip variability in $L_{i,d}$, $t_{i,d}$, and $r_{i,s,d}$. The bootstrap approach involved resampling individual interviews (at random and with replacement) from the interview data within each stratum, recalculating $\bar{L}_{j,d}$, $\bar{t}_{j,d}$, and $\bar{r}_{j,s,d}$, and applying eq. 5 to the resampled data set. Interviews were sampled as a unit to retain any correlation structure in trip-level values; the same number of interviews were sampled for each stratum as the original sample size. The point estimate of effort given by eq. 3 was used each for bootstrap iteration. Bootstrapped harvest estimates were then summarized with the point estimate as the average bootstrap value, coefficient of variation (%CV), and presented in-season as 95% confidence intervals expressed as the 2.5th and 97.5th percentiles. The CV of the total harvest by species in any given opener was generally 10%–30%, although strata with fewer interviews and low estimated harvest (often strata A and D1) sometimes had CV values exceeding 50% or even 80%.

2.3.4. Computation and reporting

Data analysis to produce harvest and effort estimates immediately following an opener has been conducted since 2016 using program R (R Core Team 2023). Further, the analysis and reporting of results has been coupled within reproducible Rmarkdown (Allaire et al. 2023) documents with output formatted as PDF files (see example in Appendix A of Staton 2021). Prior to the 2021 season, the workflow involved copying and editing code from a previous opener—this required that the analyst be familiar and comfortable with R programming. Starting in the 2021 season, a self-contained workflow was introduced with the R package ‘‘KuskoHarvEst’’ (Staton 2021, 2023*c*), which provides a series of interactive tools, accompanied by comprehensive documentation, that enable the user to perform estimation and reporting without the need to manually edit any code. Following each season, in-season estimates have been summarized and presented in season-wide reports (Table 2, ISMP column), and to facilitate inter-annual analyses (such as those presented

Table 2. Reports for the in-season and post-season harvest monitoring programs (ISMP and PSMP, respectively) documenting the sampling methods and results for each year in the analyses described in the text and supplements.

Year	ISMP[1]	PSMP
2016	Staton and Coggins (2016)	Lipka et al. (2019)
2017	Staton and Coggins (2017)	Lipka et al. (2021)
2018	Staton (2018)	McDevitt et al. (2020)
2019	Decossas (2019*b*)	McDevitt et al. (2021*a*)
2020	Decossas (2020)	McDevitt et al. (2021*b*)
2021	Russell et al. (2021)	McDevitt and Koster (2022)
2022	Bechtol and Schomogyi (2022)	Bembenic and Koster (2024)
2023	Bechtol et al. (2024)	*Unpublished*[2]

[1]Harvest and effort estimates presented here will differ slightly from those presented in the end-of-season reports as several features have evolved since the ISMP was initiated. Estimates presented here are from a complete re-analysis using consistent estimators and censoring methods.
[2]Preliminary 2023 PSMP data provided by D. Koster (Alaska Department of Fish and Game, Division of Subsistence).

herein), the data and estimates have been added to an additional R package (''KuskoHarvData''; Staton 2023*b*). All code and data not found in ''KuskoHarvData'' needed to reproduce the figures, tables, and in-text numerical results presented here can be found in Staton (2023*a*).

2.4. Validation analysis

2.4.1. Harvest validation

We "ground truth-ed" in-season (ISMP) harvest estimates with estimates that were based on household surveys as part of a long-term PSMP (e.g., McDevitt et al. 2020, 2021*a*, 2021*b*; McDevitt and Koster 2022; Bembenic and Koster 2024). The PSMP is coordinated by the ADF&G Division of Subsistence and provides annual basin- and season-wide estimates of harvest by community and species, as well as other information collected using rigorous census or random sampling (e.g., community-specific estimates of the number of fishing households, primary gear types, spoilage estimates; McDevitt and Koster 2022). Harvest estimates generated from the PSMP are used in the stock assessments that set basin-wide management goals (Hamazaki et al. 2012) and assess their attainment (Larson 2024) for Kuskokwim River Chinook salmon, making them the obvious choice for comparison when validating ISMP estimates.

This comparison could not be made without adjustment to either PSMP or ISMP estimates, as the two programs operate on different scales. Unlike the comprehensive PSMP, the ISMP is partial with respect to area, time, and gear types, so without adjustment, we should expect PSMP estimates to be greater in magnitude than ISMP estimates. Additionally, the PSMP estimates total harvest on a community-specific basis, whereas the ISMP estimates harvest by day across larger geographic areas, each containing multiple communities (i.e., geographic strata, Fig. 1). Thus, much of the validation analysis involved adjusting the PSMP estimates so that they were of a comparable scale to that monitored by the ISMP and could be apportioned to the same geographic strata as quantified by the ISMP. This was accomplished using a series of "corrections" to place PSMP estimates on the same scale as the ISMP with respect to the area (mainstem Kuskokwim River bounded by the communities of Tuntutuliak and Akiak), portion of the season (mid-June to mid-July), and gear (drift gillnets only). Correction factors were all based on empirical data and were year-specific to account for inter-annual variability in factors such as run timing, species composition, and fisheries management decisions (complete details in Supplement B). PSMP data have been finalized and published in ADF&G reports through 2022 (Table 2), but preliminary 2023 data were available for analysis (D. Koster, personal communication).

For comparison to ISMP estimates of total harvest by species ($\widehat{H}^{\mathrm{IS}}_{s,y}$) and its spatial breakdown ($\widehat{H}^{\mathrm{IS}}_{s,j,y}$), we obtained the corresponding corrected versions produced by the PSMP ($\widehat{H}^{\mathrm{PS}}_{s,y}$ and $\widehat{H}^{\mathrm{PS}}_{s,j,y}$; Supplement B). For each species, year, and geographic stratum, we obtained the mean percent error (MPE = (ISMP − PSMP)/PSMP ×100%), mean absolute percent error (MAPE = |ISMP − PSMP|/PSMP ×100%), and the Pearson's correlation coefficient (ρ). As an additional useful summary statistic, we calculated the fraction of the uncorrected PSMP harvest for the 11 overlapping communities that has been captured by the ISMP (i.e., $\widehat{H}^{\mathrm{PS}}_{s,y}/H^{\mathrm{PS}}_{s,y}$). This fraction may provide a simple means for expanding the partial harvest estimated by the ISMP to the scale of the PSMP in the future.

