GENERALIZING THE CREEL SURVEY-BASED CATCH ESTIMATION METHODOLOGY FOR RECREATIONAL AND FIRST NATIONS FOOD, SOCIAL AND CEREMONIAL FISHERIES IN THE SOUTHERN PACIFIC REGION

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By

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Subscripts

d	Day Type (weekday or weekend/holiday; subscript omitted in formulas for clarity)
i	Fisher (represents either an individual person or a boat)
j	Day of Instantaneous Count
k	Stint
s	Site (Fishing Site, Access Point, or Index Area)
t	Fishing Time Block
τ	Count Time block
η	Day of Temporal Count (used in visual-count-based ICE calculation)

Variables

A_{tks}	Expanded activity at Fishing Time Block t based on Temporal Count data collected during Stint k at Site s
B_j	Number of fishers counted during an Instantaneous Count on day j
C_i	Catch reported by interviewed fisher i (used in CPUE calculation)
E	Mean Daily Effort
$F_{t\tau ks}$	Activity recorded from fishers surveyed during Count Time Block τ, Stint k, at Site s, specific to Fishing Time Block t
F_{tks}	Activity recorded from fishers surveyed during Count Time Block τ, Stint k, at Site s, across all Fishing Time Blocks
H_i	Effort reported by interviewed fisher i (used in CPUE calculation)
$H_{day(\eta)t}$	Observed Rod-Hours or Gear-Hours during a visual count on a day η at Fishing Time Block t (used in visual-count-based ICE calculation)
I	Number of fishing interviews conducted for CPUE calculation
$I_{\tau ks}$	Number of people or boats interviewed during Count Time Block τ, Stint k, at Site s
$L_{\tau ks}$	Total number of people or boats present during Count Time Block τ, Stint k, at Site s, regardless of whether they were interviewed
m	Number of days with Temporal Counts used in ICE calculation
n	Number of days with Instantaneous Counts used in Mean Daily Effort calculation
N	Total number of days of the same Day Type in the Estimation Period
R	Calculated ratio or ratio estimator (context-dependent)
$S_{day(\eta)t}$	Scaled Temporal Count calculated when Effort Scaling is applied (used in visual-count-based ICE calculation)
T_{ks}	Total expanded activity based on Temporal Count data collected during Stint k at Site s
$W1_{\tau s}$	Weighting factor accounting for differences in the number of days each Count Time Block τ was sampled at Site s
$W2_{\tau ks}$	Weighting factor accounting for missed interviews during Count Time Block τ, Stint k, at Site s (used in interview-based ICE calculation)
$Z_{t\pm x}$	Tail calculated when interview data are used to supplement visual counts (used in visual-count-based ICE calculation)

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1 INTRODUCTION

Catch estimation is a critical component of sustainable fisheries management in the Pacific Region of Canada. Accurate estimates support resource management and conservation objectives by informing decisions such as fishery openings and closures and contributing to population assessments (e.g., run reconstruction) for key species.

This report consolidates and clearly communicates the methodology used in creel survey-based catch estimation in recreational and First Nations Food, Social, and Ceremonial (FSC) fisheries within the Pacific Region. The focus is on two Fisheries and Oceans Canada (DFO) Administrative Areas: South Coast (SCA) and Fraser and Interior (FIA).

The Pacific Region encompasses diverse non-commercial fisheries, each with unique characteristics that influence catch estimation approaches. These fisheries vary widely in scale, geographic distribution, and fishing practices. Recreational fisheries often involve dispersed effort across large areas, while FSC fisheries may follow traditional harvest patterns that differ from recreational norms. This diversity complicates the application of standardized sampling methods and requires flexible approaches tailored to each fishery's characteristics.

Key species addressed in this report include Sockeye Salmon (*Onchorhynchus nerka*), Chinook Salmon (*Onchorhynchus tshawytscha*), and Pacific Halibut (*Hippoglossus stenolepsis*).

Catch estimation in these fisheries is primarily conducted through creel surveys, which sample a representative portion of the fishery and extrapolate results to estimate total catch and effort. The term "creel survey" originates from surveys in which interviewers counted the fish in fishers' "creel baskets" (woven baskets used to carry kept fish) and recorded trip details. In modern times in the Pacific Region, a creel survey has evolved to include a combination of fisher interviews and visual counts, collecting information on kept and released catch, fishing effort, location, gear type, and sometimes fishing methods. These data form the basis for statistical estimation of total catch.

All creel survey-based catch estimation in the Pacific Region relies on a common conceptual framework. At its core is a relationship between catch and effort, expressed through the general equation (Eq. 1):

$$Total\ Catch = Total\ \ Effort \times CPUE \tag{1}$$

where CPUE is the Catch Per Unit Effort. While this equation underpins all creel survey approaches, its implementation varies across fisheries. Some differences arise from inherent variations in fishery characteristics and sampling methods, while others are a by-product of legacy factors such as older documentation, software systems, and independent development of similar methodologies. These inconsistencies are further obscured by variations in terminology within the Pacific Region, making cross-fishery comparisons challenging.

This report is part of a broader initiative to unify data management and analytical approaches for creel surveys of recreational and FSC fisheries in the Pacific Region through a project called KREST (Kept and Released Estimation Survey Tool). KREST is envisioned as a centralized database system that will store raw catch data and derived catch estimates for the Pacific Region. In addition to data storage, KREST will include an analytical component that will allow users to estimate fish catch based on the raw data. This represents a significant undertaking by DFO and is currently being developed as a pilot project, with potential for expansion to other Regions.

Within this report, we describe the methods currently employed in the SCA and FIA Administrative Areas, consolidate the methods where feasible, and propose improvements to existing methods. The methods described in this document build on previous documents by Ma et al. 2012a, English et al. 2002, Ma et al. 2012b, and DPA 1985. Section 2 begins with a conceptual introduction to catch estimation using creel survey data, followed by an overview of the spatial context, and key definitions. Section 3 provides greater detail on how the key components of the Total Catch estimate, namely CPUE and Total Effort, are calculated, including variance estimation for each component. Finally, Section 4 outlines the minimum data requirements necessary to produce reliable estimates of CPUE, Total Effort, and Total Catch.

2 METHODS OVERVIEW

2.1 Estimating Total Catch

This section provides a high-level overview of the steps involved in estimating catch from creel survey data (Figure 1). A number of important terms are introduced here and the spatial and temporal aspects of the analyses are described.

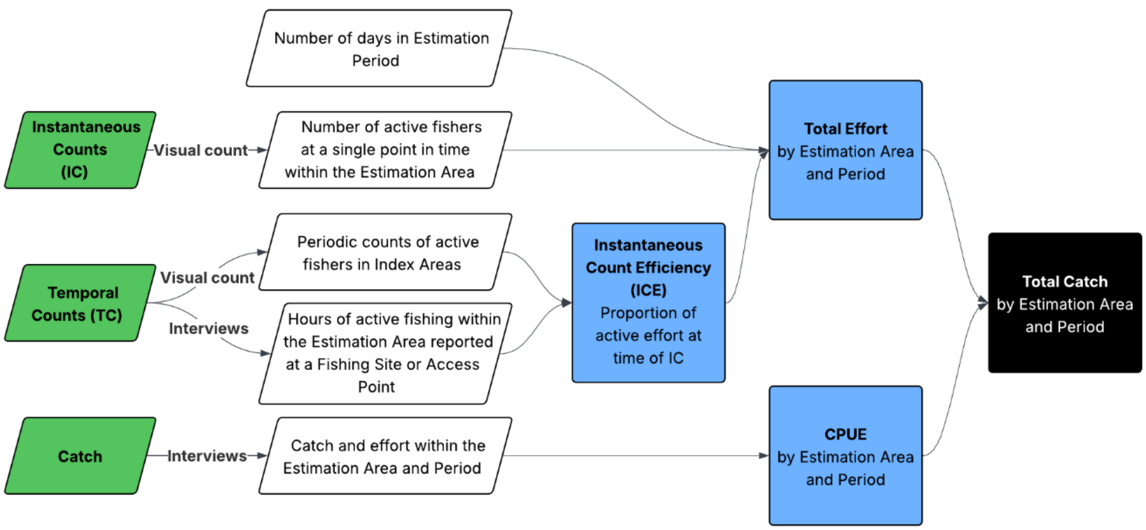

Figure 1: Schematic illustrating the collection of creel survey data (green) and how it is used to produce ICE, Total Effort, and CPUE estimates (blue), and ultimately Total Catch (black).

Basic spatial and temporal units for estimating catch are Estimation Area and Estimation Period. **Estimation Area** (Figure 2) is a stratum in a spatial stratification of fishing grounds in the Pacific Region. The Estimation Areas are established based on several factors including fishing patterns and regulations, as well as alignment with boundaries of Pacific Fishery Management Areas (PFMAs) in tidal waters and provincial or territorial management units in non-tidal waters. They tend to remain relatively constant across years. **Estimation Period** refers to the time span of the estimate. Its selection may reflect management needs, such as fishery monitoring, fishery openings, or changes in fishery regulations, as well as practical constraints such as the cost of obtaining sufficient sample sizes within each period.

