# Evaluating and addressing uncertainty in recreational fishing effort estimates in the Southern Strait of Georgia

**by**

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# Declaration of Committee

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# Abstract

Recreational fishing is a popular activity worldwide; however, growing concerns regarding its impact on aquatic ecosystems have heightened the need to monitor and manage these fisheries effectively. While the relative impact recreational fisheries have may be comparable to commercial fisheries, the two fisheries are monitored in very different ways. Unlike commercial fisheries, monitoring recreational fisheries presents unique challenges due to their decentralized and heterogeneous nature. This study evaluates the performance of current methods used to estimate recreational fishing effort in the Strait of Georgia, a region with significant recreational fishing activity and multiple fishery sectors competing for the same resources (i.e., First Nations, Recreational, Commercial). A simulation model was developed to assess the accuracy and precision of recreation fishing effort estimates under different conditions and in areas with varying levels of fishing activity. Results indicate that the current estimation methods had highest accuracy and precision in high-effort areas, while estimates in low and medium-effort areas fared much worse. Estimates across all fishing activity levels and parameter variations showed a consistent bias toward underestimating fishing effort. As fisheries change and the management regimes behind them evolve, the methods used to monitor recreational fisheries must adapt to provide relevant data to inform sustainable management. The future success of recreational fisheries will depend on robust monitoring programs that are tailored to the conditions of a fishery and the data requirements of fisheries managers. This study demonstrates how simulation studies can aid in evaluating creel programs and contribute to the sustainable management of recreation fisheries.

**Keywords**: Recreational Fisheries; Catch Monitoring; Simulation Model; Strait of Georgia; Creel Survey

## Dedication

To my parents, Russ Lemp and Kathy Petts, my brother Matthew Lemp, and my partner Fiona Young—thank you for your never-ending support and encouragement. I could not have accomplished this without you.

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# Chapter 1.

# Background

Fishing, one of humanity's oldest methods of sustenance, has persisted throughout human history, with the earliest evidence of human ancestors cooking their catch dating back 780,000 years (Zohar et al. 2022); significantly predating the earliest evidence of farming, which is only 21,000 years old (Snir et al. 2015). Wherever people have settled near water, fishing has been a central activity and becomes intertwined into the cultural, social, and economic fabric of these communities. The primal urge to fish continues to captivate millions today, with recreational fishing serving as a modern outlet.

Recreational fishing, uniquely, lacks a universal motivation; participants often do not fish for monetary gain or exclusively for sustenance (Fedler and Ditton 1994, Pitcher and Hollingworth 2002, Smith 2002, Cooke et al. 2018). Preferences vary, with some anglers opting to retain their catch while others prefer catch-and-release practices (Arlinghaus et al. 2007, Myers et al. 2008, Gaeta et al. 2013). Recreational fishing takes many diverse forms and occurs in marine and freshwater ecosystems worldwide. Despite the variability among fisheries, one constant remains: where there are fish, there are people who want to catch them.

British Columbia, Canada, epitomizes this phenomenon, boasting 25,725 km of coastline and thousands of lakes and rivers. Recreational fishing has a strong foothold in the identity of coastal communities throughout the province, particularly since the decline of logging and commercial fisheries at the end of the 20th century (Edenhoffer and Hayter 2013, Stocks and Vandeborne 2017, Walters et al. 2019). The recreational fishery now sustains many small coastal communities, contributing approximately $1.1 billion in total revenue, 39% of the GDP for BC’s Fisheries and Aquaculture sector, and 9,000 jobs annually (*British Columbia’s Fisheries and Aquaculture Sector* 2016). The Salish Sea, located in southern British Columbia, hosts the largest recreational fishery in the province and serves as the focal point of the research in this thesis.

The Salish Sea is an ecologically-rich marine environment shared between British Columbia and Washington State. It is primarily composed of the Strait of Georgia

(SOG), Strait of Juan de Fuca (JDF), and Puget Sound. This study will focus on this area's Canadian portion, which excludes Puget Sound and southern JDF. The Strait of Georgia spans approximately 5,900 km$^2$, stretching 290 km in length and 32 km in width between Vancouver and Nanaimo. The Juan de Fuca Strait serves as the southern connection between the Salish Sea into the Pacific Ocean and spans approximately 4,100 km$^2$, stretching 152 km in length, and ranges from 19 km to 40 km in width. The Salish Sea is accessible from British Columbia's two largest population centers; Vancouver lies on the southeastern side of the SOG, and Victoria is located on the southeastern tip of Vancouver Island and marks the transition zone between the SOG and JDF. The areas encompassed in this study technically includes portions of the Salish Sea and Strait of Georgia. However, when referring to the recreational fishery, the area is commonly known simply as the Strait of Georgia. Therefore, throughout this thesis, the study area will be referred to solely as the Strait of Georgia.

The SOG recreational fishery sees its peak activity during the months of May through September, accounting for approximately 85% of annual fishing trips (English et al. 2002). With the recent closures to Chinook retention during most of the peak season as of 2019, the assumption that 85% of annual effort occurs between May and September may no longer be valid. During the peak season, anglers predominantly target migrating Pacific salmon. Historically, Chinook (*Oncorhynchus tshawytscha*) and coho salmon (*O. kisutch*) were the preferred targets (English et al. 2002). However, due to declines in Chinook and coho abundance that led to reduced catch rates and managed retention opportunities, anglers have increasingly targeted pink (*O. gorbuscha*) and sockeye (*O. nerka*) salmon (English et al. 2002). This also led to greater interest in groundfish fisheries (i.e., targeting fish that live and feed primarily near the ocean floor) (see English et al., 2002), with rockfish (*Sebastes* spp.) and lingcod (*Ophiodon elongatus*) being targeted along the eastern coastline of Vancouver Island and halibut (*Hippoglossus stenolepis*) sought near Victoria in the JDF. In the off-season, the most dedicated anglers target what are known locally as "winter Chinook". Anglers are able to target winter Chinook throughout the off-season (i.e., October-March) as Chinook spend part of their ocean life stage in near-coastal waters feeding on forage fish like Pacific herring (*Clupea pallasii*) and Pacific sand lance (*Ammodytes hexapterus*; Riddell et al., 2018; Trudel et al., 2009). Most fishing activities are boat-based, however, there is some shore-based fishing effort. It is assumed that boat-based anglers represent the only significant source of effort as “boat days” is the unit used by Fisheries and Oceans Canada (commonly referred to using the outdated acronym DFO) to measure fishing effort in the SOG recreational fishery (English et al. 2002, Zetterberg et al. 2011).

The recreational fishery in the SOG has changed dramatically over recent decades. Fishing effort markedly declined from the 1960s to the end of the 20th century (English et al. 2002). Peak effort in the 1980s exceeded 600,00 boat-days, then dipping below 100,000 in 2008, with the latest 5 year average being 101,724 in 2023 (See Figure A1; English et al. 2002, Zetterberg et al. 2011, Fisheries and Oceans Canada 2024). Today, the fishery continues to change, with major sections of the SOG closed to Chinook retention during peak season since 2019 to protect stocks of concern and aid recovery of endangered Southern Resident Killer Whales (SRKWs; (Fisheries and Oceans Canada 2019a, 2019b, Hanson et al. 2021). Following these closures, anecdotal observations indicate fishing effort has concentrated in the few remaining open areas, shifted towards fall and winter months, and redirected further to other target species.

Despite reductions in effort, target switching, and new closures, the SOG recreational fishery has emerged as the dominant sector in the region, surpassing commercial catch of the main targets species (English et al. 2002). Technological advancements have played a pivotal role in the continuous change of this fishery. Tools such as electric downriggers, sonar, radar, GPS chart plotters, and high-powered marine engines have significantly enhanced recreational anglers effectiveness and expanded the range they can travel to find fish (Torres-Irineo et al. 2014, Cooke et al. 2021).

The traditional assumption that recreational fisheries have a minor impact on marine ecosystems compared to commercial fisheries is no longer widely accepted (Cooke and Cowx 2004, 2006, Coleman et al. 2004). Research indicates that catch from recreational fisheries surpass that of commercial fisheries in many cases (Cooke and Cowx 2004, 2006, Coleman et al. 2004, Ihde et al. 2011). This realization has intensified pressure on management agencies to enhance monitoring of catch and effort for the recreational fishery to enable fair resource allocation, in priority order, between conservation needs, First Nations fisheries, recreational fisheries, and commercial fisheries (Cooke & Cowx, 2006; Fisheries and Oceans Canada, 1999; Hartill et al., 2012). There is a growing sense of urgency to evaluate the current methods used to monitor the recreational fishery. This coincides with a shift in management priorities towards adopting the precautionary approach and prioritizing conservation and broader ecosystem needs (Fisheries and Oceans Canada 2005, 2009, Cohen 2012, Price et al. 2017). To address evolving management objectives while maintaining harvest opportunities across fishery sectors, management actions are being implemented at increasingly fine temporal and spatial scales. However, these actions are not necessarily aligned with the scale at which the fishery is currently monitored, highlighting the need for an evaluation of the current monitoring methods.

The recreational fishery in the SOG has been monitored by DFO since the 1950s, although the current robust methodologies for monitoring the fishery were only developed in 1983 (English et al., 2002). The Strait of Georgia Creel Survey Program (Est. 1983) marked a substantial leap forward in the methods behind catch and effort monitoring in the SOG. With over 500 landing sites and thousands of square kilometers of water, monitoring recreational anglers across this expansive area poses an incredible challenge. The SOG Creel Survey Program utilizes both aerial surveys and on-site angler interviews to generate estimates of catch and effort (English et al. 2002, Zetterberg et al. 2011). Aerial surveys provide spatially explicit instantaneous counts of individual fishing vessels along pre-determined flight paths. The flight paths and departure times are strategically designed to cover high-effort areas at peak fishing hours (English et al. 2002, Zetterberg et al. 2011). Angler interviews are conducted by surveyors stationed at high-traffic boat launches and marinas, where they interview anglers returning from their fishing trips (Zetterberg et al. 2011). Information collected includes the number of licensed anglers on board, departure and return times, the proportion of the trip dedicated to fishing, fishing locations, and a summary of retained and released catch (English et al. 2002, Zetterberg et al. 2011). For the purposes of estimating fishing effort, these methods complement each other because interview data on relative temporal and spatial fishing distribution are used to expand instantaneous counts from flights to total monthly estimates of effort. These methods were intended for and most effective during, peak fishing season when surveyors can engage with a large number of anglers, and aerial surveys have a high probability of locating active fishing vessels (English et al., 2002)

The purpose of this thesis is to evaluate the methods for estimating fishing effort in the SOG. The primary objective is to assess the accuracy and precision of the current effort estimation methods using a simulation model to replicate fishing effort and the associated sampling methods. Additionally, the secondary objective is to gauge sensitivity of the model to parameters that could reasonably change within the fishery or through an adjustment in the creel program methods (see Table 2) and its performance in areas with varying levels of effort. This study focuses on the fishery in its present state and indirectly assesses whether methods used can provide fishing effort estimates at a resolution relevant to fisheries managers. Ultimately, the intent of this work is to offer valuable insights to the Department of Fisheries and Oceans to inform decisions regarding the future of monitoring the recreational fishery.

# Chapter 2.

# Evaluating and addressing uncertainty in recreational fishing effort in the Southern Strait of Georgia

## 2.1. Introduction

Recreational fishing is economically and socially important around the world, with roughly 10% of the world's population participating in the activity (Arlinghaus et al. 2015). This has resulted in recreational fisheries becoming an increasingly important economic contributor in many countries. In the United States recreational fisheries produced 595 thousand jobs, $98 billion USD in sales, and $55 billion USD in value added impacts in 2020 (National Marine Fisheries Service 2020). However, this growth in popularity has led to an increased awareness of the strains recreational fisheries have on marine resources, contributing to their over-exploitation (Cooke and Cowx 2004). Contrary to traditional assumptions placing the blame for declines in fish stocks solely on commercial fisheries, it is now evident that recreational fisheries have a significant impact on marine resources and can even exceed commercial fisheries (Cooke and Cowx 2004, 2006, Coleman et al. 2004, Ihde et al. 2011). As a result, managing agencies are under increased pressure to improve the management of recreational fisheries and create formal resource allocation agreements between commercial, recreational, and traditional use fisheries (e.g., First Nations food, social, and ceremonial fisheries; Coleman et al., 2004; Cooke & Cowx, 2004, 2006; Fisheries and Oceans Canada, 1999; Scheufele & Pascoe, 2022). There is a growing need for rigorous monitoring programs for recreational fisheries to support sustainable management actions.