2.4.2. Effort validation

In place of independent observational data for validation, we used two types of simulation studies to test the reliability of the effort estimator used by the ISMP (eqs. 2 and 3, Supplement A). The first method considered only cases with two survey flights and generated data following the exact random processes assumed by the estimator, i.e., that

$$
\begin{aligned}
n\left(X_{f=1}\right) &\sim \text{Binomial}\left(\pi_{f=1}, N\right)\\
n\left(X_{f=2}\right) &\sim \text{Binomial}\left(\pi_{f=2}, N\right)\\
n\left(Y\right) &\sim \text{Binomial}\left(\psi, N\right)
\end{aligned}
\tag{6}
$$

We generated 1000 replicates of this random process for a fixed value of $N = 400$ total trips and various combinations of π_1, π_2, and ψ (Table 1); these sampling probability parameters took on values ranging from 0.1 to 0.9, with all pairwise combinations evaluated. Note that altering the parameters π_1, π_2, and ψ only affected the sample sizes ($n(X_1)$, $n(X_2)$, $n(Y)$, $n(X_1 \cap Y)$, $n(X_2 \cap Y)$, and $n(X_1 \cap X_2 \cap Y)$), and we did not simulate cases that violated model assumptions. We refer to this simulation method as the "simple simulation".

The second method, which we refer to as the "complex simulation", simulated an opener by drawing N replicates at random of (*a*) the start time of each trip, (*b*) the duration of each trip, and (*c*) whether each trip was interviewed. Each quantity had a range of times the outcome could occur within the day and an additional distribution that defined the relative probability that the event would occur at some given time within that range. As a result, this second method indirectly specified participation curves (i.e., the fraction of all trips N that were active at a given time of day) both for the true fishery and for only those trips that were interviewed and thus enabled evaluating the consequences of non-representative interview sampling. As part of this analysis, we wished to evaluate the effect of conducting 1, 2, or 3 flight(s) and their timing (early-, mid-, or late-opener) on the performance of the estimator in combination with perceived (via simulated interview data) timing curves that either were or were not representative of the true curve. This enabled quantifying whether additional well-timed flights could offset the effects of biased timing of interview sampling. Errors made by all estimates were expressed as the percent error in N (i.e., $\left(\widehat{N} - N\right)/N \times 100\%$) and were summarized using box plots across replicates within a given combination of simulation parameters.

3. Results

There have been 40 monitored drift gillnet openers between June and July in 2016–2023 (Tables SC1, SC2). These monitored openers accounted for nearly all such drift gillnet openers for which an estimate could have been produced; only three drift gillnet openers were "missed" due to weather impacts on safe flight conditions (24 June 2016, 24 June 2020, and 9 July 2021). The majority of monitored openers (80%) were 12 h in duration, whereas the remainder were either 6 (7.5%), 9 (2.5%), or 24 (10%) h in duration (Table SC1). An average of 4.3 days with no fishing elapsed between days with openers; 2016 was the only year in which drift gillnet openers occurred on consecutive days (16–17 June, 21–23 June, Table SC1).

3.1. Patterns in ISMP data collection

There were typically two flights flown per opener (65% of monitored openers); however, some openers had one (15%) or three (20%) flights flown. Most flights were estimated to have counted more than half of all drift gillnet trips that occurred in the opener (i.e., $\widehat{\pi}_f > 0.5$, Table SC2). Furthermore, the closely spaced nature of flights coupled with trips that often exceeded 4 h in duration resulted in high probabilities of a trip being counted on multiple flights. In the 12 June 2019 opener, for example, of the $n(Y_d) = 160$ interviewed trips, $n(X_{1,d} \cap Y_d) = 86$ reported being active during the first flight, $n(X_{2,d} \cap Y) = 110$ trips reported being active during the second flight, and $n(X_{1,d} \cap X_{2,d} \cap Y) = 55$ trips reported being active during both flights. This implies that only 50% of the $n(X_2) = 322$ trips counted on the second flight were not already accounted for by the $n(X_1) = 223$ trips counted on the first flight (Table SC2).

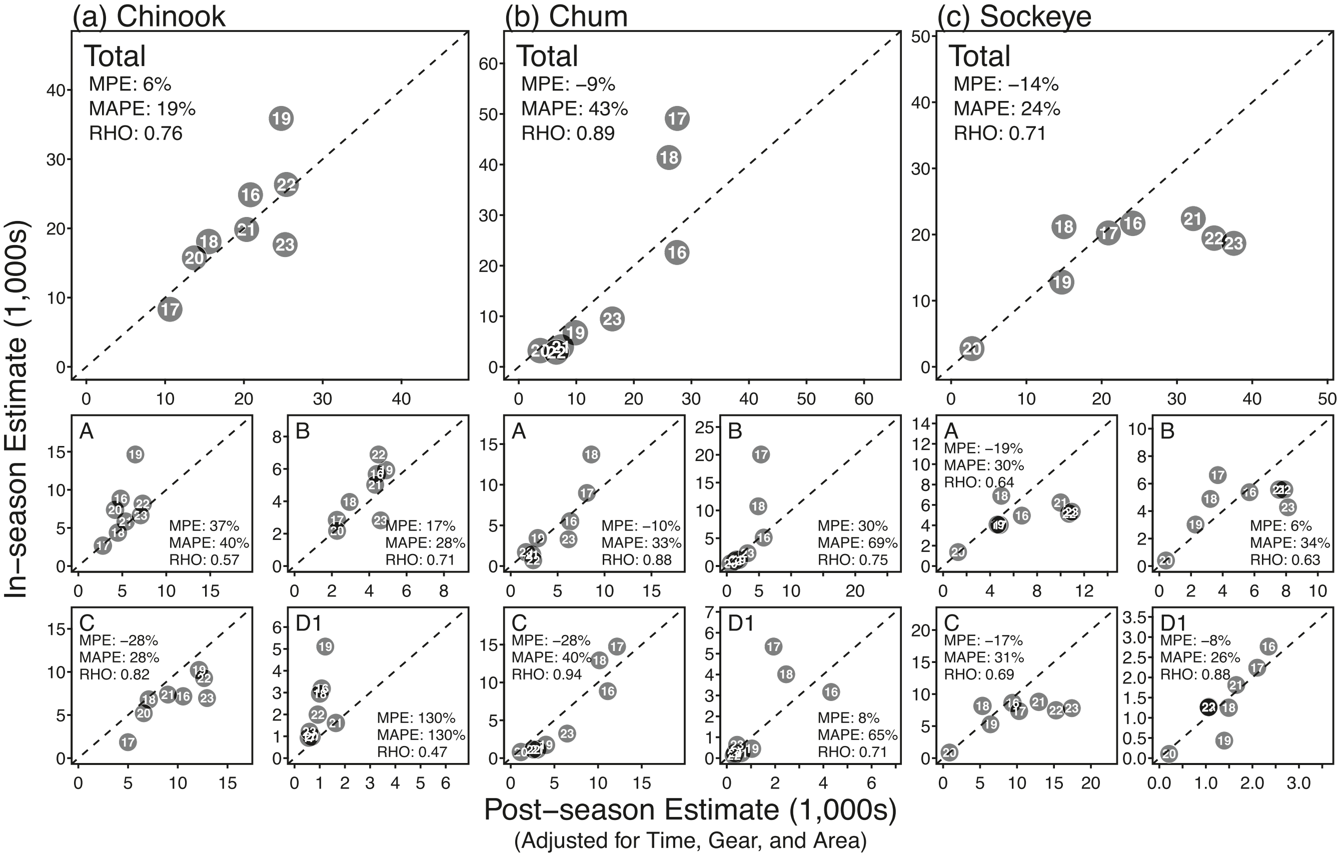
Comparing the values of $\widehat{\pi}_f$ to the participation timing curves implied by interview data provides an opportunity to assess the consistency of the two data sources as interpreted by the effort estimator (Fig. 2). Most openers had good agreement (i.e., points followed distributions; Fig. 2, indicating similarity in the relative proportion of all trips active at a given time); notable examples include 12 June 2017, 24 June 2017, 12 June 2019, and 22 June 2022. Not all openers had tight agreement, however, including the second flights on 12 June 2016, 16 June 2022, and 17 June 2023—in these more rare cases of disagreement, $\widehat{\pi}_f$ was greater than the interview data alone implied it should have been.