Surveys within an Estimation Area and Estimation Period are conducted through visual counts and interviews at various Sites (Figure 2). A **Site** may refer to: A Fishing Site, an Access Point, or an Index Area. A Fishing Site is a location where fishing occurs; it may be sampled through interviews, visual counts, or not sampled at all. An Access Point is a location where fishers completing trips can be intercepted for interviews, such as a boat launch, marina, trailhead, or parking lot. An Index Area is a defined portion of the Estimation Area assumed to have a daily effort distribution representative of the entire Estimation Area.

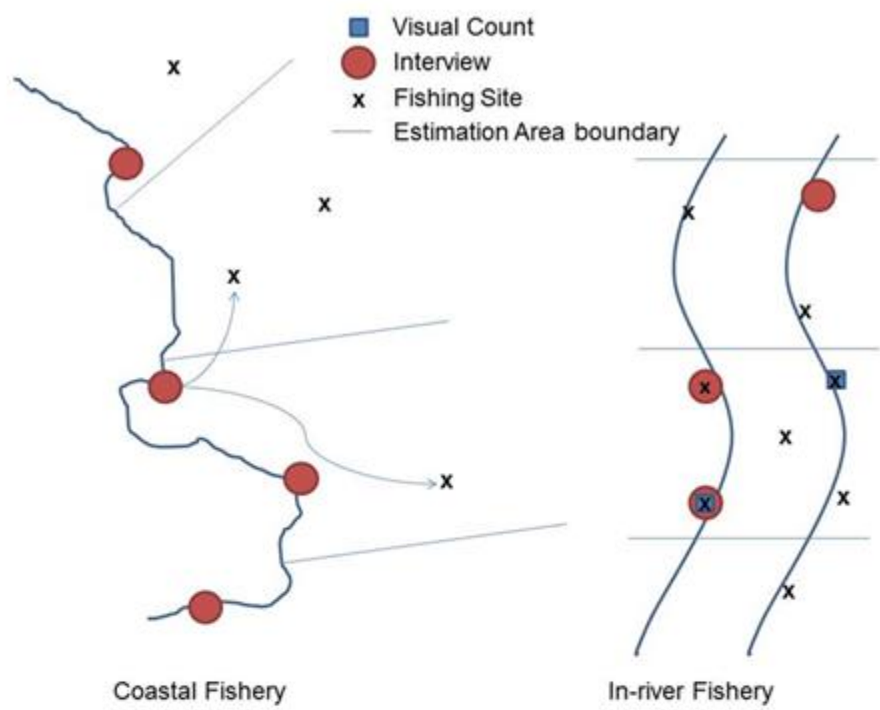

Figure 2: Illustration of the spatial components described in the methods. Visual counts (for Temporal Count data) are conducted within Index Areas. Interviews (for catch and Temporal Count data) are conducted at Fishing Sites or Access Points. Blue arrows indicate that fishing trips may originate from Access Points. Straight blue lines indicate boundaries between Estimation Areas.

Calculations are normally stratified by Day Type, meaning separate catch estimates are developed for weekdays and weekends (including holidays) within the Estimation Period and then summed to estimate the total catch in the Estimation Period. This stratified approach is used to avoid possible biases that could result when hourly fishing patterns or CPUEs differ by Day Type. Hourly fishing patterns would differ by Day Type for example due to work obligations affecting the hours working fishers can fish; thus, especially on weekdays, effort could increase in the late afternoon as many fishers are finishing work. Possible reasons why CPUE may vary by Day Type include differences in fisher skill and trip duration between the two Day Types, as well as differences in catchability by time of day combined with variation in hourly fishing patterns. By stratifying by Day Type, we avoid potential bias that could arise if such differences exist and sampling rates differ by Day Type.

Total Catch in an Estimation Area and Period is estimated as the product of CPUE and Total Effort (Eq. 1) for that Estimation Area and Period. **CPUE** is based on observed or reported catch by species in an Estimation Area obtained during fisher interviews, along with the number of effort units (Trips or Hours) that were reported. **Total Effort** refers to the expanded number of effort units within the Estimation Period. Since it is practically impossible to count all fishing trips or hours across every hour of every day in an Estimation Period, Total Effort is estimated based on a sample of trips or hours and a sample of days. It is estimated by adjusting Instantaneous Counts on a sample of days within the Estimation Period using an Instantaneous Count Efficiency (ICE) derived from Temporal Counts, and then expanding for the total number of days in the Period.

Instantaneous Counts (ICs) are a spatial census (i.e., covering the entire Estimation Area) of the number of active fishers at a single point in time. IC data may be obtained via aerial counts by plane or helicopter, boat patrols, vehicle patrols, or foot patrols. ICs are called "instantaneous", but in practice they are not collected at a single instant due to physical and logistical constraints, such as the size of the Estimation Area, visual barriers, and the counting method. Significant effort is made to minimize the duration of ICs, and since they occur relatively quickly compared to movements of fishers and fishing boats into and out of Estimation Areas, they are treated as instantaneous for the purpose of estimating Total Effort.

Temporal Counts of active fishers are used to estimate the proportion of fishers active at any given time during the day; this proportion is referred to as the **Instantaneous Count Efficiency (ICE)**. Typically, Temporal Counts are collected from a number of representative Sites within the Estimation Area and Period. Temporal Count data may be obtained through visual counts or derived from interviews. Visual counts, typically used in freshwater surveys, are recorded by foot patrols, boat patrols, or stationary observers and are taken periodically throughout the day. Interviews, typically used as the basis for ICE estimates in marine surveys, are conducted randomly by surveyors who record the start and end times of fishing activity. Records from either interviews or visual counts are then compiled (using procedures described in Section 3.2.2) to calculate ICE. When these time-specific or Time-Block-specific ICE values are combined across the entire day, they form an **Effort Profile** or **Activity Profile** (Figure 3). In practice however, it is only necessary to calculate the values of ICE which correspond to the time of the ICs.

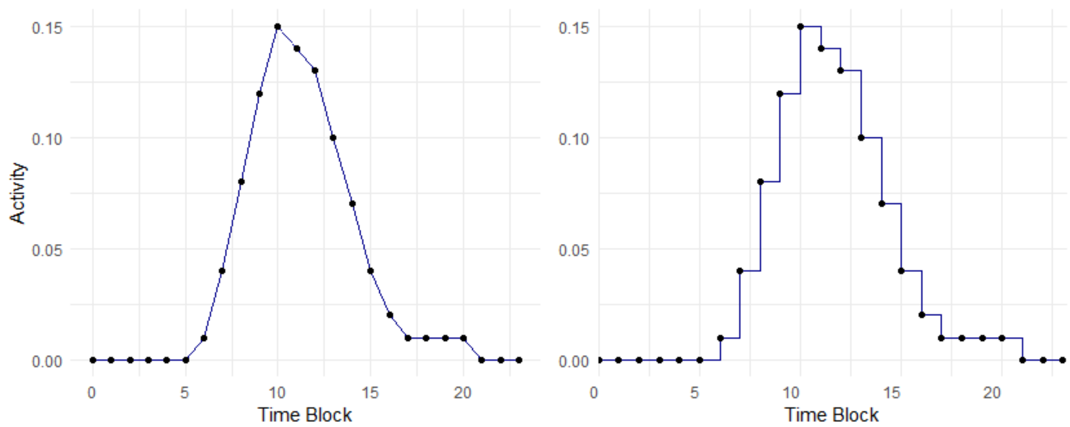

Figure 3: Two visualizations of an Effort Profile example, each showing the proportion of effort (ICE) for each Time Block throughout the day. The two visualizations display how ICE may differ when the time of IC falls between two whole hours, depending on how ICE is calculated. For example, linear interpolation is used in the first plot, while times are rounded down to the nearest whole hour in the second.

The IC provides a snapshot of the total activity in the Estimation Area at a single point in time but does not show how the number of active fishers changes throughout the day. Conversely, the Effort Profile shows how the number of active fishers changes throughout the day, but does not provide the total number of active fishers in the Estimation Area. ICE values are used to expand ICs for effort that was not active (countable) at the time an IC was made. This leads to a Daily Effort estimate for the day of an IC. These Daily Effort estimates are then averaged to calculate the Mean Daily Effort within the Estimation Area and Period. Finally, **Total Effort** is calculated by multiplying the Mean Daily Effort by the number of days in the Estimation Period (*N*). Further details about these calculations are provided in Section 3.

In some areas, Total Catch and Total Effort estimates are supplemented with Logbook data, which are collected by volunteer guides and experienced fishers. These data are excluded from the intermediate steps of the estimation process, with the full Logbook-reported effort and catch added to the final Total Effort and Total Catch estimates. Logbooks are not discussed further in this report, as they are specific to certain Estimation Areas and Periods, and are not incorporated into the general methodology, which is the focus of this report.

2.2 Reporting Units

The selection of an Estimation Area and Estimation Period defines the base spatial and temporal scale at which catch calculations are performed. Estimates may also be reported separately by additional characteristics (Table 1) or aggregated across multiple Estimation Areas and/or Periods as needed (Section 3.5).