Monitoring recreational fisheries presents unique challenges due to their decentralized and unpredictable nature. Unlike commercial fisheries, recreational anglers are rarely obligated to maintain records and are typically hesitant to disclose detailed information on fishing locations and catches (McCluskey and Lewison 2008). Additionally, recreational anglers exhibit diverse behaviours, motivations, skills, and tactics, leading to variable responses in fishing effort when there are changes in the fishery (Post et al. 2008, Arlinghaus et al. 2008, Beardmore 2013). In commercial fisheries, fishing vessels are often concentrated at centralized commercial ports, allowing for efficient catch inspections. Recreational anglers tend to originate from numerous landing sites, complicating monitoring efforts. Consequently, there is no universally accepted survey method to monitor all recreational fisheries (Hartill & Edwards, 2015; Hartill et al., 2012; Pollock et al., 1994).

Monitoring recreational fisheries requires collecting key information on when and where anglers fish, and what they catch (Pollock et al. 1994, McCluskey and Lewison 2008). This information can be collected through a variety of methods, each offering different temporal and spatial resolutions. On-site creel surveys are typically the most expensive and require two methods to collect the necessary information to estimate effort, catch per unit effort (CPUE), and total catch (Soupir et al. 2006). For example, the Strait of Georgia Creel survey in British Columbia, uses a combination of flight surveys to get spatiality explicit instantaneous effort counts (Hoenig et al. 1993, English et al. 2002) and landing site interviews to gather information on fishing activity patterns (i.e., where they fished, and for how long) and catch (English et al. 2002). Off-site creel surveys, on the other hand, sample anglers after the fishing event has occurred. Anglers are often selected and contacted from a licence database sample frame and are asked to self-report on their fishing activity and catch (Henery and Lyle 2003). While off-site surveys may be cost-effective and cover a broader range of fishing activities, they are more susceptible to biases (Fisher, 1996; Fisher et al., 1991; Hartill & Edwards, 2015; Jones & Pollock, 2012; Tarrant et al., 1993). Each fishery is unique and requires careful consideration to select the appropriate methods and tailor a monitoring program that fits the scale of the fishery and meets the requirements of fisheries managers (Hartill et al., 2012; Pollock et al., 1994).

Recreational fisheries have undergone significant transformation in recent decades. Technological advancements such as advanced GPS, sonar, and high-powered engines, are now standard on most recreational fishing vessels, enhancing their effectiveness and ability to access more water (Torres-Irineo et al. 2014, Cooke et al. 2021). The way these fisheries are managed has also changed. Fisheries managers are increasingly adopting the precautionary approach and prioritizing conservation and ecosystem needs, over those of any fishing sector (Fisheries and Oceans Canada 2005, 2009, Cohen 2012, Price et al. 2017) In the case of the Strait of Georgia recreational fishery, changes to multiple social and ecological concerns have led to management actions at increasingly fine temporal and spatial scales (Fisheries and Oceans Canada 1999, 2005, 2009, 2019a, United Nations General Assembly 2007). With these changes to recreational fisheries, every monitoring program should be periodically reassessed to ensure they still use the most cost-effective methods to produce accurate effort, catch, and CPUE estimates at the appropriate resolution (Hartill et al., 2012; Kerckhove et al., 2024). Producing estimates at a resolution relevant to managers means generating estimates that are statistically reliable at a spatial and temporal scale that's allows the efficacy of management actions to be assessed and determine if key management objectives are being met.

The current methods used to monitor the recreational fishery in the Salish Sea were developed in 1983 and were assessed and updated by English et al. (2002), yet the fundamental structure of the program remained unchanged. Since the development of this program the fishery has evolved dramatically. The most recent change began in 2019 when significant portions of the Salish Sea were closed to Chinook salmon (*Oncorhynchus tshawytscha*) fishing for what is traditionally the peak fishing season (i.e., April-August). These closures have either remained in place or expanded as of 2024 and may have contributed to a fundamental change in seasonal fishing patterns not accounted for in the current creel methodology. An assessment of the bias, precision, and alignment of current monitoring methods with the needs of fisheries managers is overdue, given the rapid changes in the fishery and the evolving management priorities.

In this study, a simulation model of recreational fishing effort in the Strait of Georgia is used to evaluate the performance of methods currently used to estimate fishing effort. This assessment entails analyzing the bias and precision of effort estimates under normal conditions and after adjusting various parameters to identify sensitivity of the model to various parameters. Additionally, the effort estimation method is compared across simulated areas with differing levels of fishing activity to gauge performance at varying levels of simulated effort. While this study does not directly address catch estimation, its findings remain relevant as catch estimation relies directly on effort estimates to extrapolate total catch estimates from CPUE. The results of this study will work to inform discussions by Fisheries and Oceans Canada (DFO) on the future of monitoring the recreational fishery and if the current methods can meet the needs of fisheries management now and into the future.

## 2.2. Methods

### 2.2.1. Study Area

The Salish Sea includes over 500 landing sites, including public boat launches, marinas, and private docks and launches. Within this area, five Pacific Fisheries Management Areas (PFMAs) (PMFAs 17, 18, 19, 20, 28, and 29) and thirty-nine creel sub-areas were selected to be included in the simulation study. These areas represent most of the area on the Canadian side of the Salish Sea. The study area consists of all the creel sub-areas covered by the southern SOG overflight route. Including only one flight path in the study area was a logical cutoff point and reduced complexity in the simulation (see Figure B1 for a map of the southern SOG overflight route).

### 2.2.2. Overview

Evaluating the fishing effort estimation process involved a simulation model, built in R version 4.3.2 (R Core Team 2023), recreating activity of individual boats and sampling from that activity to mimic the sampling process currently used to generate recreational fishing effort estimates. The simulation model reproduces individual boats leaving many landing sites to fish in one of the creel sub-areas before returning to the same landing site later in the day. The simulated fishing effort was then systematically sampled to reflect the methods used in the creel survey as laid out by English et al. 2002. Estimates of fishing effort and standard error for each month and sub-area were calculated using equations described in English et al. 2002, which DFO currently uses to estimate recreational fishing effort. These different components are detailed below.

### 2.2.3. Simulation Model Structure

The simulation model replicates fishing effort in each month across 39 distinct fishing areas representing the creel sub-areas within Pacific Fisheries Management Areas (PFMAs) 17, 18, 19, 20, 28, and 29 in the Salish Sea. Please note that the terms ‘fishing area’ and ‘creel sub-area’ refer to the same set of boundaries. The term ‘fishing area’ will be used when referring to the simulation model. Fifty-six landing sites distributed throughout the study area serve as vessel departure points. Among these, twenty-six sites correspond to actual landing sites monitored by DFO creel observers.

Additional duplicate landing sites were generated to account for unmonitored landing sites, including private docks, marinas, and boat launches. Notably, monitored landing sites, often high-traffic areas, were originally chosen by DFO assuming a substantial portion of nearby fishing activity uses these facilities. The default assumption in the simulation model is that monitored landing sites represent only 50% of total trips occurring in the SOG fishery. It is assumed that there is no difference in the behavior of anglers between monitored and unmonitored landing sites. Therefore, the proportion of effort using a monitored landing site simply refers to the proportion of the angler population that is available to be interviewed. Effort was simulated for each fishing area (i.,e creel sub-area), month, and year between 2014 and 2021 when the creel survey was active. To initiate the simulation, the number of boats fishing from each landing site each day are drawn from a Poisson distribution with mean corresponding to the empirical average for that site and month based on interview data. Each boat departs to one of the fishing areas before returning to their departure site. Departure times for each landing site and its duplicate are a random normal variable with mean and standard deviation derived from observed average departure times taken from interview data (see Table C1) . Post-departure, boats disperse across fishing areas, with their choice of landing site and fishing area determined by a gravity model. The return of boats is contingent on trip lengths, using a beta distribution of the remaining hours of the day to determine return times. The mean trip lengths were estimated from interview data for each landing site and month.

The gravity model distributed boats to fishing areas based on the probability of a boat travelling from a landing site to a fishing area. This probability is influenced by the scaled ratio of benefits to costs, with costs determined as the distance from the landing site to the fishing area ($d_{l,a}$) and benefits determined by an area-specific attractiveness ($\alpha_a$) scaled by a regulation index ($O_a$, described in Section 2.2.4.3):

$$\text{(Eq. 1a)} \qquad \theta_{l,a} = \frac{\alpha_a O_a}{d_{l,a}};$$

$$\text{(Eq. 1b)} \qquad p_{l,a} = \frac{\theta_{l,a}}{\sum_a \theta_{l,a}}.$$

Attractiveness of each fishing area and month was estimated by fitting to the number of trips from each landing site to each creel sub area in each month of interview data assuming these data follow a multinomial distribution. All months were evaluated simultaneously with attractiveness of each area estimated as a random parameter across months. Mean and standard deviation of attractiveness across sites were estimated as main effects.

The basic structure of the gravity model was inspired by Walters and Bonfil (1999), where they used a gravity model to simulate the distribution of effort between fishing grounds for a ground trawl fishery. They simulated how effort is distributed across fishing grounds based on the catchability, price, and biomass of each species present on the fishing grounds. Because we are simulating a recreational fishery, not a commercial fishery, we cannot assume that where an angler decides to fish is influenced by the same parameters equally. Recreational anglers are not driven by profit, and there is not a universal motivation among all anglers. To avoid making assumptions on what parameters affect the distribution of recreational effort, we instead fit our gravity model to creel interview data to determine the relative attractiveness of each area based on the landing site an angler is leaving from and the time of year. By fitting the gravity model to data in this way, we avoid making assumptions about how anglers decide where to fish and instead estimate relative attractiveness based on where anglers actually went fishing. The only parameters we assume to have a universal effect on the distribution of fishing effort are the distance to the fishing site (e.g., travel time and fuel use) and regulations (e.g., which target species are open to retention. These parameters are used to scale the gravity model.

### 2.2.4. Data Inputs and Model Parameterization

#### *Geospatial Data Acquisition and Processing*

A distance matrix containing the Euclidean distance between each landing site and fishing area was used in the gravity model to scale the costs associated with travelling to a fishing area from a landing site. Coordinates for each landing site were acquired from Google Maps, cross-referencing site name information from Zetterberg et al. (2011). The resulting dataset was then used for distance calculations between each landing site and the geometric center of the respective fishing areas. The geometric center of each fishing area was calculated using the centroids tool in QGIS version 3.16.1 (QGIS Development Team 2023). Opting for the geometric center rather than the nearest border ensured an accurate representation of spatial dynamics, particularly accounting for variations in this size of fishing areas.

### *Creel Interview Data*

Creel interview data spanning 2014 to 2021 provided data on fishing locations, and durations. Interviewed anglers provided times they left and returned, the area(s) they fished, and their catch per hour. A full list of interview variables and their meaning is provided in Table D1. Mean start times, trip lengths, and the mean number of boats departing each landing site for each month and day type (weekend/weekday) were extracted from this dataset. Additionally, the number of boats leaving from each landing site to fish in each subarea were calculated, which provided the dependent variable for fitting the gravity model.

### *Regulation Data Compilation and Translation*

Regulations for each fishing area and month were used to scale the costs of travelling to a fishing area from a landing site. Regulations were collected for all five spices of Pacific salmon (Chinook*;* coho, *O. kisutch*; sockeye, *O. nerka*; chum, *O. keta*; and pink *O. gorbuscha*), halibut (*Hippoglossus stenolepis*), and lingcod (*Ophidon elongatus*). Although rockfish (*Sebastes spp.*) are another common target of recreation anglers, regulations for all 38 BC species are complex and not as strongly targeted by anglers, so they were excluded. Each species was first given its own "openness" score, based on a sub-score from 0-1 for retention, proportion of the fishing area open, and proportion of the month open. The product of all sub-scores for a species provided a final score from 0-1 for a particular month and creel sub-area. A score of 0 indicates the species was closed for retention in the entire area for the whole of the month. Partial scores were not given for differences in retention limits or size restrictions because that would require an assumption on how this would affect effort. A final regulation index was calculated by taking the average openness across all species within a month and sub-area.