Based on the estimates of total effort ($\widehat{N}$), generally less than half of all drift gillnet trips were interviewed in a given opener ($\widehat{\psi}$), although this fraction has increased from <20% in 2016 to 30%–50% in recent years with the addition of more interviewers and greater fishery access point coverage (Table SC2). In 2016, only interviews conducted by ONC at the Bethel boat harbor and fish camps were available; however, more interviews have been gathered with greater spatial contrast with the initiation of the KRITFC-operated Community-Based Harvest Monitoring Program in 2017 (Table SB1). For the average opener since 2017 and considering only Bethel boat harbor and KRITFC interviews, 59% of interviews have been conducted at the Bethel boat harbor; although this fraction has ranged 41%–89% across all monitored openers, the standard deviation has been only 11%. This spatial distribution of interviews agreed well with the distribution of fishing households across communities within the ISMP study area reported by the PSMP (1795 of 2929 households 380 (61%) reside in Bethel; Bembenic and Koster 2024, Tables 1 and 2 therein). We highlight this even spatial representation of interview data because interviews conducted outside of the Bethel boat harbor reported soak times that averaged 1.65 times as long as those conducted at the Bethel boat harbor and salmon catches that were on average 1.8 times greater.

3.2. Patterns in ISMP estimates

The first drift gillnet opener of each year occurred on 12 June—set gillnet openers (not reported here) were announced prior to 12 June, but the 12 June openers provided fishers the first opportunity of the season to meaningfully target migrating salmon. At this point in the season, Chinook salmon are the predominant species running, and this was reflected by the catch rates estimated by the ISMP: Chinook salmon catch per trip averaged 8 across years (range: 4–14.6), whereas chum (average: 1.3; range: 0.1–4.6) and sockeye salmon (average: 0.9; range: 0.2–2.1) were several times lower (Table SC1). As the seasons progressed, however, these catch rates shifted towards being dominated by chum and sockeye salmon such that Chinook salmon made up an average of 11% of all catches in the 15 monitored openers that occurred after 23 June (compared to 65% in the 25 monitored openers prior to 23 June).

Fig. 3. Comparisons of harvest estimates by species and area generated by the in-season monitoring program (ISMP) (*y*-axis) and post-season monitoring program (PSMP) (*x*-axis). The ISMP estimates are the sum of all ISMP-monitored drift gillnet openers occurring in June–July 2016–2023. Larger panels show harvest across all areas within the ISMP study area for each species, and the smaller panels beneath each show spatially explicit comparisons based on each ISMP geographic stratum (Fig. 1). Since PSMP estimates are comprehensive and ISMP estimates are partial, PSMP estimates were adjusted to apply to the same timeframe, gear types, and geographic area as the ISMP to allow comparison (Supplement B).



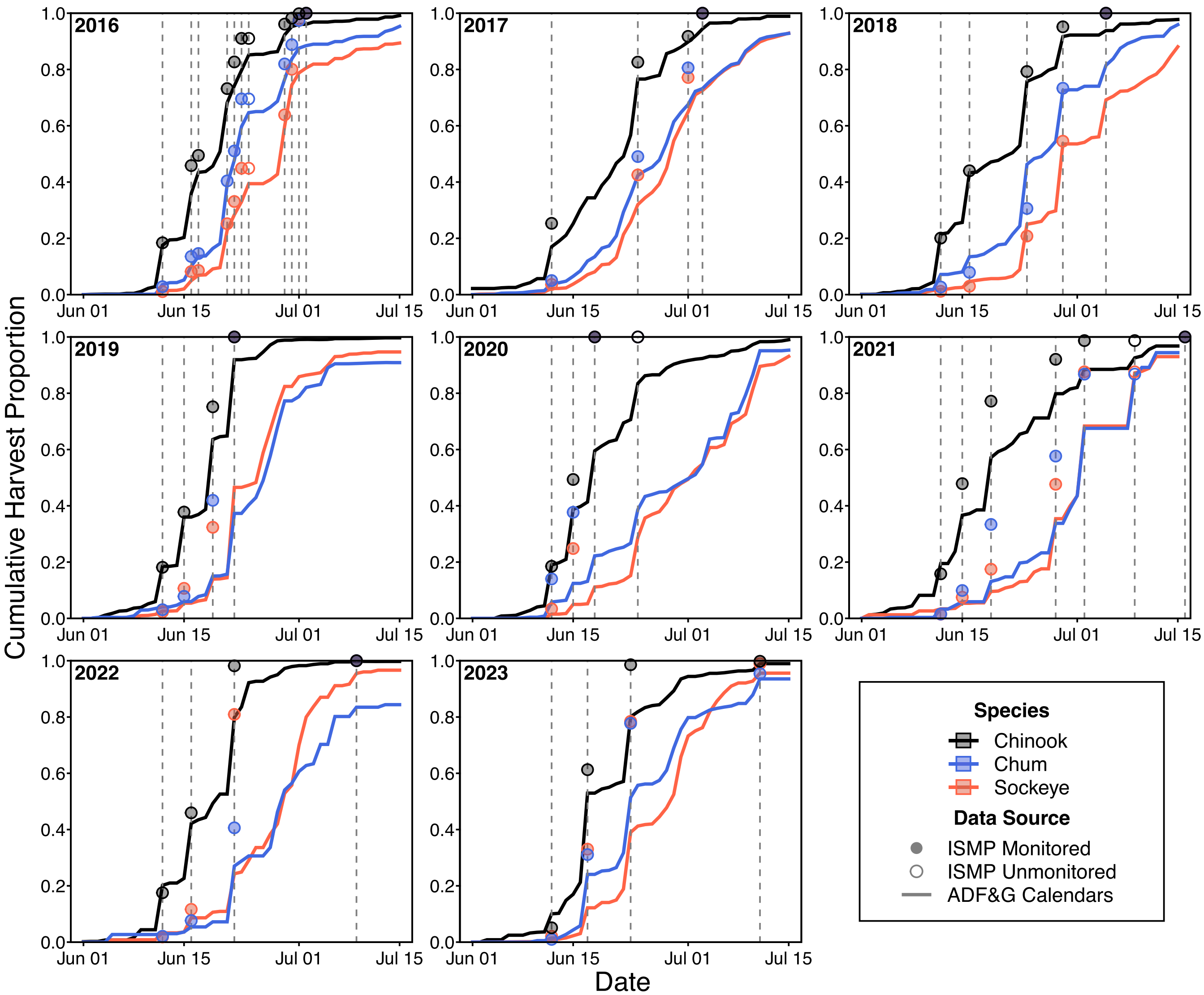
Although 23 June represents the approximate peak of the Chinook salmon return in most years (Hamazaki 2008), chum and sockeye salmon are more numerous and have a saturating effect for this fleet with limited processing capacity. Prior to 23 June, catch per trip of all salmon averaged 20.8 across years (range: 5.7–50.5) versus an average of 48.9 (range: 18.4–78.1) after 23 June.