Table 1: Description of reporting categories by which catch estimates may be produced

Characteristic	Description
Species	Species of interest
Size Class	Size category of fish; e.g., legal, sublegal
Gear Type	Gear type used to capture fish
Disposition	Kept or released status of caught fish
Mark Status	Hatchery-mark status. Unmarked fish have an intact adipose fin (marked, unmarked, unknown)
Group	Band or group associated with the fishing activity (if any)
Estimation Method	Creel survey, logbook, or both
Day Type	Weekday or weekend including holidays

2.3 Terminology

The definitions presented in Table 2 are the proposed standardized terminology for the Pacific Region. In this report, the defined terms are presented in Title Case to indicate that they are used *sensu stricto*. Terminology can vary across different fisheries; therefore, historical nomenclature used throughout the Pacific Region is also provided for reference in the "Also known as" column in Table 2.

Table 2: Description of variables, parameters, and terms for creel survey-based catch estimation in the Southern Pacific Region

Term	Acronym or Symbol	Description	Examples	Also known as
VARIABLES				
Catch Per Unit Effort	*CPUE*	The number of fish caught per unit of effort. Effort is measured in Hours or Trips.		Catch Per Effort (CPE)
Instantaneous Count	*IC*	Counts of the total number of active fishers or active fishing rods within the Estimation Area at a single point in time. These counts are assumed to be instantaneous.	Aerial counts, ground effort counts	Aerial Survey data; Overflight survey data;
Temporal Count	*TC*	The count of effort across time obtained from a single Site.	Interview-based count, visual count	Hourly Rod Count; Spiral Counts, Periodic Index Area Count (PIC); Site Count; Tally Count
Instantaneous Count Efficiency	*ICE*	The efficiency of the count within an Estimation Area measured as the proportion of total daily effort active in a given Fishing Time Block; this is a calculated value based on either visual counts, interview data, or a combination of both		Proportional Effort
Effort Profile		The proportion of effort (i.e., ICE) throughout the day, calculated for the entire Estimation Period.		Activity Profile; ICE Curve
Mean Daily Effort	*E*	Average number of Trips or Hours per day in the Estimation Area, calculated from sampled days within the Estimation Period.		
Catch	*C*	Kept and released catch by species		

SPATIAL TERMS				
Administrative Area		The administrative management units within the Pacific region.	South Coast (SC); North Coast (NC); British Columbia Interior (BCI); Lower Fraser (LF); Yukon Transboundary (YTB)	
Estimation Area		The area in which catch and effort is estimated by expansion of survey data.	Creel sub-area 23B	Management Unit; Subarea; Section
Site	s	A location or area where sampling or fishing occurs, including Fishing Sites, Access Points, and Index Areas.	Five Fingers (Fishing Site), Brechin boat launch (Access Point)	Landing Site; Interview Site; Hourly Rod Count Site

TEMPORAL TERMS				
Estimation Period		The period for which catch and effort is estimated by expansion of survey data.	Monthly (SC); Bi-weekly (LF Rec); Defined by regulations (LF FSC)	
Day Type	d	Classes of days of the week by which the analysis is stratified. Typically there are two Day Types: weekdays and weekends including holidays.		
Time Block		Periods of the day by which the analysis is discretized.	Time Block 2 is 1:00 to 1:59 AM. The day is usually divided into 16 (SC) or 24 (LF, BCI) Time Blocks.	
Fishing Time Block	t	A Time Block during which fishing activity occurs.		
Count Time Block	τ	A Time Block during which a Temporal Count occurs. For interview-based Temporal Counts, Count Time Blocks differ from Fishing Time Blocks. For visual-count-based Temporal Counts, Count Time Blocks coincide with Fishing Timeblocks.		Interview Time Block; Landing Time Block; PIC Time Block
Shift		Type of shift	AM shift; PM shift; Mid-day shift.	
Stint	k	A unique combination of Shift, Date, and Site within an Estimation Period	Shift 1 at Pedder Bay on Oct 10, 2010	
Day of IC	j	A day when an Instantaneous Count occurred		

EFFORT UNITS				
Hour		A unit of effort based on the number of hours fished per active rod. Counts rods individually rather than the number of fishers.	Three fishers, two using one rod each for two hours and one using two rods for two hours, total 8 Hours.	Fisher-Hours, Rod-Hours, Gear-Hours
Trip		A unit of effort based on the number of fishing trips. Each trip is counted once, regardless of the number of fishers involved.	A boat with two fishers going on a single trip counts as one Trip, regardless of trip duration.	Fisher-Trips, Boat-Trips, Gear-Trips

Box 1: Trips vs. Hours

We do a simple unit analysis on the difference between measuring 'unit effort' by either Trips or Hours. When using Hours, the units are

$$(\#\ of\ fish) = (\#\ of\ fish/Hour) \times (Hours).$$

When using Trips, the units are

$$(\#\ of\ fish) = (\#\ of\ fish/Trip) \times (Trips).$$

3 DETAILED DESCRIPTION OF METHODS

This section provides a detailed review of the methods used to estimate Total Catch from creel survey data. The goal is to present sufficient detail to enable straightforward replication of the estimation process. Recognizing that methods are often described briefly, which can hinder reproducibility, this document adopts a comprehensive approach to ensure clarity regarding available options and the assumptions underlying the analyses. The section summarizes the mathematical framework used to estimate Total Catch.

Throughout the detailed description of methods, we do not present all possible strata (e.g., Estimation Area, Estimation Period) or reporting units (e.g., species, gear type). Instead, we focus on clarity and aim to use as few subscripts as possible. However, it is important to understand that each of the calculations presented below are performed for specific strata and characteristics. The methods documented here are generalized across strata but the calculations are always performed on the same basic spatial and temporal units of Estimation Area and Estimation Period.

The necessary subscripts we include are Site (s), Fishing Time Block (t), Count Time Block (τ), fisher (i), Stint (k), and day of IC (j). The analysis is typically stratified by Day Type; however, for clarity and ease of reading, this factor is not included as a subscript in the formulas.

All methods in this document rely on Time Blocks to record effort during the data collection process. One-hour Time Blocks should be used when supported by the data. Surveyors typically work in complete hours; however, when staffing does not permit hourly Time Blocks, larger discrete blocks of time may be used. For example, DPA (1985) used two-hour Time Blocks, and English et al. (2002) used four-hour Time Blocks. Total Effort is then estimated by expanding these observations to the entire Estimation Period.

This report documents two methods for combining ratios in the calculations of CPUE, ICE, and Total Effort: (1) Ratio of Means, and (2) Mean of Ratios. The methods are described generally in Box 2 below.

Box 2: Ratio of Means vs. Mean of Ratios
The difference between Ratio of Means and Mean of Ratios is the order in which ratios are combined. For a ratio R, based on a vector of numerators $(a_1, a_2, \dots a_n)$ and denominators $(b_1, b_2, \dots b_n)$, the Ratio of Means method is calculated as

$$R = \frac{\frac{1}{n}\sum_i a_i}{\frac{1}{n}\sum_i b_i} = \frac{\sum_i a_i}{\sum_i b_i}$$

and the Mean of Ratios method is calculated as

$$R = \frac{1}{n}\sum_i \frac{a_i}{b_i},$$

where i is an arbitrary index ranging from 1 to the total length of the vector n.

3.1 Catch Per Unit Effort (CPUE) Calculations

Fisher interviews collect measures of the catch and the effort units expended on a given fishing trip, the data used to estimate CPUE (Figure 1). Using these data, CPUE can be calculated using the Ratio of Means or the Mean of Ratios.

Catch Per Unit Effort calculated using the Ratio of Means method:

$$CPUE = \frac{\sum_i C_i}{\sum_i H_i} \qquad (2)$$

Catch Per Unit Effort calculated using the Mean of Ratios method:

$$CPUE = \frac{1}{I}\sum_i \frac{C_i}{H_i}. \qquad (3)$$

where C_i is the number of fish caught by fisher i, H_i is the effort spent by fisher i, and I is the number of fishers interviewed. Here, “fisher” follows the definition in the List of Symbols and may refer to a person or boat engaged in fishing; it does not necessarily mean an individual person.

If effort is measured in Hours, H_i is the total Hours spent. If effort is measured in Trips, H_i is the total number of Trips by fisher i. In practice, when effort is measured in Trips, H_i is usually 1 because each trip is treated as a different interview. In this case, the Ratio of Means and the Mean of Ratios methods are equivalent. On the other hand, when effort is measured in Hours, H_i varies considerably among samples, and the Ratio of Means approach is typically preferred. The Ratio of Means corresponds to the standard ratio estimator (Cochran 1977; Lohr 1999), which is designed for cases where denominators differ across samples (here, the number of hours fished per trip).

Pollock et al. (1997) frame the choice between methods in terms of the type of interviews conducted for CPUE calculation. The two types are (1) access surveys, conducted at fixed Access Points (e.g. boat launches, marinas, parking lots), and (2) roving surveys, conducted during the course of the fishing event. During access surveys, all individuals have an equal probability of being selected, and complete trip information is collected. By contrast, in roving surveys the probability an individual is selected is proportional to the length of time they are fishing, and the trip information is incomplete (i.e., only the number of fish caught and the number of hours fished at the time of the interview are recorded). Pollock et al. (1997) argue that Ratio of Means is better when access surveys are used, while Mean of Ratios is better when roving surveys are used, since it reduces the effect of unequal selection probability by computing each individual's catch rate first and then averaging.