The absence of a comprehensive historical fishing regulations database necessitated an exhaustive search through fisheries notices. DFO uses fisheries notices (https://notices.dfo-mpo.gc.ca/fns-sap/index-eng.cfm?pg=fishery_search&ID=allhttps://notices.dfo-mpo.gc.ca/fns-sap/index-

eng.cfm?pg=fishery_search&ID=all) to enact regulations on openings and closures, retention limits, size restrictions, gear restrictions, area closures, and the implementation of protected areas. Notices for all target species were scanned to build a database for regulations in PFMAs 17, 18, 19, 20, 28, and 29 from 2014-2021.

Recreational catch and effort are monitored on a different spatial scale than regulations are given. Regulations are provided at the PFMA sub-area level; these PFMA sub-areas were designed to create easily defined areas using distinct landmarks that allow regulations to be followed by the public. Creel sub-areas were created to capture all effort at known popular locations in one area, with the lines of division located in less frequented areas (see Appendix E). This means fishing regulations needed to be translated into the creel sub-area level. If a creel sub-area contained portions of more than one PFMA sub-area, then the proportion made up by each PFMA sub-area was estimated and applied to the total openness score for that area and species. The same rules applied for closures with arbitrarily defined boundaries that did not follow the PFMA sub-area boundaries.

Effort and catch are monitored and reported monthly, so openings and closures often occur on the first or last day of a month. For cases when regulation changes occurred in the middle of a month, the number of days where retention was open in that month was divided by the total number of days to give the proportion of time open.

### 2.2.5. Sampling Simulated Effort

Our approach to simulating fishing effort closely mirrors the established methods of the DFO Creel Survey. See Zetterberg et al., 2011 for a detailed description of these methods. In simulating angler interviews, interview shifts were randomly allocated each month, stratified by day type across all landing sites within a Landing zone. Landing zones group the landing sites into regional areas to facilitate movement by creel interviewers. The zones included here are Vancouver, Victoria, Cowichan/Nanaimo, and the Sunshine Coast. Shift times were also randomized to ensure coverage across all daylight hours and work blocks (see Zetterberg et al., 2011). Different landing site groups follow specific sampling schedules, each with one or two samplers. Simulated samplers “interview” boats that returned to their landing site within the defined hours of their sampling shift and recorded information on the fishing area visited, departure times, and return times, with no error. To account for interviewer saturation a maximum of 30 interviews per hour was set, determined using the maximum number of interviews per-hour as seen in interview data from 2014-2021. If more than 30 boats arrived at a landing site within an hour then 30 boats were randomly selected without replacement to be interviewed. The return times for boats not interviewed was still recorded as missed interviews is accounted for by weighting factor 2 (*W*2; see Table 1).

Flight survey schedules were randomly assigned throughout each simulated month stratified by day type. A default of ten flights per month was used to mimic actual flight schedules, although there can be 6-10 monthly flights, depending on budgetary constraints. Flights follow a predefined path and execute an instantaneous count of boats engaged in fishing within each sub-area along the flight path. The model assumed that each vessel in each sub-area is counted without error when a flight passes overhead. Flight paths and departure times were designed to cover significant concentrations of recreational fishing activity at peak times (see English et al. 2002 for more details). Count times for each sub-area are determined based on the departure time of the flight and the sequential order of each area in the flight path. Simulated departure times for each flight are varied randomly, assuming a normal distribution based on the set departure time to account for natural variability in departure. The simulation does not account for flight cancellations, delays, poor visibility, and other events that may disrupt flight surveys. Full cancelations are rare and do not occur each season, but delays and changes to the flight path are more common. If a flight is delayed more than three hours from the designated departure time the flight is rescheduled to the next available day within the same month and day type (weekend/weekday) (Patrick Zetterberg, Fisheries and Oceans Canada, pers. comm.).

### 2.2.6. Estimating Simulated Effort

Effort estimates in this study are calculated on the scale of individual creel sub-areas within a specific month and day type (*d*), representing an estimation period. While there are cases where estimates are computed for half months, especially in the presence of significant regulation changes, our focus here is exclusively on full-month estimations.

Effort was estimated based on equations outlined by English et al. (2002), coding them in R version 4.3.2 (R Core Team 2023) and adapting them to align with our simulated data. English et al. (2002) provides a comprehensive review of creel survey methods, presenting the latest version of these methodologies.

The outcome of our effort estimation model is the total monthly fishing effort for a creel sub-area, accompanied by the standard error surrounding that estimate. Table 1 outlines equations employed in this estimation process. Given that this study explicitly addresses the effort estimation aspect of the creel survey, only equations pertinent to effort estimation will be described here.

To address sampling error weighting factors are used to correct for the relative frequency at which a time block is sampled (*W*1), and interviews that are missed by creel samplers (W2). *W*1 accounts for variations in the sampling frequency of different time blocks within an estimation period (Table 1). It is calculated as the ratio of total number of days sampled to the number of times a specific time block was sampled. *W2* accounts for interview saturation, ensuring boats that returned to a landing site when a creel surveyor was present but were not interviewed are included in the instantaneous counting efficiency (ICE) calculation. *W*2 is calculated as the ratio of the total number of boats returning to a landing site but not necessarily interviewed to the number of boats interviewed within a specific time block (Table 1). Both *W*1 and *W*2 are used in calculating the total monthly fishing trips ($\hat{T}_{dg}$) within an estimation period for a given day type (*t*) and a group of landing sites (*g*) (Table 1).

The total fishing boats per time block ($\hat{A}_{dgt}$), calculated based on creel interviews, determines the number of actively fishing boats during each time block. This is then divided by the total monthly fishing trips ($\hat{T}_{dg}$) to ascertain the average proportion of daily effort active during the hour of the flight survey ($P_{dgt}$), where $P_{dgt}$ across all hours is referred to as an activity profile (Table 1). This proportion is used to calculate the estimated number of boats fishing during the day of each flight survey.

The total estimated effort for an estimation period is derived by summing the estimates of boats fishing during the day of an overflight, dividing by the number of flights ($n_{ds}$), and multiplying by the number of days in an estimation period ($N_d$) (Table 1). Variance for daily fishing effort estimates ($S^2B_{ds}$) is used to calculate the variance for the entire estimation period ($S^2E_{ds}$). This overall variance is then used to compute the standard error for the monthly estimate, encompassing both day types (*d*) (Table 1).

English et al. (2002) recommends a minimum of 50 interviews per month at a landing site is suggested for constructing an activity profile. However, DFO has set a practical threshold of 40 interviews as the minimum for creating an activity profile, serving as the default value for this study. All interviews from landing sites within a designated group are used for the activity profile, regardless of the specific creel sub-area.

If the total interview count falls below 40, the estimation process involves borrowing interviews from nearby landing sites (Patrick Zetterberg, Fisheries and Oceans Canada, pers. comm.). Site selection for interview borrowing is subjective and based on expert judgment, typically favouring the next closest landing site. Given the simultaneous execution of the estimation model across all creel sub-areas, a departure from the case-by-case methodology for selecting landing sites used by DFO to borrow interviews was necessary. Instead, if the interview count falls below 40, interviews from the next nearest landing site to the creel sub-area are incorporated, and this process repeats until the established minimum threshold is met. This process assumes activity profiles between creel sub-areas are highly correlated.

**Table 1. Equations Used to Estimate Effort for the SOG Creel Survey as described in English et al. 20**

| Equation | Parameter and index description | Resulting Calculation |
|---|---|---|
| T1.1 $W1_{dij} = \frac{N_d}{n_{dij}}$ | $N_d$ is the number of type *d* days.<br>$n_{dij}$ is the number of times that work block *j* was sampled at site *i* on type *d* days. | Weighting factor 1: Accounts for relative frequency a time block is sampled. |
| T1.2 $W2_{dijk} = \frac{L_{dijk}}{I_{dijk}}$ | $L_{dijk}$ is the number of boats landed on type d days.<br>$I_{dijk}$ is the number of interviews on type *d* days. | Weighting factor 2: Accounts for interviewer saturation. |
| T1.3 $\hat{T}_{dg} = \sum_i \sum_j \left[W1_{dij} \sum_k \sum_q \left(W2_{dijk}\right)\right]$ | $W1_{dij}$ is weighting factor one.<br>$W2_{dijk}$ is weighting factor two. | Total fishing interviews. |
| T1.4 $\hat{A}_{dgt} = \sum_i \sum_j \left[W1_{dij} \sum_k \sum_q \left(W2_{dijk} A_{dijkqt}\right)\right]$ | $A_{dijkqt}$ can equal 1 or 0, indicating whether a specific fishing party (*q*) was actively fishing in timeclock (*t*). | Total fishing boats per time block. |
| T1.5 $P_{dgt} = \frac{\hat{A}_{dgt}}{\hat{T}_{dg}}$ | $\hat{A}_{dgt}$ is the fishing activity per time block.<br>$\hat{T}_{dg}$ is the total within the estimation period. | The proportion of daily fishing effort active during the hour of the flight survey. |
| T1.6 $B_{dsu} = \frac{B_{dsut}}{P_{dgt}}$ | $B_{dsut}$ is the number of sport fishing vessels observed actively fishing at the time of the flight survey.<br>$P_{dgt}$ is the portion of the daily fishing effort active at time (t). | Estimated number of boats fishing during the day of the flight survey. |
| T1.7 $E_{ds} = \frac{\sum_u B_{sdu}}{n_{ds}} N_d$ | $N_d$ is the number of type *d* days in a estimation period.<br>$n_{ds}$ is the total number of flights. | Final estimate of total monthly fishing effort. |
| T1.8 $S^2_{B_{ds}} = \frac{\sum_u B^2_{dsu} - \frac{\left(\sum_u B_{dsu}\right)^2}{n_{ds}}}{(n_{ds}-1)} \left[\frac{N_d - n_{ds}}{N_d - 1}\right]$ | $B_{sdu}$ is the estimated number of boats fishing during the day of the overflight.<br>$N_d$ is the number of type *d* days in an estimation period.<br>$n_{ds}$ is the total number of flights. | Variance for daily fishing effort estimate. |

| Equation | Parameter and index description | Resulting Calculation |
|---|---|---|
| T1.9 $S^2_{E_{ds}} = N^2_d S^2_{B_{dsu}}$ | $S^2_{B_{dsu}}$ is the variance for daily fishing effort estimates.<br>$N_d$ is the number of type *d* days in an estimation period. | Variance for Total monthly fishing effort estimate. |
| T1.10 $SE_{E_s} = \sqrt{\sum_d \left(\frac{S^2_{E_{ds}}}{n_{ds}}\right)}$ | $S^2_{E_{ds}}$ is the total estimation periods variance.<br>$n_{ds}$ is the total number of flights. | Standard error of total month fishing effort estimate. |

### 2.2.7. Simulation Study Structure

The framework of the simulation study adheres to a structured design outlined as follows: the simulation generates one month of effort for all 39 fishing areas. Each simulation in each area is parametrized based on data for that month and area. A compilation of months and years with sufficient creel interview data is used to parametrize the simulation, excluding off-season months (i.e., November – March) when the creel survey is inactive. Each simulation randomly selects a month and year from the list of eligible months for execution.

Simulations were repeated multiple times to generate stable predictions of accuracy and precision between simulated and estimated effort. To determine the requisite number of simulations, an initial 1,000 simulations were conducted with all variables set to their default values. By calculating the mean squared logarithmic error (MSLE) between simulated and estimated fishing effort across all areas for each simulated month, it was observed that the distribution of MSLE over the number of simulations stabilized after 500 iterations. Choosing a conservative approach, the decision was made to conduct 700 simulated months for each scenario.

A sensitivity analysis on five parameters was conducted to evaluate model sensitivity to key assumptions. Each parameter value adjusted by +/- 10% (see Table 2. All remaining variables are returned to their default values for each scenario. The simulation evaluates 700 random month-area combinations for each scenario, with the month and year for each run randomly determined. These scenarios aim to assess how accuracy and precision of the estimation model might change with these specific parameters by comparing them against the default settings.