Total salmon harvest estimated by the ISMP ranged from 21 698 in 2020 (three openers) to 80 662 in 2018 (five openers; Table SC1). The largest harvest of Chinook salmon occurred in 2019 (35 878; average of 18 682 in all other years), which coincided with the year of the largest Chinook salmon run by far across all years in the study period (219 771; average of 132 489 in all other years 2016–2023; Larson 2024). Excluding 2016, which had 10 monitored openers totaling 168 h of drift fishing and a total salmon harvest of 69 151, other years had an average of 4.3 (range: 3-6) monitored openers and 48.4 (range: 36–69) h per season. In post-2016 years, the fleet harvested an average of 1123 (range: 603–1849) salmon per hour of open fishing season-wide. The single opener with the highest salmon harvest per hour (4616) occurred on 29 June 2018 in which 387 drift gillnet trips were completed over the span of 6 h.

3.3. Validation of ISMP harvest estimates

Comparisons of season-wide harvest estimates to those from the PSMP (but adjusted to be of the same time-of-season, spatial areas, and gear type as the ISMP) revealed that in-season harvest estimation in June–July of 2016–2023 has performed reasonably well (Fig. 3). This is especially true of the estimates at the scale of the entire study area, where the correlation between ISMP and PSMP estimates was 0.76, 0.89, and 0.71 for Chinook, chum, and sockeye salmon, respectively. With only eight years of ISMP versus PSMP comparison, it is difficult to draw strong conclusions about systematic bias of the program; however, MPE for these species respectively was 6%, −9%, and −14%, implying that substantial directionality in errors is unlikely. Notable year/species combinations of less-than-ideal performance included: Chinook salmon in 2019 (ISMP overestimated harvest by 11 136; 45% of PSMP estimate), chum salmon in 2017 and 2018 (ISMP overestimated harvest by 21 568 and 15 288; 78% and 59% of PSMP estimate in 2017 and 2018, respectively), and sockeye salmon in 2023 (ISMP underestimated harvest by 18 880; 50% of PSMP estimate). At finer spatial scales, the ISMP tended to overestimate Chinook salmon harvest in strata A (MPE = 37%) and D1 (MPE = 130%), while underestimating harvest in stratum

Fig. 4. Cumulative proportion of season-wide harvest attained by date, year, and species. Data sources include estimates by Alaska Department of Fish and Game (ADF&G) subsistence harvest calendars (lines) and monitored drift gillnet openers from the in-season subsistence harvest monitoring program (ISMP; points). Estimates shown are aggregated spatially, unlike for the validation analysis, which used finer scale aggregations of community-level calendars. No chum or sockeye salmon were reported in 2017 calendar data, and the average of all other years was used in the validation analysis.



C (MPE = −28%); MPE values at the stratum level for chum and sockeye salmon were similar to those of the entire study area.

After limiting PSMP estimates to only the 11 communities within the ISMP study area, the correction for the time of the season covered by the ISMP was larger than the correction applied for gear types, since most of the harvest in the lower river is from drift gillnets, regardless of the time of the season. Harvest timing, as informed by ADF&G subsistence harvest calendars, tracked the timing of the openers such that major increases in the cumulative proportion harvested coincided with the dates of drift gillnet openers each year (Fig. 4). Further, the cumulative proportion of harvest accounted for by the ISMP tracked the timing suggested by ADF&G subsistence harvest calendars, although this was more true in some years (e.g., 2016 and 2018) than others (e.g., 2020 and 2021; Fig. 4). Additionally, the timing of Chinook salmon harvest tracked the timing suggested by ADF&G subsistence harvest calendars more closely than chum or sockeye salmon—this is likely because the monitored portion of the season encompasses nearly the entirety of the Chinook salmon run through the lower river, whereas much of the chum and sockeye runs pass after mid-July. When the ISMP and subsistence harvest calendars deviated, the ISMP proportions were higher at a given time of season than suggested by the calendars (Fig. 4)—this is because harvest between openers (e.g., in non-salmon spawning tributaries; Decossas 2019*a*) was not accounted for by the ISMP.

Relative to the comprehensive PSMP estimates for the 11 communities within the ISMP study area (i.e., without adjust-

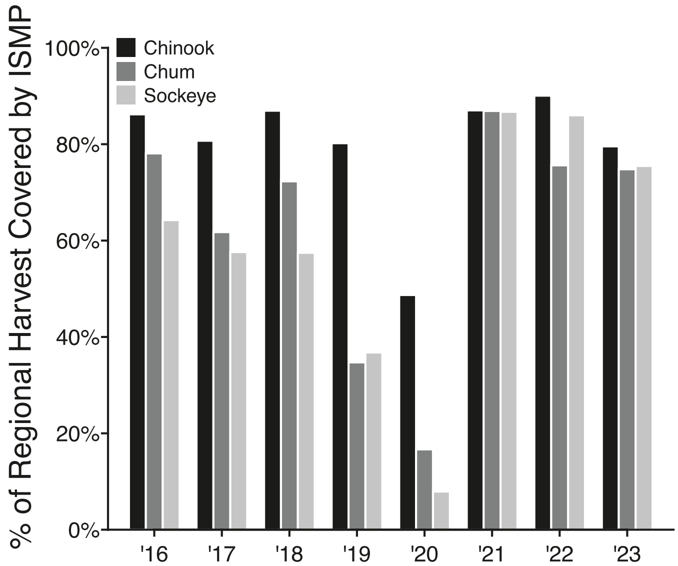


Fig. 5. Percent of the unadjusted post-season monitoring program (PSMP) estimate, which includes harvest from the entire year and all gear types for the 11 communities in the in-season monitoring program (ISMP) study area, that has been covered by in-season monitoring of drift gillnet openers in June–July 2016–2023.

ment for gear and time of season), the ISMP accounted for an average of 80%, 63%, and 59% of all harvest for Chinook, chum, and sockeye salmon, respectively (Fig. 5). This fraction fluctuated among years, although was quite stable for Chinook salmon (range: 49% in 2020 to 90% in 2022) and more variable for chum salmon (range: 17% in 2020 to 87% in 2021) and sockeye salmon (range: 8% in 2020 to 87% in 2021).

