Evaluation of a mark-recapture procedure to assess the catchability rate of the Tyee test fishing gill-net

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1. Introduction

Escapement estimates of summer run steelhead trout (*Oncorhynchus mykiss*) to various Skeena River tributaries are largely based on data from test fishing operations at Tyee each year, coupled with the DNA analyses of bio-samples taken from the steelhead caught. Substantial progress has been in recent years to determine the contributions of several Skeena River tributary populations to the total escapement (Labelle and Beere 2007). However, there remains considerable uncertainty on the relation between the actual escapement and the indices of abundance based on the test fishing catches. Basically, the test fishing gill-net catchability (i.e. fraction of fish present captured during a fishing period) is not known with certainty. It is commonly assumed that the catchability coefficient (*q*) can vary substantially due within and between seasons due to changes in escapement levels, tidal conditions, luminosity, water clarity, gear saturation, discharge levels, net condition, debris loads, and etc. This can affect the estimates of total escapement since these are typically estimated using the sum of the average daily test fishing CPUE indices times the inverse of the catchability coefficient. Even for sockeye salmon, the most well monitored salmon species in the Skeena River, some investigations have indicated that the estimated and observed escapements by ±20% or so, and that the test fishing indices may be biased in years of low flow (Walters et al. 2008, p. 6).

The catchability coefficient of the test fishing gear for steelhead is assumed to be about 0.0041. This rate is based on information from various sources, namely; an investigation by scientists from the University of Milan in the mid-1970s, plus accurate sockeye counts at the Babine River enumeration fence in recent years, and assumptions concerning the relative catchabilities of sockeye versus steelhead. The coefficient implies the test fishing gill-net intercepts (on average) about 1 out of every 244 steelhead passing by. So an expansion factor of 245 (i.e. 1/*q*) is applied to the cumulative average daily indices to determine total escapement up to the last day of test fishing. A multi-filament gill-net used for test fishing during 1955-2001, but it was replaced in 2002 by a mono-filament gill-net that was more efficient and could intercept salmon swimming deeper. Tests were conducted during 1996-2001 to determine a conversion factor so both series of indices could be linked (see Cox-Rogers and Spilsted 2002). However, estimates of this factor are also somewhat uncertain, due to data limitations, the data aggregation method, and various underlying hypotheses (see Labelle 2009 for details).

Walters et al. (2008) noted that better quantitative information was sorely needed to determine the status of Skeena River steelhead. Determining the catchability of the new test fishing gear would help improve the precision and accuracy of the steelhead escapement estimates (and those of other species). When the population size is unknown, a traditional approach to test the efficiency of a sampling gear consists of marking a portion of a population subject to sampling. The ratio of marks detected to those released is indicative of the sampling efficiency, or as in the present context, the catchability rate of the test fishing gear.

The reliability of various estimates based on even simple mark-recapture operations depends on satisfying a few basic assumptions (see Ricker 1975, p. 81-82). For instance, all marks applied should be available for recapture after release. Observer records suggest that steelhead caught by commercial gill-net and seine fishing gears (denoted by GN and PS respectively) may not survive after release because they are [often] subject to substantial injuries or stress. There is also mounting circumstantial evidence from various field operations that the recapture rate of marked steelhead released in poor condition (sluggish, bleeding, much scale loss, etc.) is considerably lower than those released in good condition. Other relevant issues concern tag loss (rejections, breakage, malfunction) during the release-recovery period, and the emigration of tagged fish from the survey area. Past tagging operations have also indicated that some salmon and steelhead tagged in the mouth of large rivers may emigrate, because some of these could be holding there before heading elsewhere, or because the stresses due to catch, tagging and handling could induce them to stray to other rivers or streams.

Another important issue concerning mark-recapture operations is sample size. The accuracy of the mark-recapture estimates tends to improve with larger numbers of tags released and recovered. During 1994, only 110 steelhead were successfully caught and tagged during 48 days of chartered PS vessel time (Koski et al. 1995). This revealed that catching and tagging large numbers of healthy steelhead in approach waters can amount to a logistically complex, time consuming and a costly operation. Ideally, future mark-recapture operations aimed at estimating the test fishing gill-net catchability should be designed to tag steelhead over several seasons (especially if the gill-net catchability is <1%), and to account for tag attrition due to various causes (emigration, tag rejection, tag breakage, tag malfunction, deaths).

Tagging operations could be designed to determine the catchability of the test fishing gear, but Walters et al. (2008, p. 7) also emphasized that steelhead mortality due to catch/release from commercial fisheries had never been determined with certainty, so historical rates of fishing mortality could not be estimated with certainty. The authors noted that many (e.g. hundreds) of steelhead should be tagged to estimate the terminal harvest rates on this by-catch species.

In light of the above comments, efforts were made to design a mark-recapture program that could potentially meet several objectives in a cost-effective fashion. The design is based on information from recent survey results, past monitoring and tracking programs, recent technological advances, plausible abundance levels and fishing effort patterns, and well-known logistic and operational constraints noted during previous Skeena River tagging programs. Basically, the design proposed relies on a combination of two complementary mark-recapture methodologies. The first involves the release of large numbers of inexpensive and easy to apply Floy tags, while the second involves the release of fewer but more expensive acoustic transmitters to quantify emigration and short term mortality. The 2008 pilot study showed that acoustic transmitters can be applied externally to steelhead. The operation is fast, less invasive, and more suitable for tracking in brackish waters than the esophageal (gastric) implants of radio-tags used in 1994-1995 for steelhead and coho tracking.