**Table 2. Pramater Values**

| Parameter | Default Value | High Value | Low Value |
|---|---|---|---|
| Number of Flight Surveys in a Month | 10 | 12 | 8 |
| Number of Interview Shifts (for one month across all areas) | 270 | 297 | 243 |
| Minimum Number of Interviews Required to Create an Activity Profile | 40 | 44 | 38 |
| Proportion of Total Simulated Effort Using Monitored Landing Site | 50% | 60% | 40% |
| Interview Shift Times (exact times depend on the month being simulated) | Regular AM and PM shift hours | Shifted 3 hours earlier | Shifted 3 hours later |

### 2.2.8. Analysis

For each scenario (700 simulations), effort estimates were grouped into high, medium, and low effort areas based on simulated effort This grouping excluded areas and times with fewer than ten simulated monthly boat trips, as the probability of counting any boats during flight surveys in these low-effort areas is extremely low. On average, 93.1% (SD = 8.5%) of flight surveys counted zero boats in areas with fewer than ten boat trips, which could skew results for the low effort category. It is already understood that these effort estimation methods do not perform well in areas with extremely low effort. Area-months were divided into groups of between 10-500 boat trips, 500-1,500 boat trips, and greater than 1,500 boat trips to assess how the estimation model performs across areas with varying effort. For comparison, creel survey effort estimates from 2014-2021 shows a mean effort estimate of 477 boat trips per sub-area per month, with a standard deviation of 1,007 boat trips.

The $\log_2$ error for each effort estimate was calculated as a metric to evaluate the error of the estimated effort compared to simulated effort. $\text{Log}_2$ error was selected because it enables the comparison of proportional differences between estimated and simulated values, which is crucial when comparing areas with varying levels of effort. Additionally, $\log_2$ error facilitates allows for assessing positive or negative biases in the effort estimates. $Log_2$ error is calculated as the base 2 logarithm of the ratio between the estimated value (E) and the simulated value (S) plus 0.1:

$$Log_2 \text{ Error } = \log_2\left(\frac{E}{S} + 0.1\right)$$

The constant term of 0.1 was added to the ratio between the estimated and simulated values to address scenarios where 0 effort was estimated but there was simulated effort.

Confidence intervals (CIs) were used to evaluate the proportion of simulated effort falling within the 95% confidence intervals of the estimated effort (i.e., coverage). The CIs were calculated assuming a normal distribution in accordance with variance and standard error calculations outlined by English et al. 2002 (see Table 1).

Correlation between activity profiles in different areas was calculated to evaluate the hypothesis that activity in nearby areas are correlated, thus borrowing interviews from landing sites outside of the designated landing site group should not affect effort estimates. Interview data from 2014-2021 was used for all areas included in the simulation study. Using the default landing site groups, activity profiles were calculated for each creel sub-area, day type, month, and year with enough interviews. The Pearson correlation coefficient was calculated for each unique combination of creel sub-areas within the same temporal strata (i.e., day type, month, and year). Euclidian distances between creel sub-areas were determined using the same methods as those to determine the distance between creel sub-areas and landing sites. Subsequently, each Pearson coefficient was plotted against the distance between the two creel sub-areas used in its calculation.

To explore potential mechanisms contributing to bias, the true portion of total effort on each day during flight surveys was compared against the estimated portion associated with the same time and day-type of the flight survey determined via creel interviews. This comparative assessment was conducted with single simulation done for the month of August. The estimated proportion of daily effort was extracted from the activity profile corresponding to the time block of the flight count. This estimated proportion of daily effort is what would be used to expand the flight count to an estimate of total daily effort, as outlined in Eq. T1.5. Therefore, any discrepancies between the estimated and true portion of daily effort active during the flight count would indicate an impending bias in the resulting estimate of total effort.

## 2.3. Results

Seven hundred months were simulated with the default parameters. 717 month-areas had greater than 1500 simulated boat trips, 1,687 month-areas had between 500 and 1500 simulated boat trips, and 4,165 month-areas had between 10 and 500 simulated boat trips. Estimates across all month-areas combined demonstrated a median bias of -0.46 and a 95th percentile of 0.96. Estimates for high and medium effort areas exhibited greater precision and less bias compared to estimates for low -effort areas. High-effort areas displayed a median $\log_2$ error of -0.33, with a 95th percentile of -0.12, suggesting precise estimations with a small negative bias. Conversely, medium-effort areas had a median $\log_2$ error of -0.34, with a 95th percentile of 0.10, and low-effort areas demonstrated a mean $\log_2$ error of -0.37, with a 95th percentile of .35 (Figure 1). Note that $\log_2$ proportional error implies a doubling or halving of the proportional error between simulated and estimated effort values for each increment of 1.0, whereas $\log_2$ proportional error of zero implies no estimation error. A median $\log_2$ error of -3.2 indicates zero estimated boats after the 0.1 adjustment, when there were in fact some boats fishing. In fact, 68.6% of simulated flights counted zero boats across all areas. Specifically, in low-effort (n=4165), areas, a mean 34.3% of flights counted zero boats, while a mean of 0.11% and 0% of flights in medium (n = 1687) and high (n = 717) effort areas counted zero boats.

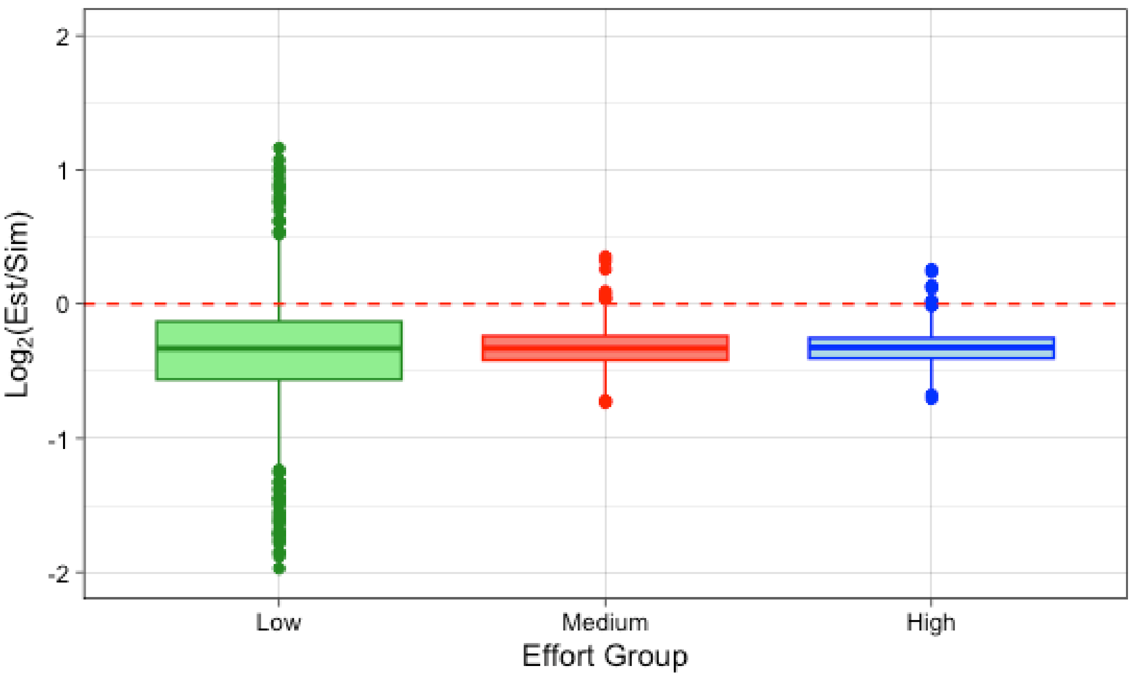

**Figure 1.** **Box plot of $\log_2$ proportional error between estimated and simulated effort across different effort groups: Low (n = 4165), Medium(n = 1687), and High (n = 717) effort areas. The red dashed line signifies where there is no difference between the simulated and estimated values.**

For the 700 simulations conducted with default parameters, only 25% of all estimates captured the true simulated effort within the 95% confidence intervals. However, these results were inconsistent across areas, as indicated when areas were separated into effort groups based on the simulated effort relative to all area-month combinations. Only 1% of estimates in high-effort areas captured the true simulated effort within the 95% confidence intervals. Medium effort areas had 2%, and in low-effort areas, 28% of estimated confidence limits overlapped with the true simulated effort (Figure 2).

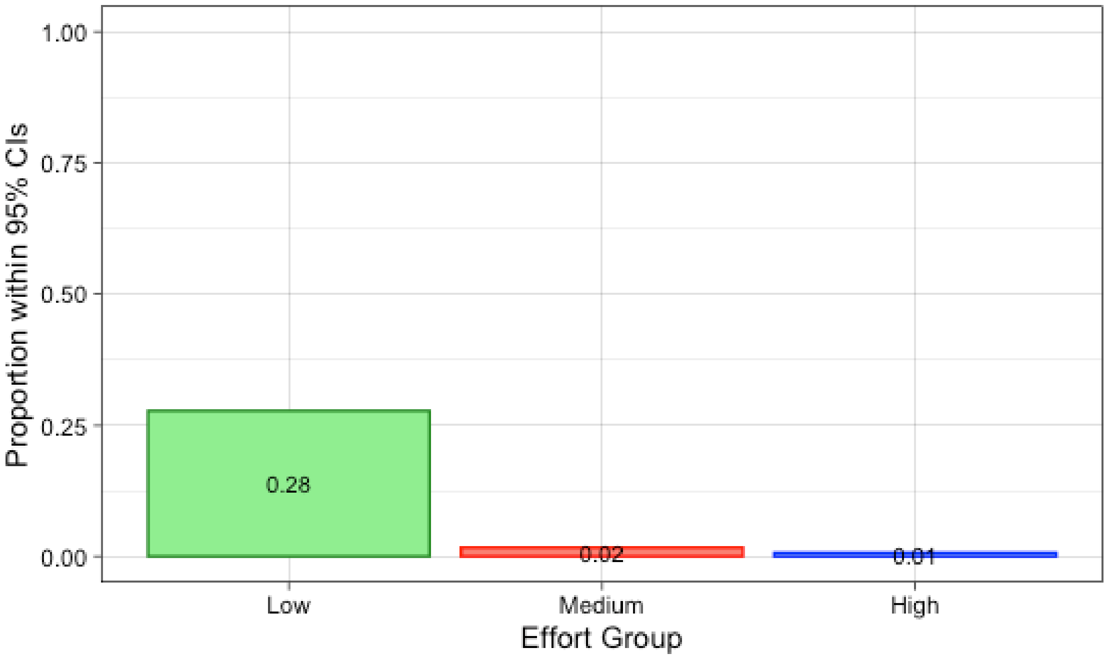

**Figure 2.** **Bar plot of coverage: the proportion of 700 simulations for which simulated fishing effort in an area is within the estimated 95% confidence intervals for that same area. The coverage is compared across Low(n = 4165), Medium(n = 1687), and High(n = 717) effort areas.**

A sensitivity analysis was used to determine how results vary with the number of flights each month, the minimum number of interviews used to calculate an activity profile, the number of interview shifts each month, the proportion of total simulated effort using a monitored landing site, and interview shift times. Model results were relatively insensitive to the number of interview shifts, the threshold number of interviews needed to create activity profiles, number of overflight surveys, or the proportion of effort occurring in monitored sites (Figures F1-3). However, when interviews were conducted later into the day, coverage for high-effort areas improved to 7%, compared to an average of 1.3% for all other scenarios. Similarly, coverage for medium-effort areas increased to 5%, compared to an average of 1.9% for all other scenarios. (Figure F5).

Pearson correlation coefficient values measuring the degree of similarity in daily fishing activity patterns demonstrate that areas within 25 km of one another are highly correlated (r > 0.9). However, correlation coefficients between activity profiles decrease with increasing distance between creel sub-areas (Figure 3). This decline highlights the influence of spatial proximity on the similarity of fishing activity patterns. Correlation coefficients between activity profiles also become more variable as distance increases.