3.4. Evaluation of effort estimator via stochastic simulation

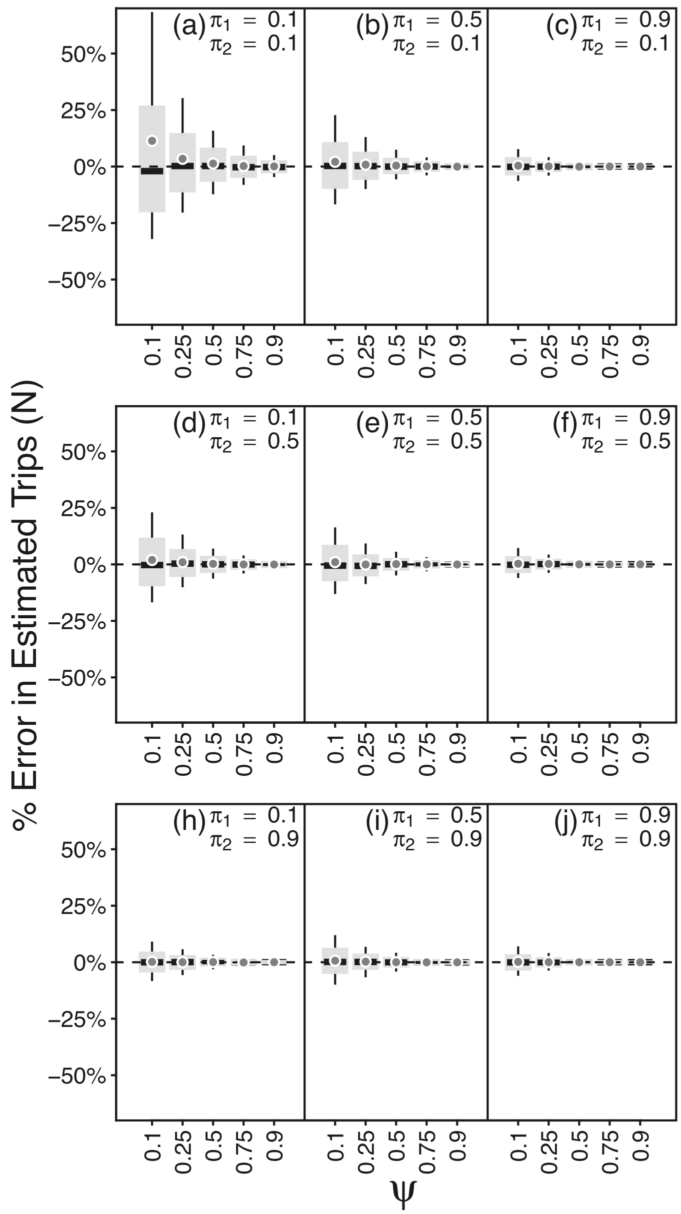
3.4.1. Simple simulation

The simple simulation showed that the effort estimator with two aerial surveys was unbiased based on median percent error for all combinations of ψ (fraction of trips interviewed) and π_1 and π_2 (fraction of trips counted on each flight), and was only biased based on the MPE in the case where all three sampling probabilities were equal to 0.1 (Fig. 6a). Only one opener (23 June 2016) came close to these sampling parameters ($\widehat{\pi}_1 = 0.11$, $\widehat{\pi}_2 = 0.33$, and $\widehat{\psi} = 0.11$, Table SC2). The majority of estimated sampling parameters from real openers had $\widehat{\pi}_1$ and $\widehat{\pi}_2 > 0.5$ and $\widehat{\psi} > 0.3$ (Table SC2), and the simple simulation suggested that under these conditions we can expect unbiased estimates and errors less than 25% (and often less than 10%) when performing two aerial surveys.

3.4.2. Complex simulation

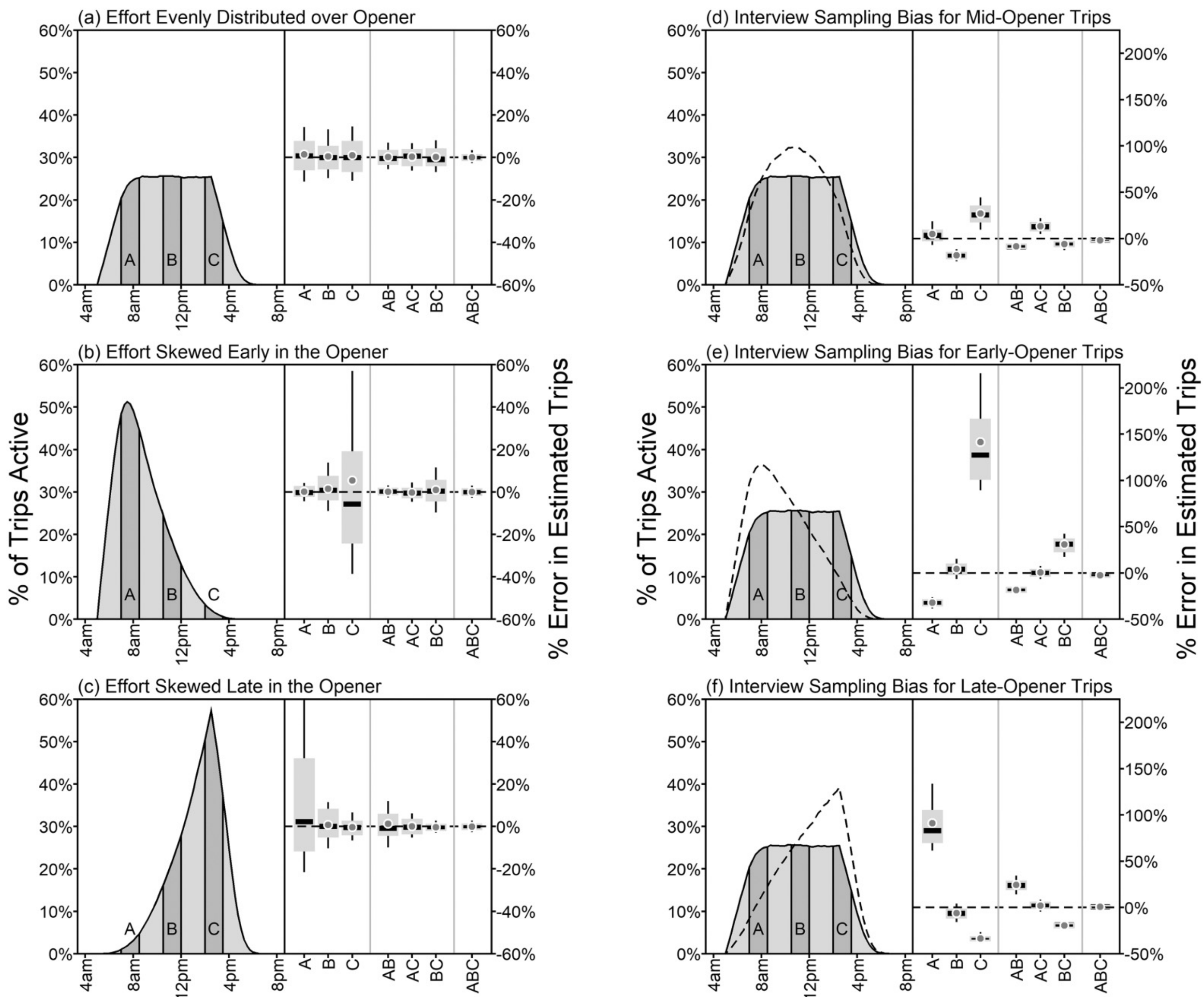
Unlike the simple simulation, the complex simulation allowed evaluating the effects of the number of flights con-