It is proposed that both tagging operations be conducted simultaneously, and concurrently with a commercial fishery observer program in the Skeena river approach waters. This type of operation would meet the recommendation of Walters et al. (2008, p. 14), namely that direct monitoring of catches and releases of all species in commercial fisheries be conducted via a large observer sampling program mainly in the DFO Statistical Area 4 (Fig. 1) where terminal GN and PS fisheries have traditionally been conducted. The gill-net fleet is much larger and can operate in the shallow waters of the Skeena River estuary. Until recently, this fleet comprised about 530 license holders (Walters, et al. 2008, p. 8). In recent years, gill-net fishery openings tended to start in early July and end in early August. Seine fishery openings tend to overlap over much of the same period (Table 1).

Details on the proposed tagging procedures and tagging effort levels are given in the next sections. The key variables are identified, and used in conjunction with background information on the fisheries and stocks in numerical simulations to provide insight on the potential cost and benefits of different options (tagging effort levels, duration of the tagging program, precision and accuracy of the resulting estimates, etc.). The simulation procedures and various results are also described in the following sections, so these can be used by fishery scientists and managers to determine if the proposed project is realistic and justifiable.

2. Materials and Methods

2.1 Symbols and notation

The following symbols and notation are used for descriptive purposes in the following sections

d	subscript denoting a calendar day, year *y*, max.=D
g	subscript denoting a fishing fleet type (1=gill-net or GN, 2=purse seine or PS)
t	subscript denoting a tag type (1=floy, 2=accoustic)
y	subscript denoting a calendar year
n	generic variable used to denote a sample size
p	generic variable used to denote a probability
z	generic variable used to denote a standard score
q_y^h	hypothesized catchability of the Tyee test fishing gill-net, year *y*
$\hat{q}_y$	estimated catchability of the Tyee test fishing gill-net, year *y*
$\hat{q}$	estimated overall catchability of the Tyee test fishing gill-net (over several seasons)
$\sigma_{\hat{q}_y}$	standard deviation of the estimated catchability, year y
$\sigma_{\hat{q}}$	standard deviation of the overall estimated catchability (across seasons)
C_{ydg1}	floy tags caught at Tyee, year *y*, day d, from fleet *g*
C_{y1}	floy tags caught at Tyee, year *y*, tag type *t* (from both fleets)
E_{ydg2}	accoustic tag escapement past Tyee, year *y*, day d, from fleet *g*
E_{y2}	accoustic tags escapement past Tyee, year *y*, tag type *t* (from both fleets)
R_{ydgt}	tag release, year *y,* day *d*, in fleet *g*, tag type *t*
$\hat{R}'_{yg1}$	estimated effective tag release, year *y,* in fleet *g*, tag type 1 (floy)
$\hat{R}'_{y1}$	estimated effective tag release (from both fleets), year *y,* tag type 1 (floy)
$\hat{R}'_{1}$	estimated effective tag release (from both fleets, all years), tag type 1 (floy)
L^h_{yg2}	hypothesized tag loss proportion, year *y,* fleet *g*, tag type 2 (acoustic)
$\hat{L}_{yg2}$	estimated tag loss proportion, year *y,* fleet *g,* tag type 2 (acoustic)
X	generic variable used to designate a number of fish, in a certain category
$\varepsilon_1, \varepsilon_{2..}$	random errors from normal distributions with given means and variances
u	symbol designating the mean of a probability distribution
σ	symbol designating the standard deviation of a probability distribution
cpue	catch-per-unit-effort

2.2 Potential tagging effort levels

There are few reliable estimates of steelhead interception rates in both fleets to determine the numbers of steelhead that could potentially be tagged in a ‘typical’ season. In recent years, steelhead caught had to be released after capture, and observers were not deployed throughout all Area 4 seine and gill-net fisheries to monitor steelhead interception. Recent records based on hail surveys (and phone in reports) for Area 4 indicate that steelhead are mainly intercepted from mid-July to mid-August (Table 1), with average catch rates being about 0.5 per gill-net vessel·day (range ≈ 0.3-1.0) and 4.0 per seine vessel·day (range ≈ 2-6). Total annual releases ranged from about 1550 to 5300, which amount to substantial portions of the corresponding total steelhead escapements reported each season.

Recent figures tend to be on the low end of the historical range. During 1982-1992, the combined gill-net and seine catch of steelhead in Area 4 ranged from 3875 to 28891 (Labelle et al. 1995). Hail survey records indicated that mean annual catch rates per vessel·day were comparatively greater for gill-net vessels (1.0), and lower for seine vessels (2.4). A follow-up comparative analysis using additional observer records indicated that during hail surveys, fishermen reported about 33% of the steelhead intercepted (Labelle 1995), so the mean annual catch rates may have been greater than the figures based on the 1982-1992 hail surveys.

In the absence of future pre-season forecasts of steelhead run sizes, the above figures were used to establish the expected numbers [and bounds] of steelhead available for tagging in the near future. These figures are used for numerical numerical simulations, based on the assumption that future run sizes and allowable fishing patterns may be similar to those of one season within the base period.

2.3 Tagging and detection procedures

To tag large numbers of steelhead cost-effectively, it is proposed that basic tagging operations be conducted by fishery observers deployed throughout both fleets when monitoring by-catches and compliance with the mandatory fishing practices. Two small, serially numbered, anchor type floy tags would be applied rapidly with a gun like applicator to all steelhead caught and released from fishing vessels in Area 4, irrespective of their physical condition. Applying two tags is a conventional method used to estimate losses due to tag breakage, rejection or malfunction. Applying tags to all steelhead would ensure that the tag recovery patterns do not reflect the faith of only seemingly healthy fish usually chosen for tracking movement patterns. The tag codes, tagging location, fishing gear characteristics, and steelhead condition would be recorded. Thus a potentially large number of floy tagged steelhead would be available for capture in the Tyee test fishery, and further upstream.