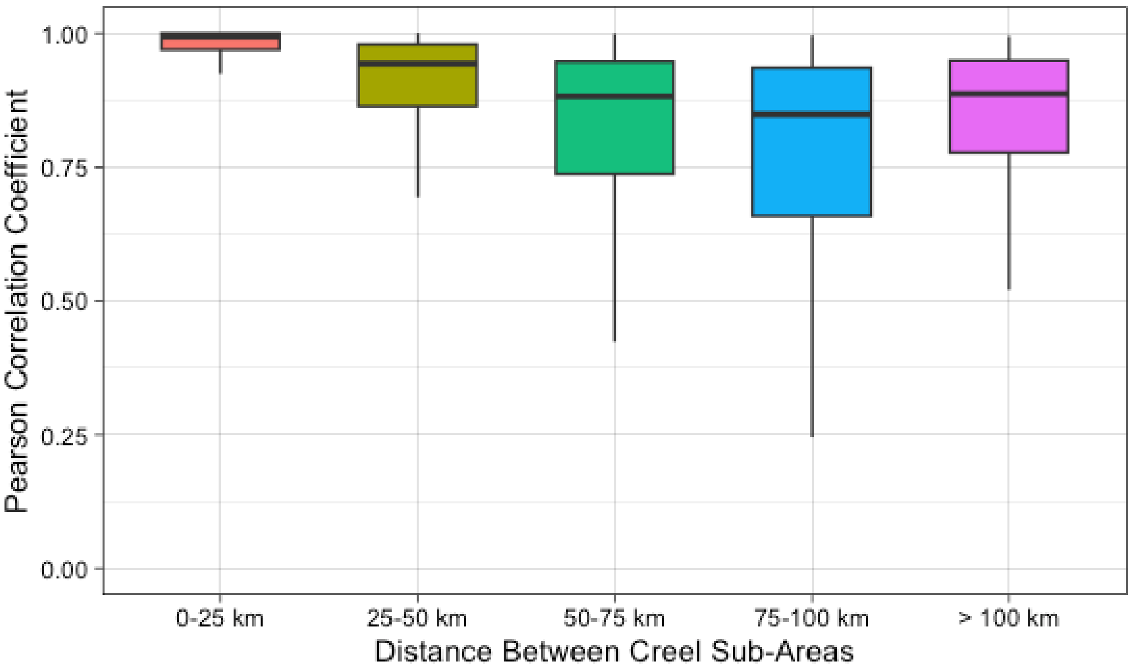

**Figure 3.** **Box plot of the distribution of calculated Pearson correlation coefficients between observed activity profiles in each of two creel sub-areas within distance categories (in kilometers). The y-axis denotes the Pearson correlation coefficient, reflecting the strength and direction of the relationship between fishing activity patters in the creel sub-areas. There were roughly 16,000 pairwise comparisons across all distance groups. Approximately 16,000 pairwise comparisons were conducted across all distance groups, with 2,000 pairwise comparisons randomly selected without replacement from each distance group to ensure comparability.**

In the analysis of true versus estimated proportions of total active effort during the hour of a flight count, 109 pairwise comparisons were conducted. Among these comparisons, 91 instances revealed the estimated proportion to be higher than the true proportion, while only 18 cases indicated the estimated proportion was lower (Figure 4). Note that when the estimated proportion falls below the true proportion of daily active effort, it underestimates the total effort, as dividing by a higher value produces a lower estimate (see Eq. T1.5).

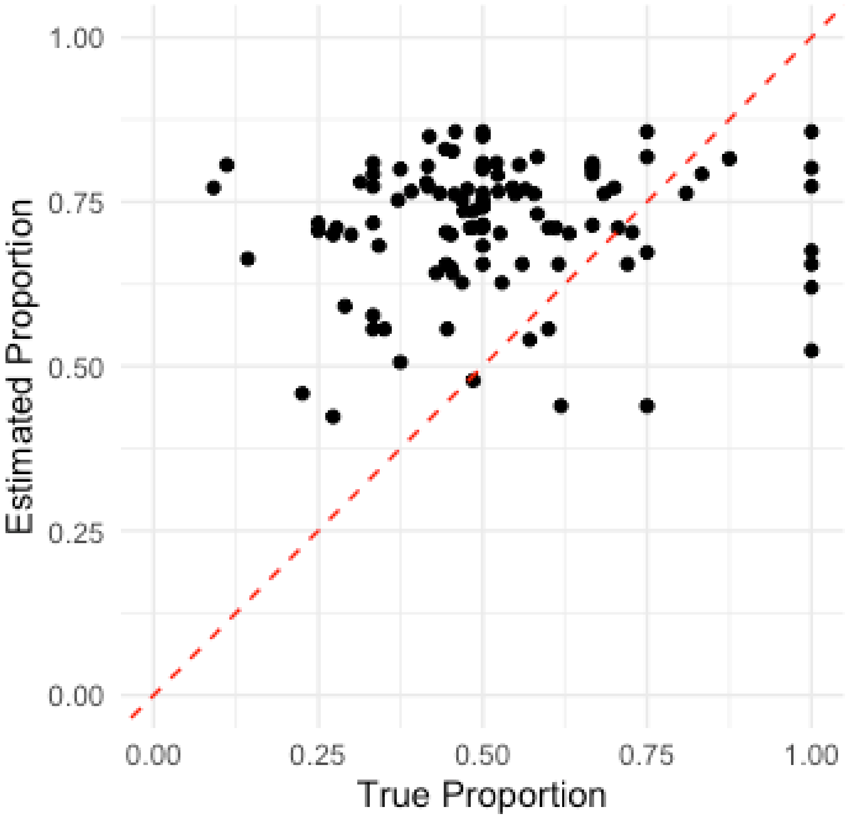

**Figure 4. Comparison of True Proportion versus Estimated Proportion of daily fishing effort during flight surveys. The dashed red line indicates perfect agreement between true and estimated proportions. Data points above the line signify instances where estimated proportions exceeded the true proportions, while those below indicate**

## 2.4. Discussion

The estimation model exhibits a consistent bias toward underestimating fishing effort across all areas, regardless of their actual fishing effort. One explanation for this is the propensity to overestimate the total proportion of fishing effort at times of flights because interviews end before all fishing effort has returned. However, the effort estimation protocol used in the SOG creel program performs notably better in areas greater than 500 monthly boat trips where precision is consistently high, while areas with less than 500 monthly boat trips show consistently low precision. This discrepancy exacerbates perceived relative importance of different areas and times, potentially underappreciating certain areas and their contribution to total effort and catch. Despite the tendency of the model to underestimate effort, low effort areas have a higher coverage. This can be attributed to increased variance associated with estimates in these areas resulting from the propensity for flights to more frequently count zero boats.

Comparing true and estimated proportions of active daily effort during flight counts unveils critical insights into the mechanisms underlying consistent underestimation of fishing effort by the model. The discrepancy between estimated and actual proportions of active daily effort underscores the importance of accurate activity profiles in ensuring estimation accuracy. Moreover, potential biases inherent in the creel program methodologies, such as under-sampling specific daily effort segments, emerge as potentially significant contributors to estimation bias. Interview shift times are designed to accommodate daylight hour variations throughout the year. The proliferation of technology, like advanced GPS systems with overlaid sonar on recreational vessels (see Cooke et al., 2021), allows boats to remain on the water later into the evening. Additionally, many anglers prefer to fish in the low light hours of dawn and dusk, expecting a higher catch rate (Cooke et al., 2017). While little research demonstrates changes in CPUE with daylight variation for recreation fisheries, there is evidence that some fish species show increased feeding activity in low-light conditions (Emery 1973, Bosiger and McCormick 2014). Therefore, it is reasonable to assume that if the timing of the angler interviews consistently misses the return of anglers fishing through dusk, they will be unaccounted for in the activity profiles.

If the SOG creel survey is regularly missing evening fishing effort, this could lead to the activity profiles overestimating the proportion of total effort active at the hour of the flight survey, causing an underestimation of total effort. This consistent underestimation of effort would also result in underestimating total catch. Such error for the recreational fisheries sector could undermine the legal process of stock allocation between fishery sectors and disrupt the assessment of management actions' effectiveness ( Fisheries and Oceans Canada, 1999; MacKenzie and Cox 2013). Therefore, a comprehensive audit of creel interview methodologies is essential to ensure that the full range of return times is captured and accurately represented in the activity profiles.

Effective monitoring and management of recreational fisheries will be increasingly relevant to the sustainable management of marine and freshwater resources (Brownscombe et al., 2019; Cooke & Cowx, 2004; Sbragaglia et al., 2023). If creel programs fail to adapt alongside fisheries, they risk becoming disconnected from reality, potentially leading to unintended consequences from misinformed management actions. In the SOG creel program is intended to provide monthly estimates at the creel sub-areas level (see Figure E1). Increasingly, management actions are enacted at finer than this this, meaning the SOG creel survey can no longer provide evidence of their effectiveness in these cases. Mismatches between the scales of monitoring and management can result in the inability to adequality quantify the outcomes of management actions. This can lead to missing crucial indications of overfishing before irreparable damage is already done. Therefore, when considering the outcomes of management actions it is imperative to consider the efficacy of current monitoring methods in detecting critical performance indicators (Hartill et al. 2012, Kerckhove et al. 2024). Otherwise, management decision are essentially made blind without the ability monitor their outcomes, intended or not.

It is crucial to recognize that a creel program that has remained largely unchanged for decades inevitably operates across different versions of the same fishery. Over time, these programs intersect with changes in management regimes, social conditions, economic environments, and ecological paradigms (de Kerckhove et al., 2024). To ensure that resource managers can make well-informed decisions about a fishery, there must be a strong alignment between the scale at which it is managed and the scale at which it is monitored (Hartill et al., 2012; de Kerckhove et al., 2024). Consequently, long-term creel programs need periodic reassessment as fisheries and their management regimes evolve (de Kerckhove et al., 2024). This should involve a quantitative assessment of the accuracy and precision of catch and effort estimates produced at same scale the fishery is managed at. If management actions rely on estimates from a creel program that lacks statistical reliability at the scale required by managers, there is a risk that these actions may be based on unreliable data, undermining the efforts of fisheries management. Therefore, ensuring the alignment between monitoring and management scales is critical for the integrity and efficacy of fisheries management actions.

While many recognize the importance of monitoring recreation fisheries, the task continues to be challenging. In response, there is a pressing need to explore innovative and cost-effective monitoring methods capable of providing data at a resolution that aligns with evolving management needs. Some have explored novel approaches such as angler apps, cameras, and drones to improve the efficiency and accuracy of recreational catch and effort monitoring (Van Poorten et al., 2015; Askey et al., 2018; Harris et al.,2019a; 2019b; Dutterer et al. 2020; Skov et al. 2021). Each approach has demonstrated promising results, but none seem to surpass the inherent challenges associated with monitoring recreational fisheries. It is unlikely that any technological solution will fully overcome the fact that recreational fisheries are inherently decentralized, unpredictable, and most importantly lack mandatory reporting structures (Beardmore, 2013; Cooke & Cowx, 2004; Hartill et al., 2012; Hartill et al., 2015; McCluskey & Lewison, 2008; Pollock et al., 1994).

Beyond technological solutions, there is a growing recognition of the need to reconsider how we approach and regulate recreational fisheries (Cooke and Cowx 2004, 2006, MacKenzie and Cox 2013, Arlinghaus et al. 2019). It is now evident that recreational fisheries can surpass commercial fisheries in their impact on fish stocks, yet they are often subject to less stringent reporting requirements (Coleman et al., 2004; Cooke & Cowx, 2004, 2006; Ihde et al., 2011). Addressing this disparity by implementing mandatory catch and effort reporting for recreational fisheries could not only enhance the reliability of estimates but also foster greater trust in the resource allocation process and reduce conflicts between user groups (Cooke and Cowx 2006, MacKenzie and Cox 2013, Arlinghaus et al. 2019). Exploring policy options to incentivize anglers to report diligently should be seriously considered, especially in fisheries where multiple sectors compete for the same resources (MacKenzie and Cox 2013, Arlinghaus et al. 2019, Goldsmith et al. 2023). Ultimately, we cannot expect traditional methods of catch and effort monitoring to keep up with the evolution of recreational fisheries. A proactive approach is needed to adapt the way we monitor recreational fisheries to ensure sustainable decisions can be made using robust estimates.