Fig. 6. Performance of the effort estimator based on the "simple simulation" showing errors from different combinations of the probability that a trip was counted on the first (π_1) or second (π_2) flight, or interviewed (ψ). Points represent the mean error; whiskers show the central 80% of errors, box shows the central 50% of errors, and the heavy line shows the median error.



ducted, their timing, and the consequences of biased timing of interview sampling. We evaluated six scenarios of interview timing coupled with fishery timing (Figs. 7a–7f), and within each scenario, we applied the effort estimator to all possible cases of one survey (flight A only, flight B only, or flight C only), two surveys (flights A and B (case AB), flights A and C (case AC), or flights B and C (case BC)), or three surveys (flights A, B, and C (case ABC)). For the scenarios with unbiased timing of interview sampling (Figs. 7a–7c), three flights performed the best with complete lack of bias and very high precision. For the scenario with a

Fig. 7. Performance of the effort estimator based the "complex simulation". Each panel (*a*–*f*) shows a type of opener based on the true (gray distributions) and interviewed (dashed distributions) participation timing curves. Panels *a*–*c* and *d*–*f* show timing of interviews that are unbiased or biased, respectively, relative to true participation timing. Striped regions show the timing of flights that could be conducted (labeled A, B, and C) and boxplots show the distribution of errors from 100 simulation replicates of combinations of these flights (e.g., A = flight A only; BC = both flights B and C conducted). Whiskers show the central 80% of errors, boxes show the central 50%, heavy line shows the median, and points show the mean. Note the different *y*-axis limits for panels *a*–*c* versus *d*–*f*.



uniform fishery participation curve and unbiased interview sampling (Fig. 7*a*), two flights gave better precision than one flight, regardless of which flights were selected (cases AB, AC, and BC all performed equally well); similarly, all single flight cases (A, B, or C) performed equally well (Fig. 7*a*). When the fishery participation curve was skewed early (Fig. 7*b*), however, cases that included the earliest flight (flight A) performed better than cases that excluded it, to such a degree that the single flight case A had higher precision than even the two flight case BC, and the three flight case ABC had negligible gains in precision over the one flight case A and two flight cases AB and AC. Similar patterns resulted for the scenario with participation skewed late in the opener (Fig. 7*c*), but with greater performance in cases that involved the latest flight of the day (cases C, AC, BC, and ABC). Scenarios with skewed participation and one flight conducted with opposite timing to the skew showed the potential for bias (Figs. 7*b* and 7*c*), even with representative interview timing.

In contrast to the three scenarios described above, those shown in Figs. 7*d*–7*f* show cases in which timing of interview sampling was ill-performed such that the perceived timing curve was biased relative to the true curve (truly uniform participation curve in all three scenarios, as in Fig. 7*a*). With interview timing biased towards mid-opener trips (Fig. 7*d*), biases in effort estimates were moderate (±~25%), but the directionality depended on which flights were conducted. For example, in the single flight case B of Fig. 7*d*, the interview data suggested that the flight counted a larger fraction of the total trips than it truly did, which implies that the expansion of the observed count was less than needed to accurately estimate the total trips. Much larger biases (>100%–150%) occurred in scenarios wherein the perceived timing curve was skewed early (Fig. 7*e*) or late (Fig. 7*f*) and a single flight was conducted opposite to the skew. Consider the early skew scenario (Fig. 7*e*) coupled with a single late flight (flight C)—interview data suggested that only ∼10% of the trips were active at the time of the flight (truly ∼25%), resulting in large positive bias. Conversely, negative biases were found when the flight timing coincided with the skewness in interview timing bias (e.g., Fig. 7*f*, case of single flight C). Biases were of similar directionality when two flights occurred, although the magnitude was lower (Figs. 7*e*–7*f*, cases AB, AC, BC). Across all three scenarios with biased interview sample timing, the three-flight case (ABC) showed negligible bias.

4. Discussion

We developed an in-season harvest and effort monitoring program in response to the recent application of the emergency order management strategy to subsistence fisheries in the lower Kuskokwim River. We believe accurate and timely in-season estimates of harvest are crucial to successful management of Chinook salmon during years of reduced run size and such information was not available to managers prior to development of this program. By combining on-the-ground fisher interviews that quantify trip-level characteristics and participation times with aerial surveys of instantaneous total participation, we have estimated both harvest and effort arising from short-duration openers over this large and remote area from 2016 to 2023. Our application of consistent analytical methods to the re-analysis of all in-season drift gillnet harvest data facilitated some generalizations and inter-annual summaries, which will likely be useful to fishery managers on their own (e.g., patterns and variability in outcomes from 12 h openers on 12 June each year). Further, following our comparison of year-total in-season estimates with time-, area-, and gear-adjusted post-season estimates, we found that in-season estimates were not only highly correlated (>0.7) at the annual/study area scale with rigorous post-season estimates, but also that differences did not show concerning levels of directionality. Our simulation evaluations revealed that the effort estimator is relatively robust to low sample sizes collected via representative sampling (introduced by, e.g., poor flight timing but good interview coverage), and that biases introduced by non-representative timing of interviews can be largely corrected for by conducting multiple flights during the opener.