To quantify tag loss due to emigration and short-term mortality after release, V9-2h Vemco acoustic transmitters would be attached to a subset of all steelhead subject to floy-tagging. These [much] more expensive tags would be attached externally to the base of the dorsal fin, using the technique developed for the 2008 pilot study (see Welch et al. 2009, for details and illustrations). This application method was found to be relatively simple, rapid, effective, non-invasive, and the acoustic tagging technology is considered more suitable for tracking in brackish waters than the esophageal (gastric) implants of radio-tags used in 1994-1995 for tracking steelhead.

A receiver array deployed across the Skeena River both upstream and downstream of the Tyee fishing site would help determine the numbers that move past it. The use of underwater receiver arrays was tried during 2008. The results were found to be quite satisfactory, with high detection efficiencies (>90%) even in locations with substantial water turbulence. Suitable sites for deploying the receiver arrays were identified during the 2008 pilot study. A good site to track acoustically tagged steelhead passing Tyee is about 2 km further upstream. At this location, there are several concrete pylons at the base of the steel structures supporting the hydro-electric power lines across the Skeena River. The receivers can be attached externally to the downstream side of the pylons to protect them from potential damage by large woody debris moving downstream. The pylons are spread apart by distances that do exceed the detection ranges of the receivers.

There are no detection sites below the test fishing location with solid structures to attach receivers. The river width below Tyee is substantial (≤ 2.5 km under high tide conditions). A 'listening line' (cable with receivers) could be deployed on the streambed across the river, but would be susceptible to damage by woody debris scouring the streambed. An alternative detection set-up is to attach receivers to buoys moored across the river. These would be less susceptible to entanglement, and those that break (if any) could be replaced fairly rapidly. The data stored in the receivers attached to the buoys can be downloaded as easily as the data from receivers attached to pylons, with no need to periodically raise the listening line, or rely on additional satellite transmission links to transmit these data in near real time.

Note that if additional receivers are deployed much further upstream of Tyee, acoustically tagged steelhead can be tracked to determine the distribution of the various run segments, and perhaps help verify the DNA stock contribution estimates based on the analysis of bio-samples collected in terminal fisheries and the test fishery from steelhead tagged with acoustic transmitters.

However, the main objective of the two mark-recapture operations is to determine the steelhead catchability rate of the test fishing gill-net. The ratio of the number of floy tagged steelhead detected at Tyee to the number released is a crude estimate of the catchability coefficient (the fraction of tags intercepted). This is a minimum estimate, since it does not account for tag loss and the emigration of tagged steelhead. Both processes reduce the number of tags susceptible to be detected or caught at Tyee. Adjustments are generally required to determine the number of ‘effective tags’ available for recovery, that are used to compute a more accurate [and likely greater] estimate of the gill-net catchability.

While tag loss due to breakage or rejection can be estimated using records of steelhead recovered with one or both floy-tags, tag loss due to emigration and death cannot be determined from these data alone. The extra information is provided from the detection of acoustic transmitters. For help visualize the process, say 100 transmitters are applied to steelhead in approach waters, but only 20 are detected by receivers deployed around the test fishing site. The results suggest that ≈80% of the transmitters were lost either due to death shortly after release, straying to other sites, rejection, breakage, or malfunction (for electronic tags only, considered rare). Based on the 2008 results, breakage are thought to be negligible over short distances, and rejections were considered to be non-existent because of the attachment procedure used (not anchored in the flesh, or inserted in the stomach). Tag breakage could be assessed using the Floy tag recovery data and the cross-validation with serial numbers that indicate if a transmitter was also applied and lost. It is anticipated that most transmitter losses will likely be caused by emigration and deaths shortly after release, and if one assumes that such losses are comparable to those of floy-tagged steelhead, then the number of ‘effective’ tags released can be computed and used to estimate the test fishing gill-net catchability. Information on the catch of transmitters at Tyee can also be used to provide an alternative estimate of gill-net catchability (numbers recovered over numbers detected by both stations), but the potential bias and variance of this estimate will likely be less representative because of the fewer releases and detections.

The above figures are used to illustrate the assessment procedure. Say 2000 steelhead are floy-tagged during a season, 100 transmitters are applied at random on every 20th floy-tagged fish, and 20% of the transmitters are detected passing Tyee. If both tag types are subject to comparable attrition rates, 80% of the floy-tags are lost, amounting to an 'effective' tag release of 400. If the catchability coefficient of the test fishery is as low as say 0.004, there would be 1-2 floy-tagged steelhead recovered at Tyee. Obviously, this number is insufficient to estimate the catchability of steelhead with certainty over a single season. If so, it seems necessary to conduct tagging/monitoring over several seasons. The figures obtained each season can be analyzed separately (if samples are large enough), or pooled to get estimates based on multi-year samples less influenced by seasonal changes in environmental conditions. The overall catchability estimate is a thus function of temporal variation of the gill-net catchability, the numbers of tags released (both types), the tag loss rates (emigration, breakage, rejection, deaths) due to various factors (gear type, release condition, etc.), and the duration of the tagging program (1+ seasons). The catchability estimate is also a function other factors whose effects are not easily quantifiable with limited data (test fishing period, number of sets, set duration, tidal phases, etc.), so only the first set of variable are considered for this exploratory investigation.

Monte Carlo simulations were conducted using combinations of plausible variable values to provide insight on the precision and accuracy of the catchability coefficients that might be obtained if a multi-year tagging program was conducted. This amounts to a simple cost:benefit analysis, with the costs expressed in terms of tagging effort patterns, and benefits expressed in terms of the bias and precision of catchability estimates. The predicted trends can be used to determine the 'points of diminishing returns', i.e., the tagging effort beyond which progressively lower gains are achieved with greater tagging effort. Such results can help determine if a project is realistic, and under the specified conditions, what could possibly be achieved given a certain effort investment, and if the investment is justifiable.