The findings of this study offer valuable insights into the sources of bias in effort estimates and the factors influencing the performance of effort estimation models. However, it is crucial to note that this simulation study cannot serve as a predictive tool for real-world estimation biases. Its primary objective is to pinpoint weaknesses in the current effort estimation procedure and understand the conditions that exacerbate these weaknesses. The simulation model was parameterized with data collected by the SOG creel program, meaning any sampling bias inherent in the creel program would be reflected in the simulation model. By introducing random variation into the simulation, we observed how the absence of evening effort returns could lead to consistently underestimating effort; particularly due to the inability of the simulation to consider departure times when assigning trip lengths, thus allowing boats to return at night. Since the purpose of this study is to only identify weaknesses in effort estimation methods and their exacerbating conditions, any biases or potential weaknesses in the SOG creel program identified by this study do not necessarily reflect the reality of the estimates being produced with these methods. Instead, this study highlights areas of interest where future research should investigate how these potential sources of bias could be affecting effort estimates.

Robust effort and catch monitoring will be pivotal for the future success of recreational fisheries (Brownscombe et al., 2019; Cooke & Cowx, 2006; McCluskey & Lewison, 2008; Sbragaglia et al., 2023). As fisheries continue to change, technology improves, and the human population grows, the impact recreational fisheries have on ecological systems will only intensify. Sustainable management of recreational fisheries necessitates the implementation of rigorous monitoring methods tailored to the unique characteristics of each fishery, capable of providing estimates that are relevant to fisheries managers (Hartill et al., 2012; Kerckhove et al., 2024). This study serves as an example of how simulation studies can aid in evaluating creel programs and contribute to the sustainable management of recreation fisheries.

# Chapter 3.

# Conclusion

This study highlights the limitations of the SOG creel survey program in providing robust effort estimates across varying levels of fishing activity. Our simulation study demonstrates that the SOG creel survey methods perform best during peak fishing seasons in areas with high fishing activity. Consequently, estimates produced using these methods for times and areas with limited fishing activity should not be relied upon to inform management decisions. This suggests that comparisons of fishing effort across areas will exaggerate differences between high and low effort areas, potentially leading to inaccurate management recommendations. The results also indicate that consistent underestimation occurs when angler interviews miss fishing effort from specific parts of the day, such as evening effort. Therefore, a comprehensive audit of interview times is necessary to ensure adequate coverage of the full range of return times. While the SOG creel program remains effective under specific conditions, future research should identify clear thresholds for when these estimates are applicable and when alternative methods should be employed. Additionally, efforts should be directed towards optimizing current methods to accommodate recent changes in the fishery.

As the SOG fishery continues to change, management priorities will have to change too. Anecdotal evidence suggests that fishing effort is increasingly being pushed into the off-season due to major closures during much of the peak season. If these anecdotal observations are correct, then a shift in the fundamental structure of the fisheries is occurring—a structure on which the SOG creel program was built around. The SOG fishery was once characterized by high effort during the summer months and negligible effort during the off-season. Now, historically popular fishing areas are increasingly closed for most or part of the peak seasons, and anglers seem to be getting pushed increasingly to times and areas where effort was normally low. If the anecdotal evidence is true, the fishery may be shifting towards a new paradigm where effort is spread across the times and areas that remain open during the peaks seasons and further into the off-season. If the fishery is changing in this direction, then managers will have to re-evaluate the times and areas that are worth monitoring. The current methods, which were intended for high levels of effort in concentrated times and areas, may no longer be suitable for the new paradigm of the SOG recreational fishery.

The limitations identified in this study do not detract from the hard work of those who developed and maintain the SOG Creel program. Monitoring this fishery is a remarkable undertaking given the vast area covered, the seasonality of anger behavior, and the diversity of target species. The identified limitations should serve as guidance for further evaluations of the SOG Creel program. The success of not only the SOG recreational fishery but all recreational fisheries hinges on robust monitoring programs that are tailored to the realities of the fishery and the needs of management (McCluskey and Lewison 2008, Brownscombe et al. 2019, Sbragaglia et al. 2023). To remain effective, creel programs must continually adapt to changing conditions, starting with a comprehensive quantitative assessment of the estimation methods to evaluate efficacy under current and possible future conditions (Hartill et al., 2012; Kerckhove et al., 2024).

A core consideration when evaluating a creel program is the scale at which the fishery is managed, and the data requirements needed to support these management actions (Hartill et al., 2012; Kerckhove et al., 2024). The sustainability of recreational fisheries in the future will likely necessitate more intensive monitoring of catch and effort at increasingly finer resolutions. However, it is unlikely that any combination recreational catch and effort monitoring methods will be both cost-effective and capable of providing estimates at the required resolution given the current assumptions inherent with recreational fisheries. We have already changed the way we think about the impacts these fisheries have on marine and freshwater resources; it is time we change the way we think about monitoring them. Management agencies should give serious consideration to shifting some of the responsibility of monitoring catch and effort onto anglers through mandatory reporting structures (Cooke and Cowx 2006, MacKenzie and Cox 2013). This is particularly true in situations where multiple fishing sectors target the same stocks (MacKenzie and Cox 2013). Ultimately, the future of recreational fisheries will rely on sustainable management decisions informed by robust monitoring programs (Brownscombe et al., 2019; Cooke & Cowx, 2006; McCluskey & Lewison, 2008; Sbragaglia et al., 2023). Therefore, dedicated research that contributes to improving catch and effort monitoring methods will be vital to the sustainability of recreational fisheries.

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# Appendix A.

## Total effort in the SOG from 1980-2023

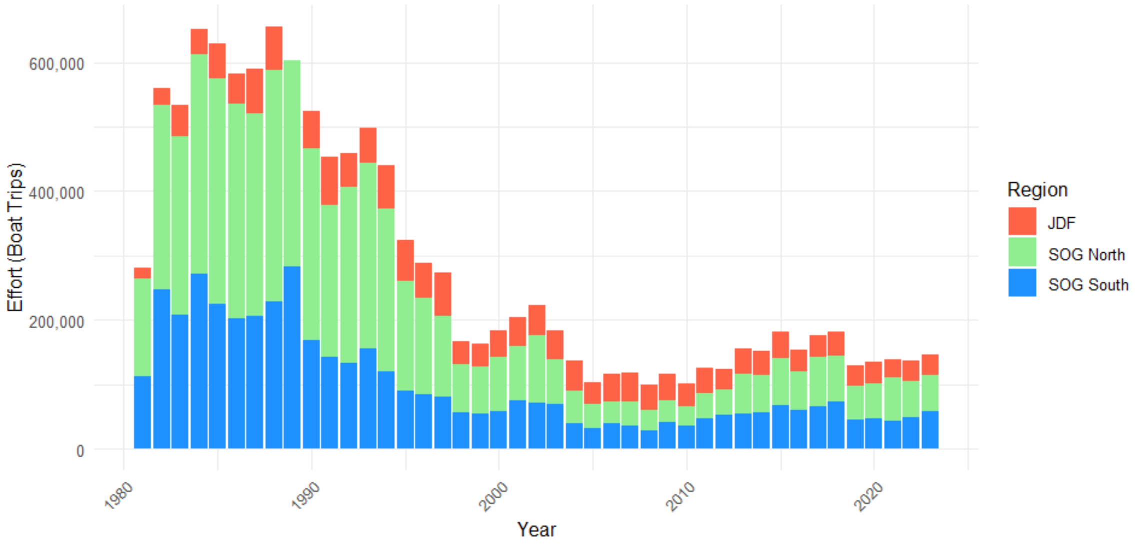

**Figure A1.** Total effort for the SOG from 1980-2023. Effort is spaerated into the three regions that make the total area the SOG Creel Survey covers.

# Appendix B.

## Creel overflight route for the southern Straight of Georgia (SOG)

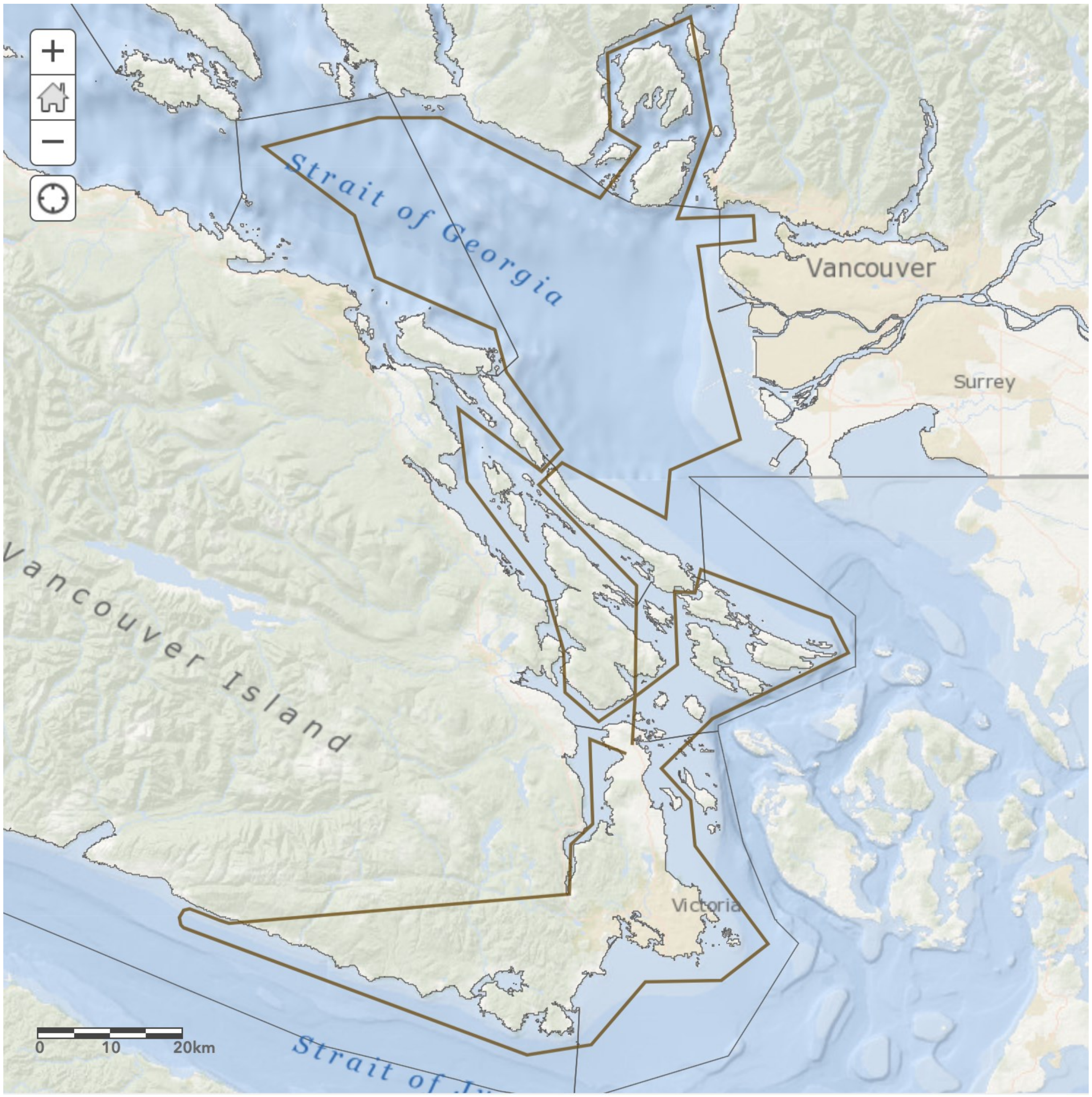

**Figure B1.** **A map showing the creel overflight route for the southern Straight of Georgia (SOG).**

Source: Image taken from the DFO South Coast Area Stock Assessment Web App (CHS, Esri, GEBCO, Garmin, NaturalVue | CHS, Esri, GEBCO, Garmin, NGS ;https://fisheries-map-gallery-crm.hub.arcgis.com/apps/stock-assessment-web-app/explore)

# Appendix C.

# Departure Times and Trip Lengths

**Table C1.** **Mean and standard deviation of departure times and trip lengths by month, based on Creel interview data from 2014-2021. November to January were excluded due to lack of data.**

| Month | Departure Time (Mean) | Departure Time (SD) | Trip Length (Mean) | Trip Length (SD) |
|---|---|---|---|---|
| **2** | 09:33 | 00:16 | 04:27 | 00:30 |
| **3** | 08:58 | 00:33 | 05:23 | 00:17 |
| **4** | 09:14 | 00:21 | 05:23 | 00:24 |
| **5** | 09:45 | 00:49 | 05:24 | 00:26 |
| **6** | 09:09 | 00:33 | 05:36 | 00:14 |
| **7** | 09:03 | 00:27 | 05:52 | 00:14 |
| **8** | 08:48 | 00:25 | 06:03 | 00:25 |
| **9** | 09:11 | 00:17 | 05:40 | 00:15 |
| **10** | 09:34 | 00:23 | 04:52 | 00:19 |