4.1. Validity of estimates

The ISMP was not designed to give exact values of harvest (nor do our simple corrections to post-season estimates ensure 1:1 comparisons) but rather to provide more quantitative information on an aggregate scale than was previously available for in-season management consideration. With eight consecutive years of operation, we felt that it was prudent and possible to evaluate the validity of the estimates generated by the ISMP. Although estimates have been considered by managers in each year since the program's inception, the absence of a formal validation has left opportunity for doubts in the reliability of the estimates it has produced. Although our harvest validation analysis did not enable an opener-by-opener evaluation, we found that estimates totaled by season across all monitored openers agreed reasonably well with the values estimated by the more rigorous PSMP (after correction of the PSMP census scale to the ISMP partial scale, Supplement B). These findings should instill confidence that the estimates produced by the program are of sufficient validity to meet the original intent. However, there are additional lines of evidence that have led us to conclude that interview and aerial survey sampling has been conducted in a manner that facilitates reliable estimates.

The first line of additional evidence is the broad consistency with the estimated fraction of trips counted on each flight ($\widehat{\pi}_f$) and the participation curve implied by completed trip interviews (Fig. 2). Although the magnitude of $\widehat{\pi}_f$ is informed by the joint analysis of interviews and flight counts, the relative change between $\widehat{\pi}_f$ and $\widehat{\pi}_{f+1}$ came solely from the flight counts (via eq. SA15). Given the independence in the collection of interview and flight data, similar rates of change in $\widehat{\pi}_f$ and the interviewed timing curve provide evidence of representative interview sampling. In the relatively rare cases of large deviations of $\widehat{\pi}_f$ from the interviewed participation curve, aerial surveys counted a larger fraction of the total trips than the interview data implied were active at that time. The directionality of these discrepancies could be at least partially attributed to one (or both) of two causes: (*a*) interview sampling preferentially sampled trips that ended earlier and missed trips that ended later in the opener or (*b*) some portion of the boats counted via aerial survey were non-fishing traffic (recall that all boats were counted and presumed to be engaging in drift fishing, including those actively fishing and those in transit). These causes could perhaps be corrected for by maintaining interviewer presence at access points later after the conclusion of the opener and maintaining records of boats returning to access points that were not fishing.

Second, following 2016 when only ONC interviews were available, the spatial representation of interviews has been largely consistent with the distribution of known fishing households as reported by ADF&G post-season monitoring (e.g., Bembenic and Koster 2024), at least with respect to Bethel versus non-Bethel area fishers. We reported that fishing behavior is systematically different in the outlying communities compared to Bethel, with the former actively fishing for longer periods of time and harvesting more fish per trip (also recently documented in Bechtol and Schomogyi 2022). Because of these spatial differences in fisher behavior, reasonably proportionate representation of Bethel versus non-Bethel fishers is key to the success of the in-season program—oversampling Bethel fishers (which would be easy to do, given their proximity to institutional offices, high concentration, and frequent transit between Bethel area fish camps and the boat harbor) would underestimate harvest.

This reality was also highlighted by Runfola and Koster (2019) as a potential concern with the ISMP described herein. That approximately an equal proportion of both in-season interviews were conducted in, and fishing households reside in, the Bethel area gives us confidence that spatial representation is not a major issue for the ISMP.

Third, openers were sufficiently short enough to lend support to the assumptions surrounding randomness and independence of sampling, even without a rigorous random or stratified random sampling design. The short duration (most frequently 12 h) has allowed multiple, relatively closely spaced aerial surveys and for interviewers to be placed at various fishery access points for much of the opener. These two aspects of the current opener structure have prevented the need to develop a rigorous random sampling design. Our thinking is that because the sampling was quite spatiotemporally complete ($\widehat{\pi}_f$ often >0.5, $\widehat{\psi}$ often >0.4), it was reasonable to assume that the samples were representative of both the sampled and unsampled fisher populations.

4.2. Additional benefits of in-season harvest monitoring in subsistence fisheries

Beyond the immediate utility of producing quantitative estimates of outcomes from a given opener, additional benefits of in-season harvest monitoring may exist for fisheries managers and the participating communities. The wealth of information gathered may prove useful for predicting outcomes of openers that have not yet occurred. Although a comprehensive description of this ongoing research is beyond the scope of this article, preliminary results indicate that relatively simple regression analyses using time-of-season and fishery-independent indices as predictor variables can produce reasonable out-of-sample predictions of fishery effort, catch rate, and species composition. These relationships show promise for aiding managers by reducing uncertainty in the outcomes of proposed openers, assuming that run conditions are consistent with years the models have been fitted to.

Further, it is possible that in-season catch data contain information that could be used to inform real-time models of run abundance. These models (e.g., Hyun et al. 2005; Michielsens and Cave 2018; Staton and Catalano 2019) integrate multiple sources of information, such as pre-season forecasts and in-season fishery-independent indices, to provide a perception of the total run size for the season, its composition (perhaps in terms of species, subpopulation, or age), and how much of the run is complete as of a given date. It is possible that fishery-dependent indices could be developed from the catch data collected by in-season subsistence harvest monitoring programs to supplement the information used by these models. Further, even if not used directly to index run abundance, harvest estimates may be used indirectly to supplement other in-season run estimates, for example, to account for fish that would have passed a sonar project had they not been harvested downstream. Beyond informing in-season management and perceptions of run size, interviewing fishers upon the conclusion of their trip also serves as a good opportunity to sample the catch for biological data needed for long-term population assessments, such as age, sex, length, and genetic tissue.

In addition to these quantitative uses of in-season harvest monitoring in subsistence fisheries, there may be more place-based benefits. The ISMP provides seasonal employment opportunities to local residents and has exposed youth to Kuskokwim area fisheries management and assessment projects. Engagement of locals in fisheries monitoring activities can contribute to building “social capital” as community awareness of fisheries-related issues increases, and existing institutions (e.g., tribal governments) and new social networks are strengthened (Bliss et al. 2001). The program also fosters understanding and trust among tribal councils, community members, and state and federal management entities through the exchange of information (Inman et al. 2021). The ISMP has also enabled local tribal governing bodies to carry out a large portion of this work in their tribal territory, thus fostering a sense of empowerment and self-determination. Local involvement in data collection is also important for local ownership and knowledge about the effectiveness of fisheries management (Oviedo and Bursztyn 2017). Finally, the ISMP allows for local input in fisheries management and has been recognized as an effective communication tool.

4.3. Future of in-season harvest monitoring in subsistence fisheries

It is reasonable to conclude that the methodology presented here for estimating harvest and effort will continue to be effective when applied to years, and even other systems, similar as those experienced in the lower Kuskokwim River subsistence fishery 2016–2023 (i.e., relatively few openers and each short in duration). The pilot studies of Runfola and Koster (2019) and Brown and Jallen (2019) are the only other attempts at producing quantitative in-season harvest estimates of subsistence salmon harvest of which we are aware, and both suffered issues of sample size and data quality. However, Brown and Jallen (2019) indicated a desire for a single harvest monitoring program that can both provide rapid in-season information and comprehensive post-season information. While we see this as a worthwhile endeavor, we believe that an advantage of our approach is its focus on rapid assessment and reporting of single openers rather than meticulous accounting of all harvest. That is, ideally a single program could exist, but we think it would be very difficult to execute while retaining the benefits of both separate programs.