2.4 Mathematical expressions

The tag loss proportion attributed to mortalities after release, breakage, tag rejection and emigration is estimated for each gear type (*g*) based on the acoustic tags releases and observed escapements past Tyee each year until the last day (D) of the tagging and test fishing period. In the absence of stochastic variation in the hypothesized values, the equations are ;

[1] $$\hat{L}_{yg\,2} = \sum_{d=1}^{D} \frac{E_{ydg\,2}}{R_{ydg\,2}}$$

The estimated tag loss proportion is assumed to apply to all steelhead simultaneously floy-tagged. No equations are provided to show the minor adjustments that can be made to account for losses due to various factors, as it is not known if sufficient data could be obtained during a typical season to compute such figures. The effective numbers of floy tags released for each gear-year combination is estimated from

[2] $$\hat{R}'_{yg\,1} = \left(1 - \hat{L}_{yg\,2}\right) \sum_{d=1}^{D} R_{ydg\,1}$$

The catchability of the test fishing gill-net for a given year is estimated given the estimated number of effective floy-tags released from both fleets over the tagging and test fishing period, and the observed catches. Omitting references for daily periods, the equation is;

[3] $$\hat{q}_y = \frac{C_{y\,1}}{\hat{R}'_{y\,1}} = \frac{\sum_{g=1}^{G} C_{yg\,1}}{\sum_{g=1}^{G} \hat{R}'_{yg\,1}}$$

A catchability coefficient is basically a proportion (symbolically denoted as *p*), which tends to be binomially distributed (Zar 1984, p. 370). When the sample size is low relative to the total population (i.e. tag sample versus escapement), the proportion is small and the variance of $p = p(1-p)/n-1$ (Cochran 1977, p. 52; Zar 1984, p. 376). The standard deviation of a low catchability rate thus reduces to

[4] $$\sigma_{\hat{q}_y} = \sqrt{\frac{\hat{q}_y\,(1-\hat{q}_y)}{\hat{R}'_{y\,1}}}$$

The general formulae used to compute the approximate 95% confidence intervals of the proportion (*q*) is $q \pm z\sigma_q$. The standard scores (*z*) are given by the normal approximation to the binomial distribution, and a continuity term is added (Zar 1984, p. 379) to correct for cases with few recoveries. The upper and lower bounds of the confidence interval of the year-specific catchability estimate are given by

[5] $$\hat{q}_y \pm \left(1.96\ \sigma_{\hat{q}_y} + \frac{1}{2\hat{R}'_{y1}}\right)$$

If tagging is conducted over several seasons, all the data should be used to provide more representative estimates. A weighted average catchability can be computed using equations for stratified sampling designs (each year being a stratum). These usually require information on total abundance by stratum, and justified when there is substantial variation between strata (Cochran 1977, p. 89-90). However, future escapement patterns are uncertain, and the year-to-year changes in catchability of the old gill-net may not be applicable to the new one. So there is little justification for the use of stratified estimators, at least at this stage.

As an alternative, the overall catchability over several seasons is estimated from pooled release and recovery records. One justification for pooling stems from the fact that biased estimates of annual catchability can be obtained if the number of releases is insufficient. Ricker (1975, p. 79) notes that low recovery rates are Poisson distributed, and ≥4 recoveries are needed to reduce the probability that the ratio will be biased (as when the 95% confidence intervals of the number recovered includes zero). The estimated catchability over several seasons and the associated confidence intervals are computed from;

[6] $$\hat{q} = \frac{C_1}{\hat{R}'_1} = \frac{\sum_{y=1}^{Y}\sum_{g=1}^{G} C_{yg\,1}}{\sum_{y=1}^{Y}\sum_{g=1}^{G} \hat{R}'_{yg\,1}}$$

[7] $$\sigma_{\hat{q}} = \sqrt{\frac{\hat{q}(1-\hat{q})}{\hat{R}'_1}}$$

[8] $$\hat{q} \pm \left(1.96\ \sigma_{\hat{q}} + \frac{1}{2\hat{R}'_1}\right)$$

If the above estimators are used, efforts should be made to ensure that comparable numbers of releases are made each year, so the catchability estimate is not heavily influenced by seasons with substantially more releases. As the number of tagging seasons increase, the total numbers of releases and recoveries also increases, leading to an increase in the precision and accuracy of the estimated catchability.

2.5 Numerical simulation figures and assumptions

The above equations can be used to determine what might be expected under specific conditions. However, some future conditions cannot be forecasted with certainty. Monte Carlo simulations are conducted to determine the plausible range of estimates that might be obtained given the actual data under a range of plausible conditions. The ‘known’ values can include the actual observations, control variables with fixed values (e.g., tag releases), and reliable parameter estimates based on previous surveys and investigations. The ‘unknowns’ generally include the uncertain parameter values, and various error structures that must be hypothesized based on theoretical grounds or ancillary observations.

The variables, parameters, and relations used to estimate the gill-net catchability includes both knowns and unknowns (Table 2). The numbers of tags of each type released during a season can be fixed to values ranging from zero to several thousand given the tagging effort target. However, the proportion of tags released from the seine and gill-net vessels that may be lost each season is not known beforehand, and must be hypothesized. Existing information on electronic tag loss is largely based on the results of numerous field operations conducted in BC, but the influence of various factors causing the loss (breakage, rejection, emigration, deaths) has rarely been quantified with certainty. Based on actual observations and circumstantial evidence from various sources, Bison and Labelle (2007) hypothesized that the loss proportions (all factors combined) for steelhead intercepted in the Area 12-13 PS fisheries ranged from 0.2 to 0.4 (mean = 0.3), and those in the Area 29 GN fishery ranged from 0.6 to 0.8 (mean = 0.70). Most of the losses are assumed to be observed deaths when the catch is retrieved plus those that occur shortly after release. The figures translate into survival rates of 70% and 30% respectively.