# Appendix D.

# Description of terms, variables and subscripts used by English et al. 2002

**Table D1. Description of terms, indices and variables used in effort estimation procedure described in English et al. 2002**

| Terms | Description |
|---|---|
| Shift/Stint | Represents a combination of a day type and landing site which was sampled on a single day (i.e. one sampling stint performed by an interviewer). |
| Work Block | Represents one of four possible periods at a particular site of a given day type:<br>Work Block 1 is before 11:00<br>Work Block 2 is 11:00 – 15:00<br>Work Block 3 is 15:00 – 19:00<br>Work Block 4 is after 19:00 |
| Day type | There are two day types: weekdays and weekends; holidays are classified as weekend days. |
| Time Block | Each day is divided into 16 time blocks which are:<br>Before 07:00<br>07:00 – 07:59<br>08:00 – 08:59<br>…<br>…<br>20:00 – 20:59<br>After 21:00 |
| Indices | |
| $a$ | Age |
| $g$ | A set of landing sites |
| $d$ | Day Type |
| $i$ | Site |
| $j$ | Work block |
| $k$ | Stint |
| $l$ | Landing time block |
| $m$ | month |
| $q$ | Fishing party interviewed |
| $s$ | Creel sub-area |
| $t$ | Time block |
| $u$ | flight |
| Variables | |
| $A$ | Number of boats actively fishing |
| $B$ | Number of boats observed on a flight |
| $E$ | Effort (Estimated total number of boats trips) |

| Terms | Description |
|---|---|
| $I$ | Number of boats interviewed and found to have been fishing |
| $L$ | Number of boats landing |
| $n$ | Number sampled |
| N | Population size from which n samples were observed |
| $P$ | Proportion |
| $T$ | Number of boat trips |
| $W1$ | Weighting factor to expand for all possible stints at each site |
| $W2$ | Weighting factor to expand for all boats that landed in each work |

# Appendix E.

## Comparison of Creel sub-areas and PFMA sub-areas in the Strait of Georgia

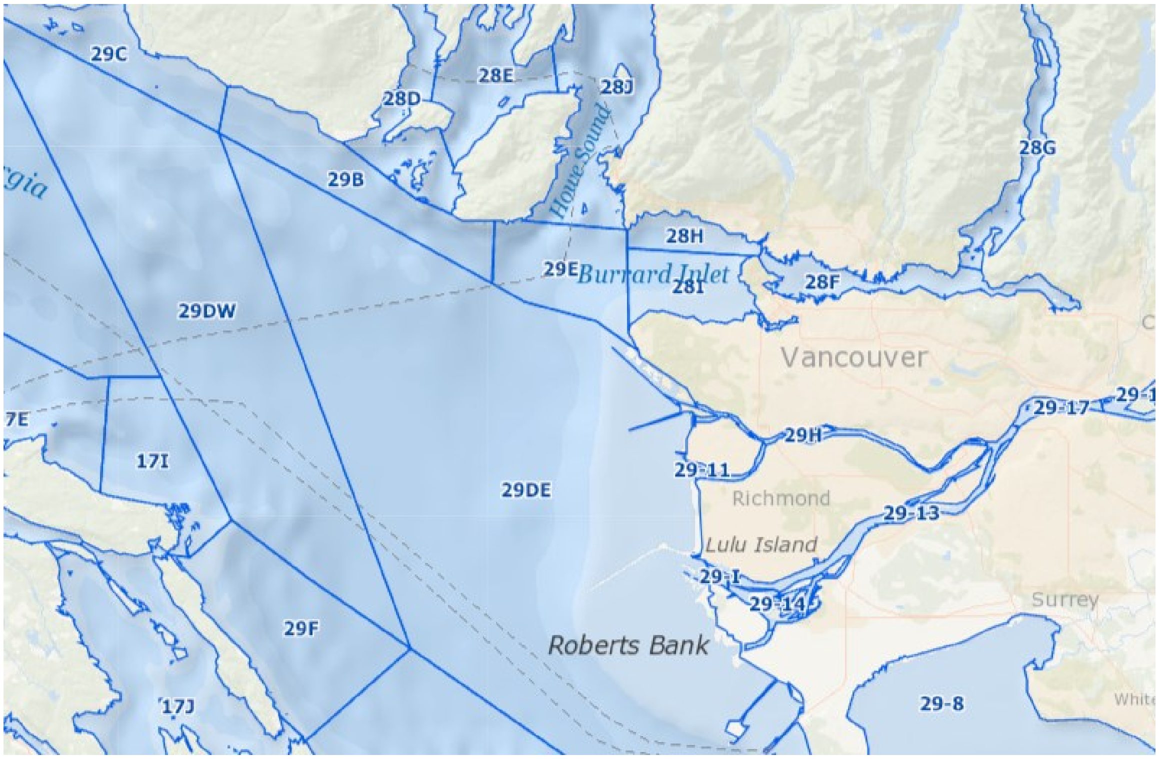

**Figure E1. A map showing an example of Creel sub-area boundaries within the southern Straight of Georgia (SOG).**

Source: Image taken from the DFO South Coast Area Stock Assessment Web App (CHS, Esri, GEBCO, Garmin, NaturalVue | CHS, Esri, GEBCO, Garmin, NGS ;https://fisheries-map-gallery-crm.hub.arcgis.com/apps/stock-assessment-web-app/explore)

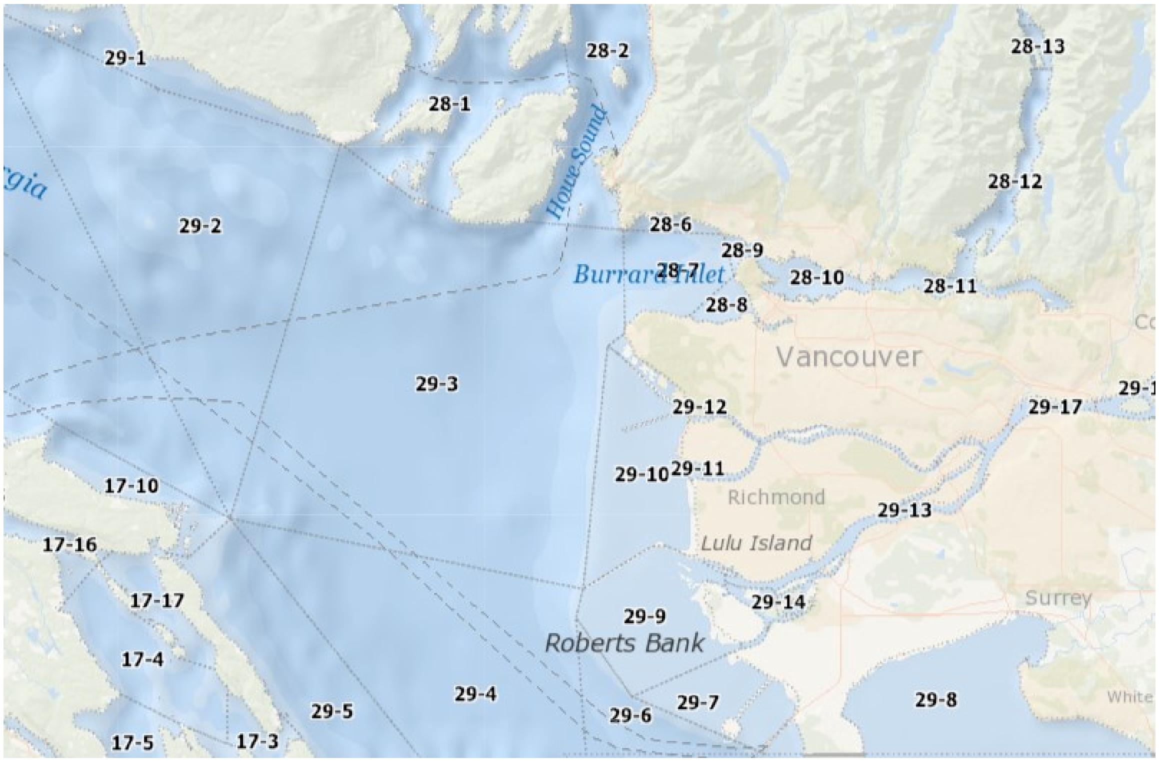

**Figure E2. A map showing an example of PFMA sub-area boundaries within the southern Straight of Georgia (SOG).**

Source: Image taken from the DFO South Coast Area Stock Assessment Web App (CHS, Esri, GEBCO, Garmin, NaturalVue | CHS, Esri, GEBCO, Garmin, NGS ;https://fisheries-map-gallery-crm.hub.arcgis.com/apps/stock-assessment-web-app/explore)

# Appendix F.

## Confidence interval and $\log_2$ error plots for all scenarios run as part of the sensitivity analysis

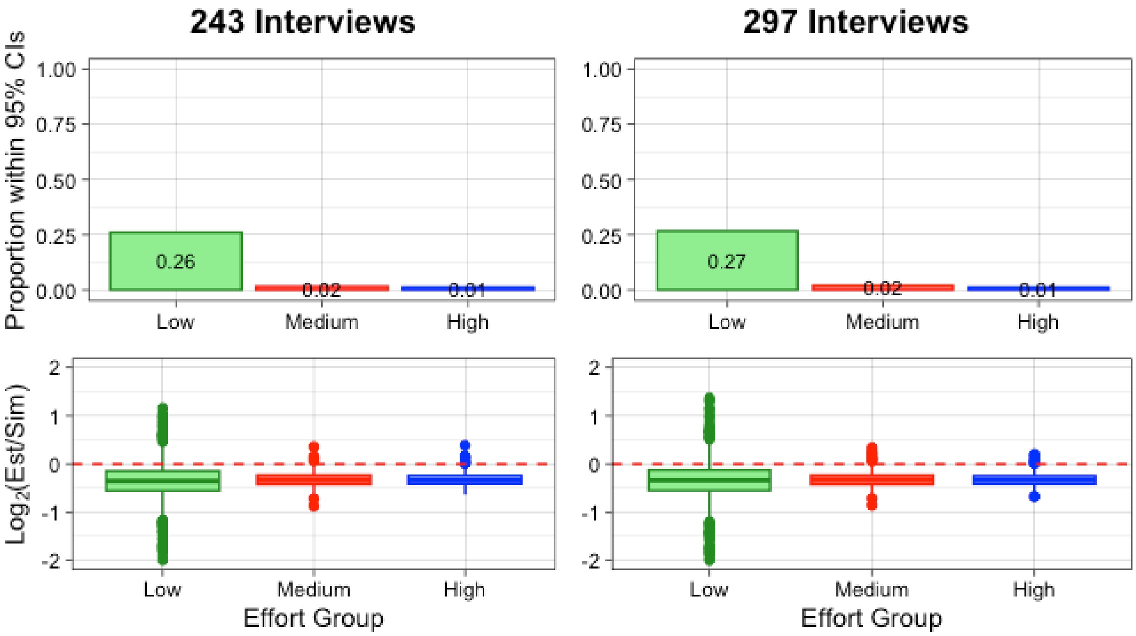

**Figure F1. Grid of four plots illustrating the high and low values for the number of interview shifts per month parameter, grouped by low, medium, and high effort areas.**

The left-hand column represents 700 simulations ran with 243 interviews per month, and the right-hand column represents 700 simulations ran with 297 interviews per month. The top row consists of bar plots showing coverage, representing the proportion of 700 simulations for which simulated fishing effort in an area is within the estimated 95% confidence intervals for that same area. The bottom row displays box plots of $log_2$ proportional error across the low, medium, and high effort groups. A red dashed line signifies where there is no difference between simulated and estimated values. In the 297 interviews per month scenario, the sample sizes were 4,136 for low, 1,633 for medium, and 729 for high effort groups. In the 243 interviews per month scenario, the sample sizes were 3,995 for low, 1,630 for medium, and 720 for high effort groups.