3.1.1.1 CPUE Assumptions

The analysis assumes that interview sampling is effectively random, leading to a representative sample of fishers. This assumption is critical because CPUE can vary substantially over time and space due to factors such as the number of individuals on a boat, fishing duration, weather conditions, fish abundance, fisher skill, and time of day. Further, since the data rely on fishers' reports, it is assumed that both catches (including released fish) and fishing durations are reported accurately.

Other considerations and methods which are not discussed in this document include accounting for bag limits (particularly with roving interviews) (Pollock et al. 1997), the assumption of constant catch rate (Dauk and Schwarz 2001), accounting for variance within complex multi-stage designs (Dauk and Schwarz 2001), use of a combination weighted method when different types of interviews are used (Alexander 2000), and a method for CPUE calculation using maximum likelihood methods to estimate either per fisher catch and effort (bivariate approach) or per fisher CPUE (univariate approach) (Richards and Schnute 1992).

3.2 Effort Calculations

3.2.1 Instantaneous Count (IC)

Instantaneous Counts are always visual counts that record the number of effort units (Trips or Hours) active within the Estimation Area at the time of count. For each IC, data include the number of Trips or Hours counted during the IC (B) and when the count occurred. As shown in Figure 1, ICs are expanded using the ICE value applicable to the time of the IC. Then, Total Effort on a given Day Type is estimated using the average of these expanded values for ICs on that Day Type, multiplied by the number of days of that Day Type in the Estimation Period. Depending on the program, ICE values used to expand a given IC may be the value corresponding to the start time or the midpoint of the start and end time of the IC.

Although called “instantaneous”, ICs are not truly instantaneous in practice. Each IC requires some time to complete, as observers move through the Estimation Area and record fishing activity. For analysis, however, ICs are treated as if they occur at a single point in time. This allows us to extract the corresponding value of ICE from a continuously changing Effort Profile at the exact time of the count. The duration of an IC can be influenced by several factors, such as the counting method (e.g., aerial versus ground-based surveys), the size of the Estimation Area, and whether the count must be divided into multiple segments due to logistical constraints or visibility limitations. However, significant effort is made to conduct ICs as quickly as possible, without compromising accuracy. This supports the analytical treatment of ICs and reduces the chance that fishers move between Estimation Areas during the counting process.

3.2.1.1 IC Assumptions

When using IC data, several assumptions are made: all fishers present are seen and counted exactly once; all observed fishers are correctly identified as actively fishing or not-fishing and as recreational or FSC; and fishing behavior is not influenced by the survey. Finally, days on which ICs are conducted are either randomly scheduled or, if not random, are assumed not to introduce bias into the estimates.

3.2.2 Instantaneous Count Efficiency (ICE) Calculations

In general, the three components necessary to calculate ICE are (1) the corrected activity at the Fishing Time Block of interest t (A_{tks}) (Eq. 6), (2) the total activity for the day (T_{ks}) during Stint k at Site s (Eq. 7), and (3) the number of days with Temporal Counts (m). Depending on the data source and the quality of the data (e.g., temporal completeness) the approach for calculating A_{tks} and T_{ks} varies.

Using Ratio of Means,

$$ICE_t = \frac{\sum_s \sum_k A_{tks}}{\sum_s \sum_k T_{ks}}. \tag{4}$$

Using Mean of Ratios,

$$ICE_t = \frac{1}{m} \sum_s \sum_k \frac{A_{tks}}{T_{ks}}. \tag{5}$$

The source data for ICE varies by fishery, and can be from interviews, visual counts, or a combination of the two (Figure 1). We present the three different methods used for calculating ICE depending on the data source and type:

- Interview-based ICE:
  - Approach 1 – Data Collection Area based ICE
  - Approach 2 – Target Fishing Area based ICE
- Visual-count-based ICE

Interview-based approaches are typically tied to coastal fisheries. They capture the full duration of each fishing trip, providing a complete temporal record of fishing activity. However, interviews typically sample a smaller number of fishers because they take longer to conduct than visual counts. Interviews may occur within the Estimation Area where the fishing activity takes place or outside of it. For example, they may occur at the Fishing Site within the Estimation Area or at an Access Point, which may be located either inside or outside the Estimation Area.

Visual-count-based approaches, on the other hand, are easier to perform in freshwater fisheries. Visual counts measure activity at discrete observation times, allowing a larger number of fishers to be sampled in a shorter period. In contrast to interviews, visual counts are always conducted within the Estimation Area, at designated Index Areas.

3.2.2.1 Interview-based ICE Calculations

When using interview data to obtain Temporal Counts, interviewers record the start and end time of fishing on each trip and use this to calculate ICE.

The general methods for estimating activity (A_{tks} and T_{ks}) for each Stint k and Site s are shown in Eq. 6 and Eq. 7 respectively, where $F_{\tau ks}$ is the total activity (in Trips or Hours) recorded from fishers surveyed at Count Time Block τ, $F_{t\tau ks}$ is the activity recorded from fishers surveyed at Count Time Block τ that were specifically fishing during Fishing Time Block t, and $W1_{\tau s}$ and $W2_{\tau ks}$ represent weighting factors that correct the activity estimate under different scenarios. When effort is measured in Hours, the sum of the activity recorded at Count Time Block τ for all

Fishing Time Blocks t, $\sum_t F_{t\tau ks}$, will naturally equal $F_{\tau ks}$. However, this is not the case when effort is measured in Trips since a trip can span over multiple Fishing Time Blocks.

$W1$ (Box 3) weighting accounts for differences in the number of days each Count Time Block τ was sampled (within an Estimation Period). $W1$ becomes necessary since typically, midday Time Blocks are surveyed more often than early morning or evening Time Blocks due to shift overlapping. In cases where there is equal sampling across all Time Blocks, the effort profile is the same with and without $W1$ weighting applied. Therefore, it is recommended to use $W1$ weighting in all cases. $W2$ weighting corrects for interview saturation (i.e., situation where not all observed fishers can be interviewed) (Box 4).

$$A_{tks} = \sum_{\tau} \left(W1_{\tau s} \times W2_{\tau ks} \times F_{t\tau ks} \right) \quad (6)$$

$$T_{ks} = \sum_{\tau} \left(W1_{\tau s} \times W2_{\tau ks} \times F_{\tau ks} \right) \quad (7)$$

Box 3: $W1$ weighting – differences in number of days sampled

$W1$ weighting accounts for differences in the number of days each Count Time Block τ was sampled (within the Estimation Period). If all Time Blocks sampled are sampled on the same number of days at a given Site, then counts for a Count Time Block can be summed and divided by the number of days sampled. However, when there are fewer days of sampling for some Time Blocks, a bias occurs because site counts for a Time Block with fewer days of sampling are being summed and divided by the total number of days sampled rather than the number of days that specific Count Time Block was sampled. The bias result is a lower proportion of effort attributed to that Time Block than there should be for that effort profile. $W1$ weighting corrects for this bias.

As detailed by Ma et al. (2012, eq. A1), $W1$ is the ratio of the number of days in the Estimation Period (N) to the number of days each Count Time Block (τ) is sampled within the Estimation Period (n_τ).

$$W1_{\tau} = \begin{cases} \dfrac{N}{n_\tau}, & \text{if } n_\tau > 0 \\ 1, & \text{if } n_\tau = 0 \end{cases} \quad (8)$$

A previous method for calculating $W1$ used 'Work Blocks' to represent different portions of the day that were sampled (English et al. 2002). Work Blocks are four-hour sections of time that have at least one hour of overlap between them. In this document, we use Time Block based $W1$ calculations exclusively because the Work Block based method inherently over-represented Time Blocks that overlapped between Work Blocks.

Box 4: $W2$ weighting – interviewer saturation

$W2$ weighting expands for fishers that were not interviewed but were counted within a Time Block (English et al. 2002). This weighting is therefore a correction factor for saturation of interviewers. This correction factor only applies to interview-based Temporal Counts.

For instance, if an interviewer only has the capacity to interview 50 boats within a Count Time Block but there are 100 boats in the area, $W2$ weighting would correct the ICE calculation to account for this by multiplying the fishing activity reported during the 50 interviews by a factor of 2 (that is, 100 divided by 50). Without $W2$ weighting, the activity in Sites and Time Blocks with many fishers may be underrepresented. $W2$ weighting is Count Time Block (τ), Site (s), and Stint (k) specific. The equation for $W2$ weighting is

$$W2_{\tau ks} = \begin{cases} \frac{L_{\tau ks}}{I_{\tau ks}}, & \text{if } I_{\tau ks} > 0 \\ 0, & \text{if } I_{\tau ks} = 0 \end{cases} \quad (9)$$

where $L_{\tau ks}$ is the total number of people or boats present at Count Time Block τ but not necessarily interviewed, and $I_{\tau ks}$ is the number of people or boats interviewed within that Count Time Block.

When using an interview-based approach, a challenge is how to link interview data to an Estimation Area. There are two approaches: a Data Collection Area based approach, or a target Fishing Area based approach.