During the 1994 Skeena River steelhead radio-tagging study, about 70% of the tags released from PS vessels in approach waters were subsequently detected further upstream

(Koski et al., 1995). During the 2008 Skeena River acoustic tracking operations, 56% of the transmitters applied to steelhead caught/released from the Tyee test fishing gill-net were detected at a station 100 km further upstream, with fewer detected beyond it (Welch et al., 2009). During both studies, only healthy steelhead were tagged, so the proportions detected subsequently were likely greater than would have been observed if tags had been applied at random to steelhead caught in commercial fisheries, and particularly for gill-net vessels that tend to induce greater incidental mortalities (see Labelle 1995 for comparisons). Still, the results support the notion that tag loss proportions tend to be greater for fish released from GN vessels than from PS vessels. The tag loss proportions are comparable to those used by Bison and Labelle (2007) for PS releases, and slightly greater for GN releases. In light of such facts, the latter figures were used for simulation purposes so the predicted tag recovery rates are not overly optimistic.

The catchability of the test fishing gill-net is not known with certainty and must also be hypothesized. That of the old multi-filament net was assumed to be ≈0.0041. A recent analysis of the comparative data collected during 1996-2001 suggests that the mono-filament net used since 2002 is about 1.36 times more efficient (Labelle 2009), so the new gill-net catchability could be ≈0.0056. There is no information to determine the level of temporal variation in catchability rates due to various factors. Walters et al. (2008, p. 6) noted that for sockeye, the catchability could vary by ±20%. For lack of a better alternative, this figure was used as the hypothesized error of the annual catchability rate of the new gill-net.

For simulation purposes, the transmitter loss proportions for each fleet were assumed to be the subject to stochastic variation, represented by normally distributed errors, centered on the expected value and within the bounds specified (Table 2). This is accomplished by substituting $\hat{L}_{yg2}$ for $L^h_{yg2} \pm \varepsilon$ in Eq. 2, using error ranges that ensure L^h_{y12} and L^h_{y22} respectively fall within 0.7±0.1 and 0.3±0.1 during each realization. Tag releases were set to 700 for both the GN and PS fisheries, in part to facilitate comparisons of survival rates for steelhead released from each vessel type. This number of releases is also realistic given the number of steelhead released from both types of vessels is most years since 2006 (Table 1). Transmitters are applied at random to 5% of all steelhead released with floy tags. The catchability coefficient is also assumed to be subject to stochastic variation, represented by normally distributed errors, centered on the expected value and within the bounds specified previously (Table 2). This is accomplished by computing the catches of floy tags (C_{yg1} in Eq.3) from $C_{yg1} \cdot (q^h_{yg1} \pm \varepsilon)$, using an an error range that ensures q^h_{yg1} falls within 0.0056 ± 0.001 during each realization.

The above substitutions remove the need for Equations 1, 4-5, 7 and 8 since the lower and upper bounds estimated catchabilities are obtained directly from the distribution of outcomes generated by the Monte Carlo simulations. Each of these involved conducting 100,000 trials (or realizations), with different random numbers used each time to mimic stochastic variation in tag loss rates and gill-net catchability. Note that that are inevitable rounding errors (catches are integers, not whole numbers) that mainly affect the results when small numbers are used to compute the ratios, so one does not always obtain smooth and symmetrical distributions. The mode of the distribution is considered to represent the most likely catchability estimate obtained, with the 2.5 and 97.5 percentiles of the cumulative frequency distribution of catchabilities representing the lower and upper bounds respectively. These figures are somewhat analogous to the estimated catchability and the 95% confidence intervals obtained using Eq. 1-8, but are not identical because of the effects of stochastic variation in hypothesized values. The results obtained for several tag release patterns (within and between seasons) are presented in the following section.

3. Results

3.1 Predicted catchability patterns

The predicted annual catchability distribution based on the most basic scenario is discontinuous and multi-modal (Fig. 2, top). Some of the discontinuities observed are simply caused by the intervals used on the abscissa (number of categories), but not all of them. Given the conditions specified, the numbers of tags released usually translates into 3, 4 or 5 recoveries, which when divided by the number of effective releases (also subject to rounding errors), yields a discontinuous distribution of outcomes with some catchability values never obtained.

The multi-modal pattern stems from divisions with numerators of 3, 4 or 5 recoveries, with 4 (the target) being the most common which accounts for the middle mode. Discontinuities in the predicted catchability distribution are reduced by increasing the proportion of steelhead released with transmitters from 5% to 10% (Fig. 2, bottom). This translates into a greater range of estimated tag loss figures, and in turn, a greater range of effective floy tag releases and catchability estimates. However, because the number of recoveries is still 3, 4, or 5, the distribution of annual catchability is still multi-modal.

A largely uni-modal distribution of annual catchability can be obtained by increasing the number of floy tags and transmitters released. If 2000 steelhead are released with floy tags, and transmitters are applied to 5% of these, the predicted catchability distribution is less discontinuous, more uni-modal, symmetrical, and centered on the hypothesized catchability rate (Fig. 3, top). Even greater gains in precision and accuracy can be achieved by increasing the proportion of tagged steelhead bearing transmitters from 5% to 10% (Fig. 3, bottom). Note however that this tagging objective may be unachievable as it can exceed the numbers of steelhead released in each fishery. This observation highlights the need to assess the merits of applying tags over several seasons.