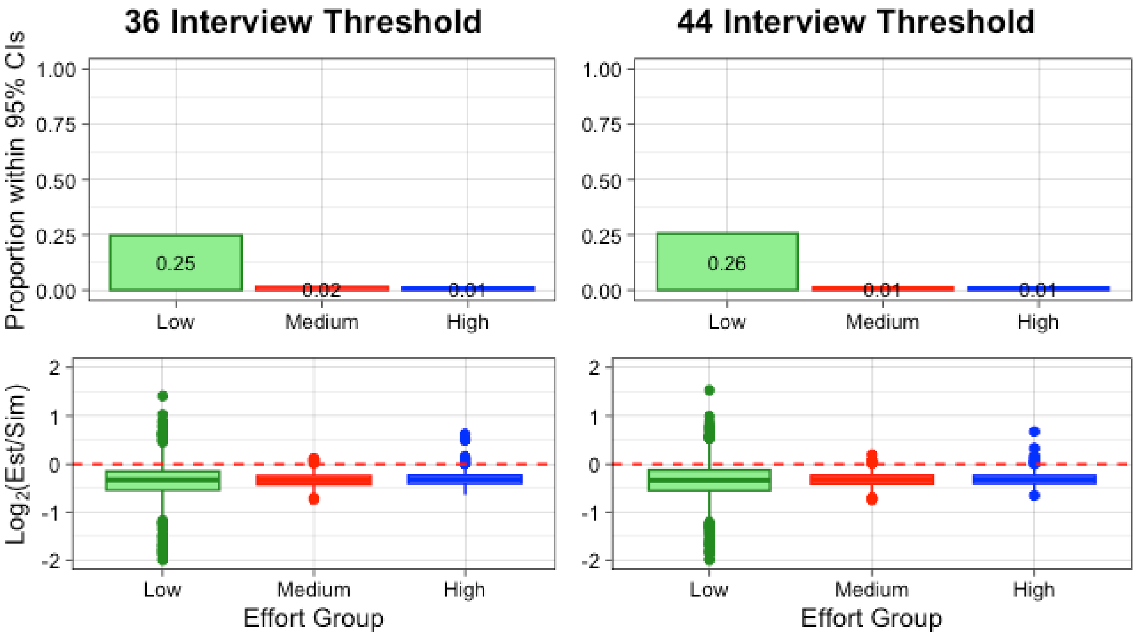

**Figure F2.** **Grid of four plots illustrating the high and low values for the number of interviews required to create an activity profile parameter, grouped by low, medium, and high effort areas.**

The left-hand column represents 700 simulations ran with a 36-interview threshold, and the right-hand column represents 700 simulations ran with a 44-interview threshold. The top row consists of bar plots showing coverage, representing the proportion of 700 simulations for which simulated fishing effort in an area is within the estimated 95% confidence intervals for that same area. The bottom row displays box plots of $log_2$ proportional error across the low, medium, and high effort groups. A red dashed line signifies where there is no difference between simulated and estimated values. In the 36 interviews threshold scenario, the sample sizes were 3,853 for low, 1,635 for medium, and 731 for high effort groups. In the 44 interview threshold scenario, the sample sizes were 4,193 for low, 1,679 for medium, and 720 for high effort groups.

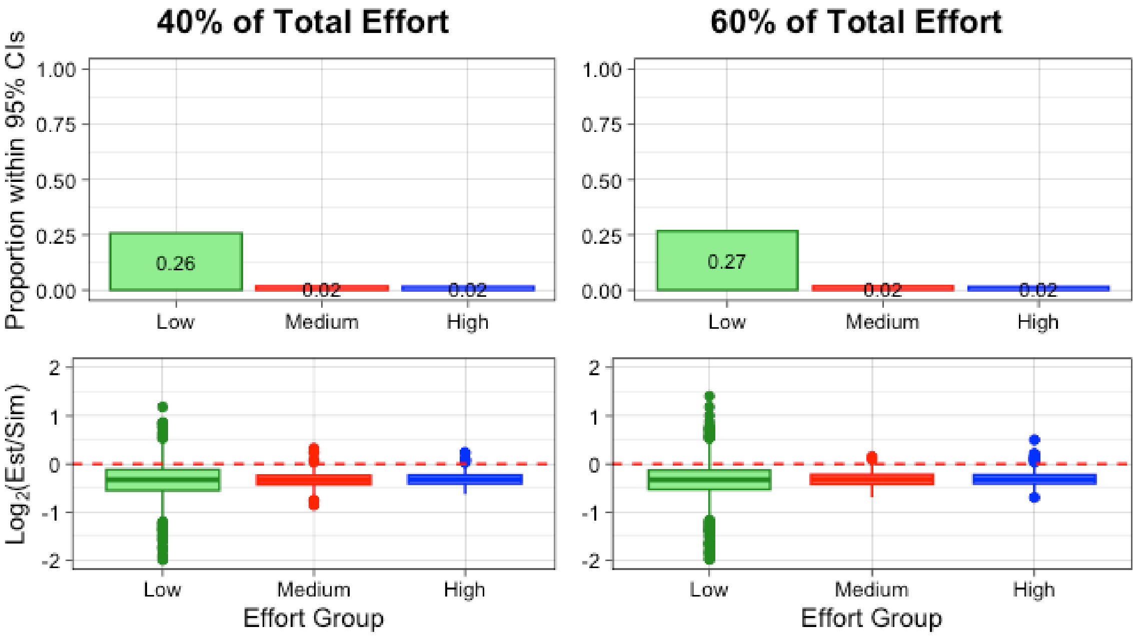

**Figure F3.** **Grid of four plots illustrating the high and low values for the proportion of total effort using monitored landing sites parameter, grouped by low, medium, and high effort areas.**

The left-hand column represents 700 simulations ran with 40% of effort using monitored landing sites, and the right-hand column represents 700 simulations ran with 60% of effort using monitored landing sites. The top row consists of bar plots showing coverage, representing the proportion of 700 simulations for which simulated fishing effort in an area is within the estimated 95% confidence intervals for that same area. The bottom row displays box plots of $\boldsymbol{log_2}$ proportional error across the low, medium, and high effort groups. A red dashed line signifies where there is no difference between simulated and estimated values. In the 40% total effort scenario, the sample sizes were 3,879 for low, 1,726 for medium, and 688 for high effort groups. In the 40% total effort scenario, the sample sizes were 4,248 for low, 1,724 for medium, and 666 for high effort groups.

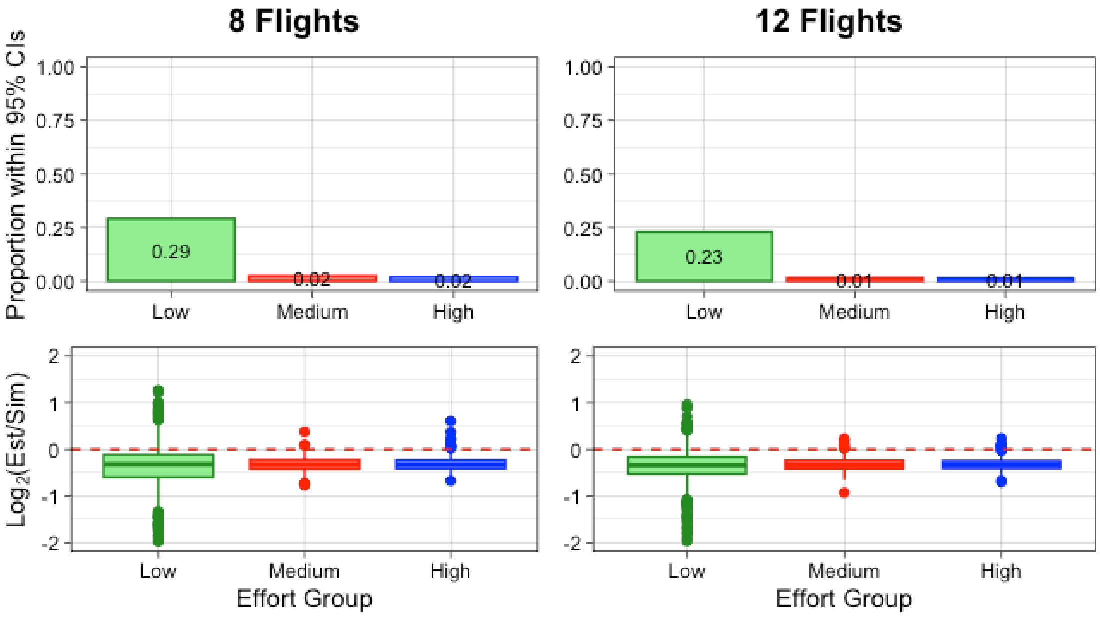

**Figure F4.** **Grid of four plots illustrating the high and low values for the number of flights per month parameter, grouped by low, medium, and high effort areas.**

The left-hand column represents 700 simulations ran with 8 flights per month, and the right-hand column represents 700 simulations ran with 12 flights per month. The top row consists of bar plots showing coverage, representing the proportion of 700 simulations for which simulated fishing effort in an area is within the estimated 95% confidence intervals for that same area. The bottom row displays box plots of log2 proportional error across the low, medium, and high effort groups. A red dashed line signifies where there is no difference between simulated and estimated values. In the 8 flights scenario, the sample sizes were 4,117 for low, 1,676 for medium, and 726 for high effort groups. In the 12 flights scenario, the sample sizes were 4,221 for low, 1,700 for medium, and 699 for high effort groups.

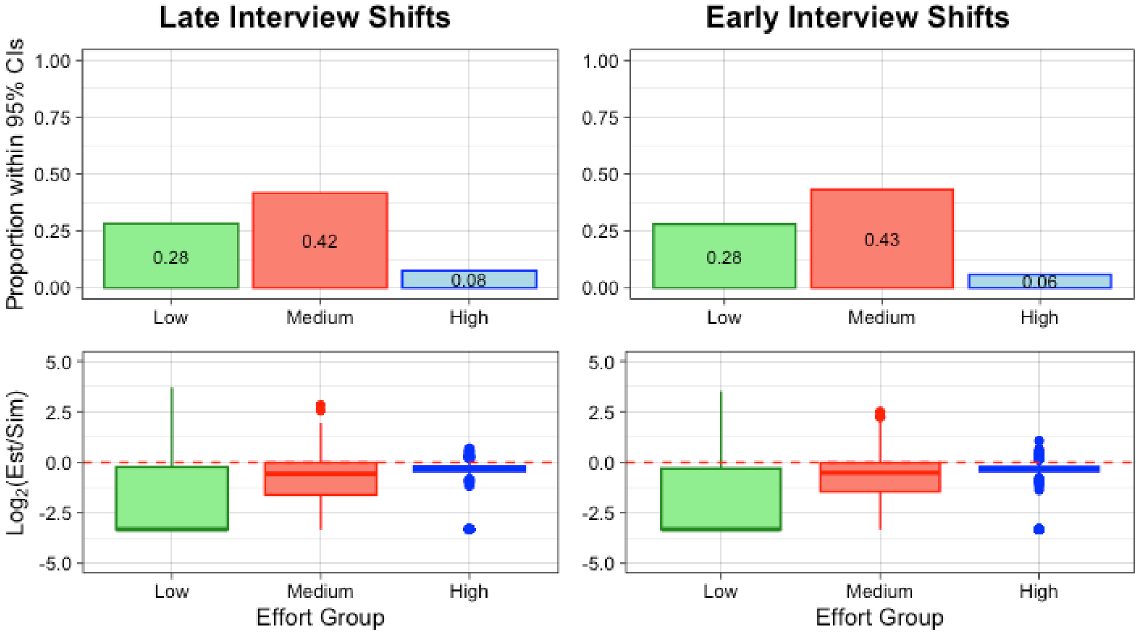

**Figure F5. Grid of four plots illustrating the high and low values for the interview shift times parameter, grouped by low, medium, and high effort areas.**

The left-hand column represents 700 simulations ran with interview shifts shifted three hours later, and the right-hand column represents 700 simulations ran with interview shifts shifted three hours earleir. The top row consists of bar plots showing coverage, representing the proportion of 700 simulations for which simulated fishing effort in an area is within the estimated 95% confidence intervals for that same area. The bottom row displays box plots of $log_2$ proportional error across the low, medium, and high effort groups. A red dashed line signifies where there is no difference between simulated and estimated values. In the late interview shifts scenario, the sample sizes were 3,873 for low, 1,660 for medium, and 710 for high effort groups. In the early interivew shifts scenario, the sample sizes were 4,139 for low, 1,735 for medium, and 677 for high effort groups.