Approach 1 – Data Collection Area based ICE

A Data Collection Area based approach uses data collected from interviews from a group of Sites, typically Fishing Sites or Access Points, that are representative of the fishing effort in the Estimation Area of interest. For instance, when interviews take place at various Landing Sites, such as boat launches or marinas, ICE for a given Estimation Area will be calculated based on a group of Landing Sites deemed relevant to that Area. The rationale for using this approach is that the information gathered represents typical fishing behaviour in the Estimation Area and that the $W1$ and $W2$ weighting factors can be performed to reduce bias. Also, it does not require the same level of comprehensive survey as the target fishing area based ICE (see below).

A drawback of this approach is that it does not account for where the fishing actually takes place. If fishers from multiple Estimation Areas are interviewed at the same Site, the resulting ICE calculations may be inaccurate.

Approach 2 – Target Fishing Area based ICE

An alternative approach is to calculate ICE from fishers who fished at Fishing Sites within the Estimation Area of interest. In this approach, interview data are linked to the Fishing Site where the activity occurred and to the Estimation Area in which the Fishing Site is spatially located.

$W2$ weighting does not apply for Target Fishing Area based ICE calculations because missed interviews cannot be attributed to different target sites (Ma et al. 2012). A potential extension for this would be to attribute the missed interviews to the different target sites proportionally. The math is not developed here.

A potential concern with this approach is that the search for data must account for all potential Fishing Sites where fishers may be interviewed. This may be impractical from a data management point of view.

3.2.2.2 Visual-count-based ICE Calculations

In visual-count-based ICE, total activity is always estimated in terms of Hours (Rod-Hours or Gear-Hours); Trips cannot be used as a measure of daily effort as visual estimates cannot distinguish between unique fishers across different hours. The weighting factor $W2$ is not applicable to visual-count-based ICE calculations (unless there are more fishers than the surveyor can count within the duration of the Time Block) and it can be dropped from Equations (6) and (7) presented earlier.

To calculate the corrected total Hours A_{tks} at Fishing Time Block t during Stint k at Site s, only visual counts conducted during Time Block t are used. In other words, no summation over multiple Count Time Blocks is needed in Equation (6), since activity at Fishing Time Block t is measured only during that Time Block. Equation (6) is simplified to the following form:

$$A_{tks} = W1_{ts} \times F_{tks} \tag{6a}$$

where F_{tks} is the total Hours counted at Time Block t during Stint k at Site s.

To calculate the total corrected activity for the day T_{ks} during Stint k at Site s, the hourly values are summed across all Count Time Blocks τ in the day. In the case of visual-count-based ICE, this is equivalent to summing over all Fishing Time Blocks t, since visual counts are collected directly at the time of fishing. Therefore, Equation (7) becomes:

$$\begin{aligned} T_{ks} &= \sum_t \left(W1_{ts} \times F_{tks} \right) \\ &= \sum_t A_{tks} \end{aligned} \tag{7a}$$

A potential weakness of visual counts is that there may be periods within the day when no patrols are present (typically at the beginning and end of the day, or the ‘tails’). It is possible to use interview data to supplement the visual counts during the tails, thus improving the accuracy of the ICE calculations. This method is known as ‘Tail Estimation’ (Box 5). Alternative and potentially simpler approaches have also been explored, such as extrapolating the first or last visual count downward until it reaches zero.

Another problem that can occur is when counts from different days within the Estimation Period do not span the same Time Blocks, adding a potential bias due to day-to-day differences. Effort Scaling (Box 6) addresses this issue, and even when the Time Blocks sampled are the same across all days (i.e. scaling is not necessary), applying scaling will still provide a correct estimate of effort. Therefore, scaling should be conducted unless there is certainty that Time Blocks sampled are the same across all days sampled. Effort Scaling does not alter the proportion of activity throughout a day, which is what matters for ICE calculation; it only multiplies the hourly activity by a calculated day-specific factor R (see Box 6 below).

Box 5: Tail Estimation

When ICE is estimated using visual counts, the number of fishers included in the estimation is limited to the Count Time Blocks in which counts were conducted. However, fishing can sometimes occur before visual counts start or after visual counts end; this results in visual-count-based ICE underestimating effort. Information from interviews can be used to supplement visual count data in estimating effort. This approach is called Tail Estimation. Tail Estimation is used to gain a more accurate estimation of the number of fishers present throughout a day using data from interviews to estimate the number of fishers present before and after visual counts.

The requirements for Tail Estimation are that (1) there are both visual counts and interviews conducted at the Site of interest, and (2) that the information from the interviews demonstrate that there is fishing activity before (or after) visual counts have ended.

To perform Tail Estimation, the interview-based number of fishers before visual counts begin (or after they end) is compared with the first (or last) visual count conducted. For a given first Time Block t of visual counts, the ratio (R) for a preceding Time Block ($t - x$) is calculated based on the number of fishers at the prior Time Block ($F_{t-x,interview}$) divided by the number of active fishers at the first Time Block of interviews ($F_{t,interview}$). The parameter x represents the number of time blocks prior to the first visual count where fishing activity was seen (based on interviews).

$$R_{t-x} = \frac{F_{t-x,interview}}{F_{t,interview}} \qquad (10)$$

Using the ratio, a visual count tail (Z_{t-x}) is estimated for all Time Blocks fishers report fishing prior to the first Time Block of visual counts by multiplying the count from the first Time Block of visual counts ($F_{t,visual}$), with the calculated ratio (R_{t-x}).

$$Z_{t-x} = F_{t,visual} \times R_{t-x} \qquad (11)$$

The values for Z_{t-x} are then treated as visual count data for the Time Block $t - x$.

To estimate fishing effort past when visual counts occurred, the same methods as above apply, but visual counts are expanded from the last Time Block that fishing activity occurred based on interviews (F_{t-x} is replaced with F_{t+x}, where t is the last Time Block of visual counts and x is the number of Time Blocks past the last Time Block of visual counts). This is done for all Time Blocks fishers report (during interviews) they plan fishing past the last Time Block of visual counts.

Box 6: Effort Scaling

Temporal Counts are typically collected on a shift-to-shift basis, which may lead to inaccurate calculation of ICE. Consider the following example:

Visual counts are done in the AM on Day 1 and in the PM on Day 2. Day 1 had exceptionally nice weather, and Day 2 had exceptionally poor weather. Assuming more fishers are present in nice weather, an Effort Profile using just these two days of data without scaling would result in a higher weighting of effort in the morning than the afternoon.

Effort Scaling is a method used to produce an equal weighting of effort between days that addresses this potential shortcoming of shift-based Temporal Counts. The requirements for Effort Scaling are that (1) the shape of the Effort Profile is similar across days, and (2) that there are some Time Blocks from each Stint that overlap for all days. .

For each sampled day η, the sum of observed Hours (H) in the overlapping Time Blocks for day η is divided by the sum of observed Hours in the overlapping Time Blocks for day 1 (i.e. the first day with a Temporal Count in the Estimation Period) to calculate a ratio R:

$$R_{day(\eta)} = \frac{\sum_{t_{\min}}^{t_{\max}} H_{day(\eta)t}}{\sum_{t_{\min}}^{t_{\max}} H_{day(\eta^*)t}} \tag{12}$$

where t_{min} is the first overlapping Time Block and t_{max} is the last overlapping Time Block. Using the calculated ratio for day η ($R_{day(\eta)}$), a scaled Temporal Count (S) is calculated for each Time Block (t).

$$S_{day(\eta)t} = \frac{H_{day(\eta)t}}{R_{day(\eta)}} \tag{13}$$

Then for each Time Block, scaled Temporal Counts are used to calculate ICE values.

At this point, it is helpful to clarify that Effort Scaling and $W1$ weighting address different sources of imbalance in the data, and both are necessary to estimate ICE accurately. Effort Scaling adjusts effort across days so that no single day with unusually high or low activity skews the estimate. In contrast, $W1$ weighting adjusts effort across Time Blocks, correcting for differences in how often each Time Block is sampled. Thus, even when Effort Scaling is applied, $W1$ weighting is still recommended to ensure that each Time Block's contribution to the ICE calculation is properly represented.

3.2.2.3 ICE Assumptions

When ICE is calculated based on interview data, it is assumed that the start and end times of each fishing trip are reported accurately by fishers and recorded correctly by the surveyors. In addition, expansion by $W2$ assumes that fishers are randomly selected for interviews within each Count Time Block, so that interviewed fishers are representative of all fishers present.

When ICE is calculated from visual counts, the Effort Profile derived from the selected Index Areas is assumed to represent the Effort Profile of the entire Estimation Area. Visual counts are conducted periodically throughout each shift, and it is assumed that only actively fishing units of gear (such as rods or nets) are counted.

In any case, it is assumed that the days on which each Count Time Block is sampled must be randomly scheduled within the Estimation Period. This ensures that the sampled days are representative of the unsampled days.

3.2.3 Total Effort Calculations

Once ICE has been estimated, Mean Daily Effort can be calculated by expanding the number of fishers counted during the ICs (B_j for day of IC j) by the inverse of the proportion of fishers active at the time of the IC. In some instances, there is more than one IC within a day. When this occurs, either a single IC is selected for inclusion in the calculations, or the IC and ICE values are averaged for the day, before calculating the mean for the entire Estimation Period. Doing this ensures that we do not pseudo-replicate days where there are more ICs. In other words, without doing this within-day averaging, days where there were more ICs would have a greater weight than days with fewer ICs.