If the basic tagging plan described previously is conducted over several consecutive years (Table 3), the distribution of catchability estimates based on pooled records improves as expected over the seasons. By the end of the second season the distribution is bi-modal (Fig. 4, top), and after 3 seasons, the distribution of results is largely uni-modal (Fig 4, bottom). Some of the spikes in the frequency distribution of results obtained after 3-5 years of tagging are partly caused by the intervals used for the abscissa, so it is generally best to assess precision and accuracy using the summary statistics rather than from the visual examination of the frequency distributions. These indicate that for all years (1-5), the most likely catchabiilty estimate obtained (mode) would have been very close to the [hypothesized] value used for simulations (.0056), but there is a reduction in the coefficient of variation (CV) obtained with longer tagging operations (years 1→5). For instance after only one tagging season, the CV was 0.102, with the minimum and maximum catchability estimates obtained range from 0.003 to 0.008. This implies that, by chance alone, one could have obtained a catchability figure that was only 53% of the actual figure, or that exceed it by 42%. After 3 seasons of tagging, the CV decreased to 0.062, with minimum and maximum catchability estimates of 0.004 and 0.007 respectively, so the estimates are roughly within ±27% of the actual value. After 5 seasons of tagging, the CV decreased to 0.049, and the catchability estimates are within ±23% of the actual value. The minimum and maximum estimates include extreme values that are unlikely, so one typically uses a less extreme range to gage the likelihood of getting estimates close to the actual value. The 50 percentile range is often used for this purposes, which indicates that the is a 50% chance that after 5 tagging seasons, the catchability estimate obtained could have been within ±5% of the actual value.

A second set of simulations were conducted using 1000 floy tag releases in both the GN and PS fisheries, with the same proportions subject to acoustic tagging. As expected the CVs were slightly lower for each tagging season, with those of catchability estimates in years 1 and 5 being 0.097 and 0.046 respectively (versus 0.102 and 0.048 for the previous scenario). So increasing the number of tags released across all seasons helps improve the precision of the estimates just as it does over a single season.

4. Discussion

The simulation results indicate that the test fishing gill-net catchability could be estimated after a single season, using both tagging methodologies, and with tagging effort levels that are commensurate with the availability of steelhead, as least based on the 2006-2008 hail survey figures. However, the reliability of the estimate obtained with a given level of tagging effort may not be considered acceptable. Greater levels or precision and accuracy can be obtained by increasing tagging effort in a year, but as illustrated by the scenarios used for simulations, the numbers of steelhead required for tagging may exceed the numbers released in Area 4 during recent years.

The simulation results indicate that this constraint can be overcome by spreading tagging effort over several seasons, and get estimates with the greater prevision and accuracy. This also ensures that the catchability estimate is more representative of 'average' conditions, and does not reflect only the performance of the gill-net during a single season. The results indicate that the precision of the estimate increases with the number of tagging seasons, although the gains achieved do not appear to be linear functions of the number of seasons, at least when the same tagging effort is applied each year.

It is beyond the scope of the present investigation to compute a wide spectrum of results for a multitude of potential tagging conditions. This exercise could be pointless as there is no certainty that future steelhead run sizes will comparable to past levels, and that commercial GN and SN fishery openings and effort levels will be similar to those observed in recent years. Should DFO opt to minimize GN fishing effort in Area 4 for conservations purposes, tagging objectives might still be achieved using only PS vessels, or alternatively, a combination of PS vessels and smaller vessels equipped with 'tangle' nets (TN). In fact, Walters et al. (Addendum, 2008) recommended that large scale experiments be conducted with 'tangle' nets. The authors also recommended that "hundreds" of steelhead should be tagged in Area 4 to provide better information on fishery impacts. Both of these objectives would be met by implementing the basic mark-recapture program outlined above using a combination of PS, GN, and TN Vessels, at least for a minimum of 3 seasons. After this initial trial period, a re-assessment could be made using the results obtained to determine if there is a need to modify the tagging objectives, or extend the number of tagging seasons.

The floy tag and acoustic tag release figures used for simulation purposes are considered realistic, and close to the minimum required to provide an accurate and reasonably precise estimate overall catchability. The program is also cost-effective, relying mainly on cheap floy tags, with the proportion of tagged fish bearing acoustic transmitters being very small to minimize costs (5% is often thought to be an 'insignificant' level). The proposal also suggest that most of the tagging be conducted by trained fishery observers to minimize cost, since these may have to be deployed throughout both fisheries (or on vessels using tangle nets) for monitoring purposes (as strongly recommended by Walters et al. 2008). Still the project may be considered expensive to implement by some. As noted by Labelle and Beere (2007), "conducting a detailed GN observer program in 2008, comparable to that conducted in 1994 would cost about $200,000/yr plus what is already provided by the DFO to monitor some seine activities in Areas 3/4 (Jim Thomas, J.O.T & Assoc., pers. comm.)". A recent estimate of the price of Vemco transmitters is about $350 a piece, so applying 70 tags would cost ≥$25,000/yr. The cost of deploying receiver arrays above and below the Tyee test fishing site, and downloading the data periodically would likely be ≥$50,000/yr. So the annual cost of this program is tentatively estimated to be about $275,000/yr, but it includes the necessary observer program. Substantial economies of scales could be achieved if the DFO staff opted to use the proposed tagging program to get data on other salmon stocks subject to conservation concern, including stock compositions of fishery catches and escapements, test fishery catchabililty rates on non-sockeye species, and so forth.

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TABLES

Table 1. First and last day of gill-net (GN) and seine (SN) fishery openings in DFO Statistical Area 4, and corresponding total number of vessel-days and steelhead releases, 1995-2008. Dash indicates no openings allowed, while blanks indicate no records were provided to the author for those periods. 2005-2008 records updated by DFO staff, July 2009. Dash indicates that the data records are unavailable (no fishing) or could not be obtained before the report submission deadline.