We acknowledge that the analytical approach we developed is data-intensive, which is why a devoted sampling program was required to implement it. This aspect makes it difficult to envision how it could be supplied with data from existing sampling programs elsewhere to provide useful results. However, our work shows that an in-season subsistence harvest monitoring program such as the one we describe *can* be initiated, despite the formidable challenges faced (i.e., large remote area, rapid reporting needed, costs) and comparative non-success found by similar attempts. It is our hope that future attempts at developing in-season subsistence harvest monitoring programs may benefit from our work as something of a template.

There is much about the approach that could be adapted for other, perhaps more data-limited, cases. First, aerial surveys were the most efficient method to obtain counts of instantaneous participation in our case; however, less expensive methods could be used for fisheries occurring over a smaller area (e.g., boat-based surveys) or with fewer fishery access points (e.g., boat ramp parking lot trailer counts)—these methods are unlikely to work in rural western Alaska for a variety of reasons, but may be effective in smaller, less remote systems. Second, if effort surveys are too cumbersome or expensive to conduct with the desired frequency necessary for complete coverage, it is possible that they could instead be conducted only periodically after developing relationships between interview sample size and interviewing effort. Third, the geographic stratification could be simplified or removed for fisheries occurring over a smaller area that lack spatial heterogeneity in fishing conditions; this (necessary) complexity in our analysis essentially reduced the information content of each interview. Fourth, the calculations involved in estimation are quite simple (with the exception of the bootstrap) and can be accomplished with spreadsheet software; the use of a devoted R package (i.e., ''KuskoHarvEst''; Staton 2023*c*) has emerged as the project matured and has provided analytical consistency and sustainability (e.g., user-friendly workflows and automated report generation), but would not be necessary in new applications. Fifth, the specific effort estimator we derive in Supplement A and present in eq. 3 could be replaced with estimators more appropriate for a different case, perhaps that make fewer assumptions or require less data.

Further, so far as we are aware, the estimator for the multiflight case (eq. 3) is novel and we believe warrants further exploration for improvements and potential use cases. For example, finer scale stratification of survey counts (i.e., at the scale of $n(X_{f,j,d})$) and time stamps (e.g., $F^{\text{start}}_{f,j,d}$, $F^{\text{end}}_{f,j,d}$) could be coupled with similarly stratified interview data to add resolution and account for spatial heterogeneity in active fishing times. Although possible in theory, we did not derive variance estimators for $\widehat{N}$; our reasoning has been that the bootstrap could be used if desired; however, we have not yet evaluated this. Another interesting idea for the effort estimator would be to integrate the data from multiple openers and fit the model hierarchically, such that the parameters π_f and ψ are modeled as logit-linear functions of opener- and flight-level covariates; our derivations in Supplement A already provide the probability model for linkage of these parameters to observed count data. Finally, in Supplement A, we highlight an analogy between the two-sample mark–recapture estimator for closed populations (Seber 1986) and the single-flight effort estimator: view the survey flight as the marking period and the interviewing process as an interrogation period. Extending to multiple flights, the analogy breaks down (multiple marking periods in which it is impossible to interrogate for already marked individuals, and interrogation occurs continuously); however there may well be applications of this estimator—perhaps even outside of fisheries science—that we have not yet thought of.

An important consideration that will be faced by this and similar in-season harvest monitoring programs is the difficulties brought by longer and more frequent openers, as could occur if abundances of returning salmon increase from their current depressed status. This is a scenario the current sampling program is not designed for—unlike for a 12 h opener, it is unrealistic to maintain near-continuous interview sampling at multiple access sites for the majority of multiple long openers that occur over consecutive days. The longer and more frequent openers become, the more difficult it will be to justify the assumption of random sampling with current ISMP sampling, staffing, and financial regimes.

There are several aspects of longer and more frequent openers that would make the current sampling design inappropriate. First, longer open periods will almost certainly reduce fisher density at access points (i.e., fewer prospective interviewees per unit surveyed time) because fishers could allocate their time fishing when they see fit, rather than needing to funnel into specific allowed times. In seasons after 2016, interview coverage ($\widehat{\psi}$) was estimated to be approximately 50%; however, with longer openers, it seems that fewer interviews would be obtained without large increases in interviewing efforts. Similar to the issues created by low sample sizes for other in-season harvest monitoring efforts (Runfola and Koster 2019), this would reduce the representativeness of interviews, potentially introducing bias and almost certainly affecting precision. Second, because the whole entire period cannot be sampled, considerations about when and where to sample most frequently would become important. It is standard practice in creel surveys to place more sampling effort on the portion of the fishery where most fishing effort occurs (e.g., weekends vs. weekdays; Bernard et al. 1998). Something similar could be developed for the lower Kuskokwim River (or similar) subsistence salmon fisheries, but ensuring appropriate weighting would be difficult. Third, aerial surveys are resource-intensive, and the USFWS aircraft are in high demand for other flight missions in summers, so they would likely need a similar subsampling design—this could require substantial alterations to the effort estimator and careful considerations about the timing of interviews to maintain the independence assumption. The model developed for the complex simulation presented herein could be adapted (e.g., adding harvest as well as effort dynamics, spatial heterogeneity, etc.) for use in testing different strategies for this endeavor.

While these considerations present formidable barriers, they do not seem impassable with directed development efforts should in-season harvest monitoring be desired in years with less restrictive harvest. However, in this case, managers should consider carefully whether in-season harvest estimates are truly necessary. The primary utility of in-season harvest estimates is to track the cumulative harvest towards the attainment of a season-wide harvest limit. Because subsistence fisheries have internal limits resulting from household needs and processing/storage capacity (Esquible et al. 2024), they will require fewer restrictions in larger runs than commercial fisheries. In fact, there may again be run sizes large enough such that the season-wide harvest limit implied by management objectives is greater than this cultural limit. As a result, the value of real-time harvest information to successful in-season management of subsistence salmon fisheries—to the extent that it is used primarily for tracking attainment of a harvest limit—will likely decline with fewer harvest restrictions. This perhaps implies that in-season harvest monitoring could be conducted with less intensity (or forgone entirely) in years of larger runs and implemented with more complete coverage only in years of conservation concern where the in-season need is greatest.

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Data availability

Raw data and estimates generated by the ISMP are accessible from the R package "KuskoHarvData" (Staton 2023*b*); estimates were produced using the R package "KuskoHarvEst" (Staton 2023*c*). Organized and annotated code with descriptions and instructions to reproduce all figures and tables is archived at Staton (2023*a*).

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Competing interests

The authors declare no competing interests.

Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/cjfas-2023-0369.

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