Mean Daily Effort (E) can be estimated using either a Ratio of Means or Mean of Ratios approach.

The Ratio of Means calculation (Alexander et al. 1999) is

$$E = \frac{\sum_j B_j}{\sum_j ICE_{\substack{t=\text{time of IC} \\ \text{on day j}}}} \tag{14}$$

where j is an arbitrary index for days that have an Instantaneous Count, B is the number of fishers counted during the IC on day *j*, and the ICE value is the proportion of active fishers at the Fishing Time Block *t* corresponding to the time of the IC.

The Mean of Ratios calculation for estimating Mean Daily Effort is

$$E = \frac{1}{n} \sum_j \frac{B_j}{ICE_{\substack{t=\text{time of IC} \\ \text{on day j}}}} \tag{15}$$

where n is the total number of days with Instantaneous Counts.

When the time of an IC falls between two Time Blocks, the corresponding ICE value can be estimated by any of the following methods: (i) using the ICE from the hour of the IC and ignoring the minutes, (ii) using the ICE based on the time rounded to the nearest hour, (iii) using a mean ICE value (i.e., 50% weighting for each) of the two Time Blocks that surround the time of the IC, or (iv) using linear interpolation.

When visual counts are used to calculate ICE, which are typically conducted consistently on the hour, interpolation is the recommended approach. This is because interpolation better reflects the gradual change of fishing activity from one Time Block to the next. For interview-based ICE, the choice is less straightforward since hourly ICE values represent reported activity over entire Time Blocks rather than specific instants, as with visual counts. Nevertheless, interpolation has typically been used for interview data as well, and remains the recommended approach as it maintains consistency with established methods and provides smoother transitions between Time Blocks. Alternatively, using the ICE from the hour of the IC (ignoring the minutes) offers a simpler option that may better align with how interview data are collected.

To calculate Total Effort, the following equation is used.

$$Total\ Effort = E \times N \tag{16}$$

where N is the number of days where fishing is open within the stratum.

3.2.3.1 Total Effort Assumptions

Equation (16) implicitly assumes that the shape of the Effort Profile on each day within the Estimation Period and stratum is similar. However, there are cases where this assumption is not upheld. For example, in some First Nations FSC gillnet fisheries, an Estimation Period can span three days but the effort in each of these three days differs because the fishery opens in the evening of Day 1 and ends in the evening of Day 3. In this situation, Day 2 would experience a full day of effort, but Days 1 and 3 would experience only a partial day of effort. When this occurs, Total Effort may be calculated using alternative approaches, which can vary depending on the fishery and data available.

3.3 Total Catch Calculations

Total Catch is calculated as shown in Equation (1), which is repeated here for reference.

$$Total\ Catch = Total\ \ Effort \times CPUE\ .$$

The mean daily catch could be calculated as

$$Mean\ Daily\ Catch = Mean\ Daily\ Effort \times CPUE\ . \tag{17}$$

3.4 Variance Calculations

It is important to understand the degree of certainty in the catch estimate. In this section, we begin with a description of the basic principles necessary to derive variance estimates including simple variance, combining variance of two variables, and finite population correction. We then apply these basic principles to calculate the variance for each of the components of Total Catch.

3.4.1 General Description of Variance Calculations

3.4.1.1 Random Variables

It is important to understand the difference between a random variable and a constant. A **random variable** X can be thought of as random outcomes of an experiment. For example, X could denote the number of heads from an experiment where a coin is tossed multiple (e.g., $n = 10$) times. The outcome may differ each time the experiment is completed, and therefore we might be interested in the variance in this outcome. In contrast, the number of times the coin was tossed (n) is a constant (not a random variable) and we are not interested in the variability around n. Total Catch, CPUE, and Total Effort are random variables.

3.4.1.2 Sample Variance

The sample variance is a useful measure of variability or how observations deviate from the mean (Equation 18). Variance calculations are all fundamentally based on this simple concept, but the formulae for more complicated random variables are not always obvious. Although the underlying math is relatively straightforward, variance estimates are usually presented without explicitly describing the underlying assumptions and derivations.

Sample variance (conceptual formula):

$$s^2 = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}\ , \tag{18}$$

where s^2 is sample variance, n is the number of samples, i is the index of the sample, x is the sample value, and $\bar{x}$ is the sample mean. This formula may be expressed in a slightly different format which is easier to calculate (Equation 19), but it is nothing more than a simple rearrangement of the formula for sample variance. This is the form used later in this section.

Sample variance (computational formula):

$$s^2 = \frac{\sum_{i=1}^{n} x_i^2 - \frac{\left(\sum_i^n x_i\right)^2}{n}}{n-1} \tag{19}$$

3.4.1.3 Calculating the Variance of a Combination of Random Variables

Total Catch is estimated as the product of CPUE and Total Effort, and the various components used to calculate Total Catch are often sums, products, or ratios of two or more random variables. To calculate the variance of Total Catch, we must first estimate the variance of each of the components. These results are then combined using several fundamental theorems (Equations 20 – 27).

The more random variables involved in calculating an estimate (e.g., Total Catch), the more complicated the variance math, although fundamentally they are all based on the same underlying equations. As a simplification step, all random variables are assumed to be independent, which implies that their covariances are zero. For Total Catch estimates in this document, this assumption is made at all stages of the analysis.

3.4.1.4 Sums of Random Variables

For random variables $X_1, \dots, X_n,$

Expectation: $$E\left(\sum_1^n X_i\right) = \sum_1^n E(X_i) \tag{20}$$

Variance: $$Var\left(\sum_1^n X_i\right) = \sum_1^n Var(X_i) + 2\sum_{i<j} Cov(X_i, X_j) \tag{21}$$

Note that if the two random variables X_i *and* X_j are independent, then $Cov(X_i, X_j) = 0$. This means that if all X_i's are independent with each other, then the variance of the sum is simply the sum of variances of the random variables.

3.4.1.5 Product of Random Variables

For random variables X *and* Y *with expected values* $\mu_X = E(X)$ *and* $\mu_Y = E(Y)$ respectively,

Expectation: $$E(XY) = \mu_X \mu_Y + Cov(X, Y) \tag{22}$$

If X and Y are independent (Goodman 1960; Cochran 1963), the $Cov(X, Y) = 0$, and variance can be estimated as

Variance: $$Var(XY) = \mu_Y^2 \, Var(X) + \mu_X^2 \, Var(Y) + Var(X) \, Var(Y) \tag{23}$$

The case where X and Y are not independent is complex and is not shown here; refer to Mood et al. (1974) or other mathematical statistics texts for reference.

3.4.1.6 Quotient of Random Variables

For the quotient of random variables, the calculations become more complex again. No simple and exact formula exists for the expectation or variance of the quotient of two random variables. Approximate formulas are found by taking a first-order Taylor Series expansion of X/Y (where all terms of order higher than 2 are dropped) and then taking the expectation and variance of both sides (Mood et al. 1974, Theorem 4). This approach for approximating the expectation and variance of the quotient of two random variables is also known as the 'delta method'.

For random variables X and Y,

Expectation: $$E\left(\frac{X}{Y}\right) \approx \frac{\mu_X}{\mu_Y} - \frac{1}{\mu_Y^2} Cov(X,Y) + \frac{\mu_X}{\mu_Y^3} Var(Y) \tag{24}$$

If X and Y are independent, the $Cov(X,Y) = 0$ and variance can be estimated as

Variance: $$Var\left(\frac{X}{Y}\right) \approx \left(\frac{\mu_X}{\mu_Y}\right)^2 \left(\frac{Var(X)}{\mu_X^2} + \frac{Var(Y)}{\mu_Y^2}\right). \tag{25}$$

3.4.1.7 Constants and Random Variables

For a random variable X and a constant a,

Expectation: $$E(aX) = aE(X) \tag{26}$$

Variance: $$Var(aX) = a^2 Var(X) \tag{27}$$

3.4.1.8 Finite Population Correction

Sampling error is the variability that results from the fact that we haven't sampled all individuals in the population. For example, 10 different samples from the *exact same* population will result in 10 different outcomes (i.e., random variables). In general, it is assumed that the sample size (n) is small relative to the number of individuals in the population (N). When this is true, the sample variance asymptotes to the formula provided in Eq. 18 regardless of the size of N (notice that N is not in the formula). However, when n is relatively large compared to N, the sample variance is reduced. Imagine the extreme case where $n = N$ (i.e., a census). In this case it doesn't matter how many times you sample the population, you will always get the same answer; the sampling error is zero. Therefore, when n is relatively large compared to N, the finite population correction (FPC) factor is used. In general, 5% is often used as a threshold for applying the FPC (e.g. $n/N > 0.05$), however it can always be used as it approaches 1 when $n << N$.

FPC: $\frac{N-n}{N} = 1 - \frac{n}{N}$ (Cochran 1977)

Or alternatively: $\frac{N-n}{N-1}$ (Cochran 1977) (28)

3.4.1.9 Standard Error

The standard error of an estimator $\hat{\theta}$ is its standard deviation or the positive square root of its variance $\sqrt{Var(\hat{\theta})}$ (Devore 1995). The most common estimator is the sample mean, and as a result many people use the term standard error as synonymous with the standard deviation of the sample mean $s/\sqrt{n}$. However, this causes a great deal of confusion when the estimator (e.g., Total Catch) is not a simple mean, but rather a complex function of several random variables. Calculating the standard error or standard deviation of an estimator such as Total Catch is done by first calculating the variance and then taking the positive square root. Simply dividing the standard deviation by $\sqrt{n}$, does NOT give you the standard error for *all estimators*.