Year	GN_first_day	GN_last_day	GN_Vess_d	ST_Rel.	SN_first_day	SN_last_day	SN_Vess_d	ST_Rel.
2008	Jul-07	Aug-07	3319	3336	Jul-22	Aug-06	275	1835
2007	Jun-20	Aug-05	2621	933	Jul-23	Aug-21	136	622
2006	Jun-28	Sep-06	6376	3906	Jul-16	Sep-03	682	1460
2005	-	-	-	-	-	-	-	-
2004	Jul-05	Aug-12	2350	-	-	-	-	-
2003	Jul-01	Aug-05	3425	-	-	-	-	-
2002	Jul-01	Aug-08	5269	-	-	-	-	-
2001	Jul-02	Aug-06	7935	-	-	-	-	-
2000	Jul-01	Aug-08	6611	-	-	-	-	-
1999	-	-	-	-	-	-	-	-
1998	Jul-02	Jul-18	1289	-	-	-	-	-
1997	Jul-01	Jul-31	8286	-	-	-	-	-
1996	Jul-01	Sep-20	13432	-	-	-	-	-
1995	Jul-04	Aug-21	12016	-	-	-	-	-

Table 2. Summary of variables, values, error levels and functions used in numerical simulations to compute the annual catchability (an associated bounds) under certain conditions. Figures under the 'Source' column are either (i) mathematical relations between variables using letters under the 'Label' column or equations presented in the text, (ii) control variables, or (iii) hypothesized values labeled as 'Hyp.'.

Label	Variable/Parameter name	Value	Error	Source	Comments
A	Floy tags released PS	700		Control	
B	Floy tags released GN	700		Control	
C	Prop. w/accoustic tags	0.05		Control	
D	Accoustic tag rel. PS	35		A x C	
E	Accoustic tag rel. GN	35		B x C	
F	Total accoustic tag rel.	70		D + E	
G	Hypothesized accoustic tag loss PS	0.30	± 0.1	Hyp.	normal error, ±33% of value
H	Hypothesized accoustic tag loss GN	0.70	± 0.1	Hyp.	normal error, ±15% of value
I	Accoustic tag escapement PS	25		D x (1-G)	Rounded to nearest integer
J	Accoustic tag escapement GN	11		E x (1-H)	Rounded to nearest integer
K	Estimated tag loss PS	0.29		1-(I/D)	Escaped/released (integers)
L	Estimated tag loss GN	0.69		1-(J/E)	Escaped/released (integers)
M	Effective floy tags rel. PS	500		A x (1-K)	
N	Effective floy tags rel. GN	220		B x (1-L)	
O	Total effective floy tags rel.	720		M + N	
P	Hypothesized test fishery catchability	0.0056	± .001	Hyp.	normal error, ±20% of value
Q	Effective floy tag catch	4		O * P	Rounded to nearest integer
R	Estimated catchability	0.0056		Q / O	
S	SD catchability	0.0028		Eq. 6	
T	Initial_LB_CI	-0.0006		Eq. 7	
U	Adj_LB_CI	0		Eq. 7	Constraint: LB≥0
V	UB_CI	0.0117		Eq. 7	

Table 3. Summary of variables, values and conditions used in numerical simulations to compute the overall catchability of the test fishing gill-net catchability using pooled records over a 5 year period, given minimum and equal tagging effort in each year. Hypothesized error structures are identical to those given in Table 2, but the test fishery catcability is computed using Eq. 6.

Label	Variable/Parameter name	Yr 1	Yr 2	Yr 3	Yr 4	Yr 5
A	Floy tags released PS	700	700	700	700	700
B	Floy tags released GN	700	700	700	700	700
C	Prop. w/accoustic tags	0.05	0.05	0.05	0.05	0.05
D	Accoustic tag rel. PS	35	35	35	35	35
E	Accoustic tag rel. GN	35	35	35	35	35
F	Total accoustic tag rel.	70	70	70	70	70
G	Hypothesized accoustic tag loss PS	0.213	0.346	0.310	0.283	0.236
H	Hypothesized accoustic tag loss GN	0.718	0.705	0.666	0.687	0.664
I	Accoustic tag escapement PS	28	23	24	25	27
J	Accoustic tag escapement GN	10	10	12	11	12
K	Estimated tag loss PS	0.20	0.34	0.31	0.29	0.23
L	Estimated tag loss GN	0.71	0.71	0.66	0.69	0.66
M	Effective floy tags rel. PS	560	460	480	500	540
N	Effective floy tags rel. GN	200	200	240	220	240
O	Total effective floy tags rel.	760	660	720	720	780
P	Hypothesized test fishery catchability	0.00507	0.00485	0.00459	0.00573	0.00599
Q	Effective floy tag catch	4	3	3	4	5
R	Estimated catchability	0.00526	0.00493	0.00467	0.00490	0.00522
S	SD catchability	0.0026	0.0027	0.0025	0.0026	0.0026
T	Initial_LB_CI	-0.0005	-0.0012	-0.0010	-0.0009	-0.0005
U	Adj_LB_CI	0.0000	0.0000	0.0000	0.0000	0.0000
V	UB_CI	0.0111	0.0110	0.0103	0.0107	0.0109

FIGURES

Figure 1. Major geographical features and management zones of the DFO Statistical Area 4 at the entrance to the Skeena River. Area 3 is further north, and Area 5 is further south. The commonly termed "River", "Gap", and "Slough" regions respectively correspond to sub-area 4-15 above Telegraph Passage, sub-Area 4-12 section between Smith Island and Kennedy Island, and the passage in sub-Area 4-12 northeast of Smith Island.