The derivation of the standard deviation of the sample mean or standard error of the estimator $\bar{x}$ is provided as an example. First the variance of the mean is estimated:

$$Var(\bar{x}) = Var\left(\frac{1}{n}\sum_{i=1}^{n} x_i\right) = \frac{1}{n^2} Var\left(\sum_{i=1}^{n} x_i\right)$$ (Eq. 27, because n is a constant)

$$= \frac{1}{n^2}\sum_{i=1}^{n} Var(x_i)$$ (Eq. 21, assuming $x_1, \ldots, x_n$ are independent)

$$= \frac{1}{n^2} n Var(x)$$ (assuming $x_1, \ldots, x_n$ are identically distributed)

$$= \frac{Var(x)}{n} = \frac{s^2}{n}$$ (n's cancel each other out)

The standard error of the estimator $\bar{x}$ (i.e., standard deviation of the sample mean) is the positive square root of the variance:

$$SE(\bar{x}) = \sqrt{Var(\bar{x})} = \sqrt{\frac{s^2}{n}} = \frac{s}{\sqrt{n}} \qquad (29)$$

3.4.2 Calculating Variance for Components of Total Catch

Given the theorems for how to calculate the variance of functions of random variables and how to apply the finite population correction factor, the variance for Total Catch and its component random variables CPUE and Total Effort can be derived. The resulting formulae are presented.

3.4.3 CPUE Variance Calculations

3.4.3.1 Ratio of Means Method

The variance of the CPUE estimate for the Ratio of Means method is derived as follows.

$$Var(CPUE) = Var\left(\frac{\sum C_i}{\sum H_i}\right)$$

Let $\sum C_i, \sum H_i$ be represented by the random variables C_{total} and H_{total} respectively. Then, using Eq. 25 for the variance of the quotient of two random variables and assuming that C_{total} and H_{total} are independent:

$$Var(CPUE) = Var\left(\frac{C_{total}}{H_{total}}\right)$$

$$\approx \left(\frac{\mu_{C_{total}}}{\mu_{H_{total}}}\right)^2 \left(\frac{Var(C_{total})}{\mu_{C_{total}}^2} + \frac{Var(H_{total})}{\mu_{H_{total}}^2}\right)$$

Due to linearity of expectation (Eq. 20), the expected totals $\mu_{C_{total}}$ and $\mu_{H_{total}}$ can be estimated by the observed sample totals C_{total} and H_{total} respectively. Therefore, we can derive that

$$Var\left(CPUE\right) \approx \left(\frac{C_{total}}{H_{total}}\right)^2 \left(\frac{Var(C_{total})}{C_{total}^2} + \frac{Var(H_{total})}{H_{total}^2}\right).$$

Now, to further calculate $Var(C_{total})$ and $Var(H_{total})$, we can follow the steps below:

$$Var\left(C_{total}\right) = Var\left(\sum C_i\right)$$

$$= \sum Var\left(C_i\right) \qquad \text{(Eq. 21, assuming that } C_i\text{'s are independent)}$$

$$= I \cdot Var\left(C\right) \qquad \text{(assuming that } C_i\text{'s are identically distributed)}$$

$$= I\left(\frac{\sum C_i^2 - \frac{\left(\sum C_i\right)^2}{I}}{I-1}\right) \qquad \text{(Eq. 19)}$$

Similarly, we can show that

$$Var\left(H_{total}\right) = I\left(\frac{\sum H_i^2 - \frac{\left(\sum H_i\right)^2}{I}}{I-1}\right).$$

3.4.3.2 Mean of Ratios Method

The variance of the CPUE estimate for the Mean of Ratios method is derived as follows,

$$Var\left(CPUE\right) = Var\left(\frac{1}{I}\sum_i \frac{C_i}{H_i}\right) = Var\left(\overline{CPUE_i}\right),$$

where I is the number of fishing interviews, C_i is the number of fish caught by fisher i, and H_i is the effort spent by fisher i. Notice that we have replaced $\frac{C_i}{H_i}$ by the random variable $CPUE_i$.

Since in this case we are using the sample mean as an estimator for CPUE, we can, by following the same steps as for Eq. 29, derive that

$$Var(CPUE) = Var\left(\overline{CPUE_i}\right) = \frac{Var(CPUE_i)}{I}.$$

$Var(CPUE_i)$ can be calculated using Eq. 19, and combined with the above, we compute

$$Var(CPUE) = \frac{\sum CPUE_i^2 - \frac{\left(\sum CPUE_i\right)^2}{I}}{I(I-1)}. \quad (30)$$

3.4.4 Mean Daily Effort Variance Calculations

3.4.4.1 Ratio of Means Method

The variance of the effort estimate for the Ratio of Means method is derived as follows:

First note that the estimate of daily fishing effort (E) is a function of two random variables (B and ICE). Let $\sum_j B_j$, $\sum_j ICE_{\substack{t=\text{time of IC}\\ \text{on day j}}}$ be represented by the random variables B_{total} and ICE_{total} respectively, for corresponding Time Blocks. $Var(E)$ is therefore the variance of the quotient of two random variables (Eq. 25), assuming they are independent:

$$Var(E) = Var\left(\frac{\sum_j B_j}{\sum_j ICE_{\substack{t=\text{time of IC}\\ \text{on day j}}}}\right) = Var\left(\frac{B_{total}}{ICE_{total}}\right)$$

$$\approx \left(\frac{\mu_{B_{total}}}{\mu_{ICE_{total}}}\right)^2 \left(\frac{Var(B_{total})}{\mu^2_{B_{total}}} + \frac{Var(ICE_{total})}{\mu^2_{ICE_{total}}}\right)$$

Due to linearity of expectation (Eq. 20), the expected totals $\mu_{B_{total}}$ and $\mu_{ICE_{total}}$ can be estimated by the observed sample totals B_{total} and ICE_{total} respectively, deriving the formula:

$$Var(E) \approx \left(\frac{B^2_{total}}{ICE^2_{total}}\right)\left(\frac{Var(B_{total})}{B^2_{total}} + \frac{Var(ICE_{total})}{ICE^2_{total}}\right). \quad (31)$$

For the subcomponents of *Var*(*E*), the variance of B_{total} and ICE_{total} are outlined as follows.

$$Var\left(B_{total}\right) = Var\left(\sum B_j\right)\left(\frac{N-n}{N-1}\right) = n\,Var(B)\left(\frac{N-n}{N-1}\right)$$

$$= n\left(\frac{\sum B_j^2 - \frac{\left(\sum B_j\right)^2}{n}}{n-1}\right)\left(\frac{N-n}{N-1}\right), \quad (32)$$

assuming B_j are independent and identically distributed, where B_j is the number of fishing parties counted during the day of the Instantaneous Count j at the time t of the IC, n is the number of days in which instantaneous counts occurred, and N is the total number of days during the estimation period where the fishery is open. The additional factor on the right side of the equation represents a correction for a finite population size.

The variance in the proportion of fishing parties active (ICE) during the time t is calculated below.

Let the random variable A_t represent the number of fishing parties active at some time t during the day. Then, A_t follows a binomial distribution with parameters: T and ICE_t, where T is the total number of fishers active at some point during the day and ICE_t is the proportion of fishers who are active at time t.

In general, the expectation and variance of a random variable X with a binomial distribution $X \sim Bin(n, p)$, are $E(X) = np$ and $Var(X) = np(1-p)$ respectively. When we consider $\frac{X}{n}$ to be an estimator for the probability p, we can calculate the variance of the estimator by following the steps below:

$$Var\left(p\right) = Var\left(\frac{X}{n}\right) = \left(\frac{1}{n}\right)^2 Var(x) = \frac{1}{n^2} np(1-p) = \frac{p(1-p)}{n} \quad (33)$$

In our case, the fraction $ICE_t = \frac{A_t}{T}$ has been used as an estimator for the proportion of active fishers, and using Eq. 33 we can conclude that

$$Var\left(ICE_t\right) = \frac{ICE_t(1-ICE_t)}{T}$$

Now,

$$Var\left(ICE_{total}\right) = Var\left(\sum_j ICE_{\substack{t=\text{time of IC}\\ \text{on day j}}}\right)$$

$$= \sum_{\substack{t=\text{time of IC}\\ \text{on day j}}} Var\left(ICE_t\right)$$ (Eq. 21, assuming that ICE_t are independent across days with instantaneous counts)

$$= \sum_{\substack{t=\text{time of IC}\\ \text{on day j}}} \frac{ICE_t(1-ICE_t)}{T}$$

It should be noted that if T also considered a random variable then yet another Taylor Series approximation would be made to estimate the quotient $\frac{A_t}{T}$. Bootstrapping is another viable approach to estimating variance given that there is not an exact analytical solution.

3.4.4.2 Mean of Ratios Method

The variance of the effort estimate for the Mean of Ratios method is derived as follows:

$$Var\left(E\right) = Var\left(\frac{1}{n}\sum_j \frac{B_j}{ICE_{\substack{t=\text{time of IC}\\ \text{on day j}}}}\right)\left(\frac{N-n}{N-1}\right),$$

where j ranges from 1 to n, the total number of days with an instantaneous count, and N is the number of days in the estimation period where the fishery is open. Let $\frac{B}{ICE}$ be represented by the random variable Y, which represents the estimated total number of fishers on day j of the IC. Then:

$$Var\left(E\right) = Var\left(\frac{1}{n}\sum_j Y_j\right)\left(\frac{N-n}{N-1}\right)$$

$$= \frac{1}{n^2} Var\left(\sum_j Y_j\right)\left(\frac{N-n}{N-1}\right)$$ (Eq. 27, since n is a constant)

$$= \frac{1}{n^2} \sum_j Var\left(Y_j\right)\left(\frac{N-n}{N-1}\right)$$ (Eq. 21, assuming Y_j's are independent)

$$= \frac{1}{n^2} n\, Var(Y) \left(\frac{N-n}{N-1} \right) = \frac{1}{n} Var(Y) \left(\frac{N-n}{N-1} \right)$$ (assuming Y_j's are identically distributed)

Finally, using Eq. 19, we have:

$$Var(E) = \left(\frac{\sum (Y_j)^2 - \frac{\left(\sum Y_j\right)^2}{n}}{n(n-1)} \right) \left(\frac{N-n}{N-1} \right) \tag{34}$$

The additional factor on the right side of the equation represents a correction for a finite population size.

3.4.5 Total Effort Variance Calculations

The Total Effort for the estimation period is the product of the estimate of daily effort (E) and the number of days in the estimation period (N) (Eq. 16). The variance of the total effort is derived as follows regardless of the method (i.e., Ratio of Means or Mean of Ratios) used to estimate daily effort (E).

$$Var(Total\ Effort) = Var(E \cdot N) = N^2\ Var(E) \tag{35}$$

where N is the number of days in the estimation period where the fishery is open; N is constant.

3.4.6 Total Catch Variance Calculations

Total catch is estimated as the product of Total Effort and *CPUE*. The variance for the total catch is estimated by combining the variance for total fishing effort and variance for Catch Per Unit Effort, assuming that they are independent of each other, using (Eq. 23):

$$Var(Total\ Catch)$$

$$= Var(Total\ Effort \times CPUE)$$

$$= \mu^2_{Total\ Effort} \times Var(CPUE) + \mu^2_{CPUE} \times Var(Total\ Effort)$$

$$+ Var(Total\ Effort) \times Var(CPUE)$$

By replacing the population means with the corresponding sample estimates, we conclude:

$$
\begin{aligned}
&Var(Total\ Catch) \\
&\quad = Total\ Effort^2 \times Var(CPUE) \\
&\qquad + CPUE^2 \times Var(Total\ Effort) \\
&\qquad + Var(Total\ Effort) \times Var(CPUE)
\end{aligned}
\tag{36}
$$

3.5 Combining Estimates

We often require estimates of Total Catch and Total Effort to be aggregated across Estimation Areas or Estimation Periods. These estimates are combined by direct summation. For example:

$$Total\ Catch_{ADMIN\ AREA} = \sum_a Total\ Catch_a \tag{37}$$

where a represents the Estimation Areas within the Administrative Area of interest for that Estimation Period.

When combining estimates, they must represent unique combinations of Estimation Areas and Estimation Periods; overlapping areas or periods would lead to double counting and therefore cannot be summed.

To calculate standard error, the variances of the component estimates are summed and the square root is then taken:

$$SE(TotalCatch_{ADMIN\ AREA}) = \sqrt{\sum_a Var(TotalCatch_a)} \tag{38}$$

This calculation is based on the assumption that the component estimates are independent, so their covariances are zero (Eq. 21).

4 DATA REQUIREMENTS AND BORROWING

Before catch is estimated, there are certain criteria that must be met. These can be broken down into three categories:

- Data Availability
- Reasonableness
- Special Cases

4.1 Data Availability

A minimum amount of data must be available for the analyses to proceed. These data requirements ensure that estimates are reliable and not based on too small or unrepresentative samples. The required minimum data can be classified by the following types:

1) A minimum number of interviews for CPUE calculation.
2) A minimum number of Temporal Counts for Effort Profile estimation, which may correspond to either of the following two:
    a) A minimum number of interviews if ICE is interview-based, or
    b) A minimum number of days with visual counts if ICE is visual-count-based.
3) A minimum number of days with Instantaneous Counts.

The above are manager-defined thresholds for the number of data points necessary to perform calculations, determined based on professional judgment and subject-matter expertise. Several studies have discussed specific values or criteria for minimum data requirements, including Alexander, C.A.D. 2003, English et al. 2002, and Korman et al. 2005. When these minimum thresholds are not met, data are borrowed or catch estimation is not performed.

Data borrowing is often used to deal with deficiencies in data. Data borrowing is defined as the use of data from spatial strata, temporal strata, or other reporting units to supplement existing data within the Estimation Area and Estimation Period of interest when calculating catch and effort. Typically, the rules used around when and where to borrow are based on expert knowledge of the fishery.

4.2 Reasonableness

Reasonableness typically involves the identification of data outliers, which are determined by expert judgment. Data that are examined include catch and time spent fishing. To facilitate the identification of outliers, we recommend five-number summaries of data which include the minimum, lower quartile, median, upper quartile, and maximum values within a data set. Where the data are expected to have a large number of zeroes, we recommend excluding zeroes from the data set when performing five-number summaries.

4.3 Special Cases

There are a number of special cases where catch estimates cannot be calculated unless additional assumptions are made. We break this down on a case-by-case basis and discuss the different options available. All of the special cases are in relation to the combination of IC and ICE as shown in Table 3.

Table 3: Special cases for estimating effort and the corresponding sections

IC value	ICE value	Relevant Section
> 0	> 0	Section 3
> 0	= 0	Section 4.3.1
= 0	> 0	Section 4.3.2
< *ICE*-estimated activity at time of *IC*	> 0	Section 4.3.3
= 0	= 0	Section 4.3.4

4.3.1 IC > 0 and ICE = 0

It is possible to have fishers counted during an IC while the ICE value is zero. An example of when this might occur is when there are ICs for Fishing Sites 1 to 5 and fishers are counted at Sites 2, 4, and 5, but temporal counts or interviews only happened at Sites 1 and 3, where there were no fishers.

There are several options for dealing with this special case, and these options are dependent on whether there is information within the Effort Profile:

- Exclude the IC from the effort calculations if there are enough other ICs available.
- Borrow to calculate ICE.

By excluding the IC (first option), the user ignores the fishers recorded by the Instantaneous Count. Assuming there are other ICs during this Estimation Period, this may reduce precision.

Data borrowing can also be applied to calculate ICE (second option). This option uses Temporal Count data from Sites outside the Estimation Period or Area of interest to calculate ICE values for the target Estimation Period and Area. Borrowing requires subject matter expertise on the local fishery.

4.3.2 IC = 0 and ICE-estimated activity at time of IC > 0

In some cases, an IC may record zero fishers, but the ICE based on visual counts or interviews show that there is some effort at the same time t. This may occur due to observation errors (e.g., because of overhead brush coverage, fog, or on-water glare), because the IC was not taken at the exact time the visual counts occurred, or due to reporting errors during interviews. When IC = 0 and the ICE-estimated activity at the time of the IC > 0 (calculated using Equation 39), there are several options:

- Do nothing; treat the IC = 0 as a true measure of effort.
- Exclude the IC if there are enough other ICs available.
- Use the number of active fishers back-calculated from ICE (Eq. 39) instead of the zero IC.

$$ICE - estimated\ activity\ at\ time\ t = ICE_t \times Total\ Daily\ Effort\ , \qquad (39)$$

where Total Daily Effort refers to the total effort recorded by visual counts or interviews that day.

We recommend the second option. This uses the existing data while providing a conservative estimate of effort.

4.3.3 IC < ICE-estimated activity at time of *IC* with ICE > 0

In some cases, an IC may record fewer fishers than the number counted during visual counts or interviews at the same time. The rationale for this is similar to that described in Section 4.3.2: ICs may be lower because of observation error, because the IC was not conducted at the exact same time as the visual counts, or because of reporting errors during interviews. The activity at the time of the IC can be back-calculated using ICE (Eq. 39).

Due to this similarity, the options for dealing with such cases are the same as in Section 4.3.2:

- Do nothing; treat the IC as a true measure of effort.
- Exclude the IC if there are enough other ICs available.
- Use the number of active fishers back-calculated from ICE (Eq. 39).

Typically, the first option is used, and it can still provide an accurate measure of effort. This is our recommended approach. The third option, on the other hand, will overestimate Total Effort compared to the first. This is because the effort recorded from visual counts or interviews that day will be higher than the effort estimated by expanding the IC (IC divided by ICE_t), resulting in a higher Mean Daily Effort for the Estimation Period.

4.3.4 ICE = 0 and IC = 0

When there is no ICE and IC information, we drop the IC for that day. If there are no ICs with non-zero values, we assume that Total Effort is zero, and therefore Total Catch is also zero for the Estimation Area and Estimation Period.

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