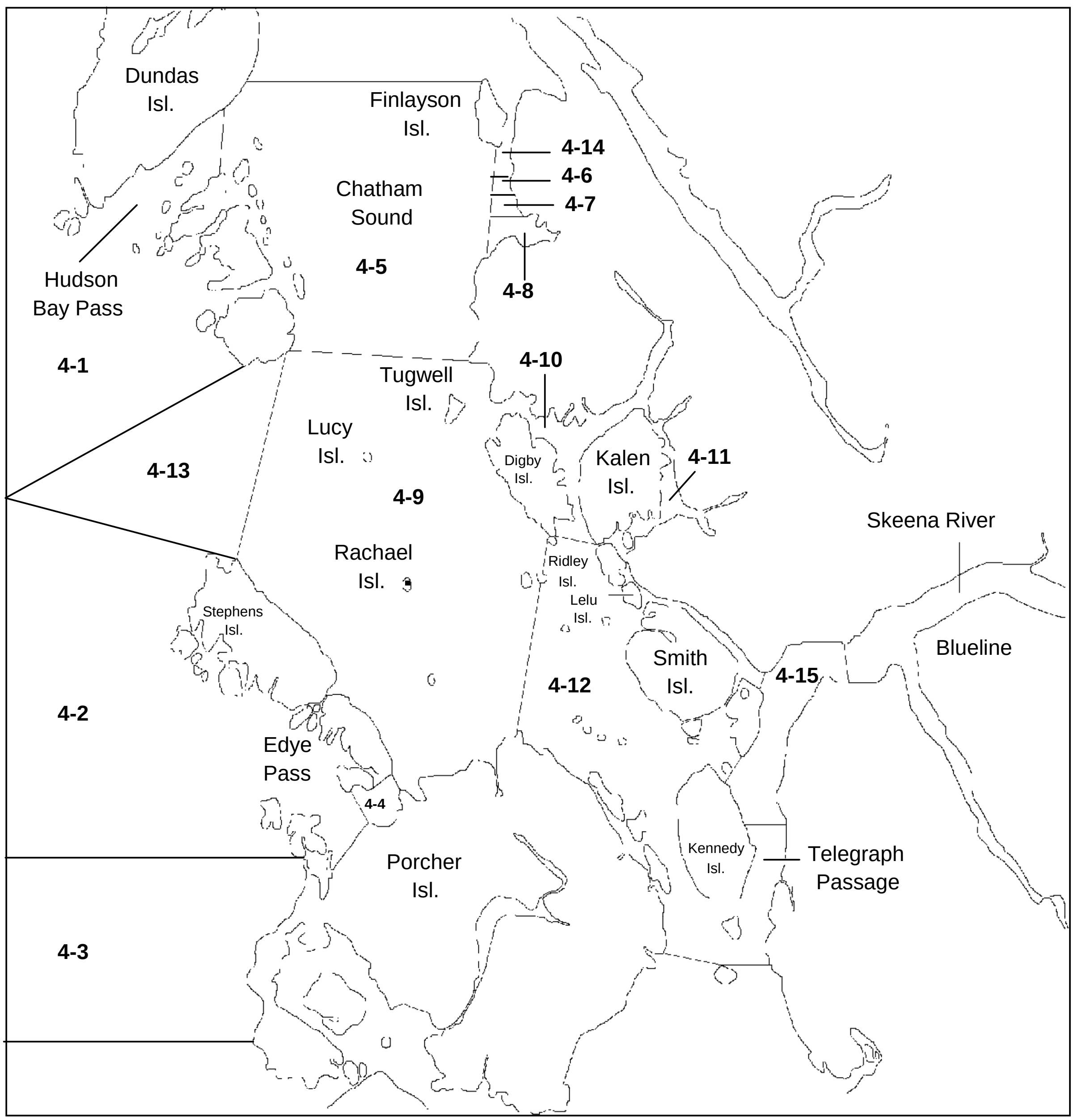
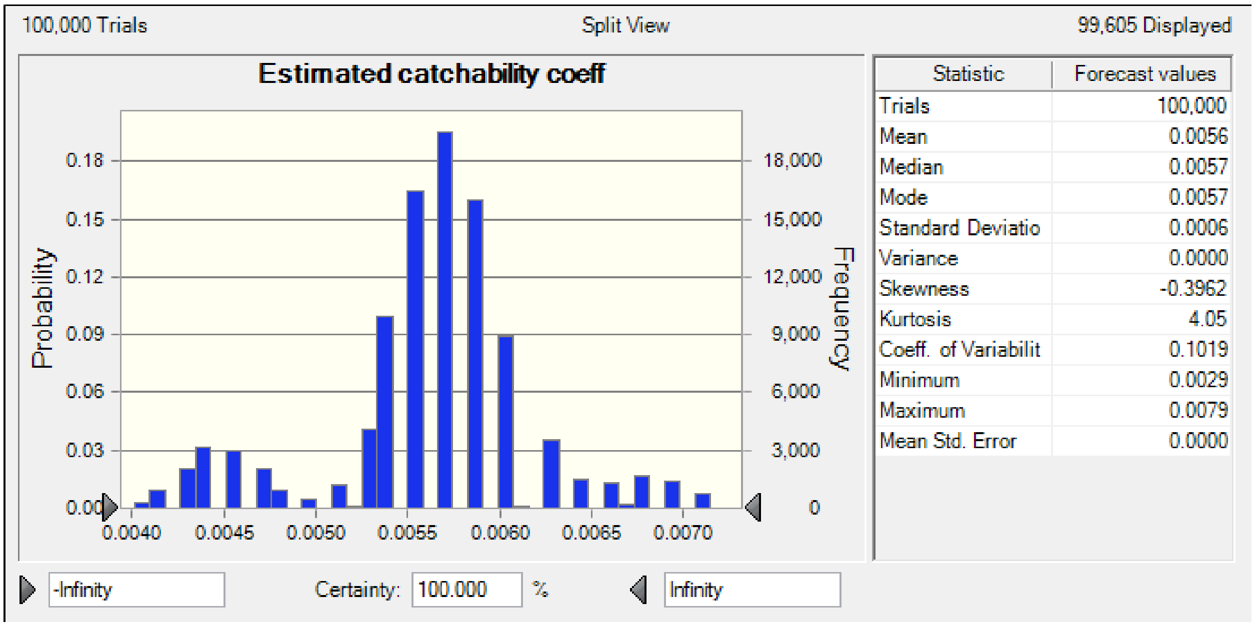


Figure 2. Distribution of catchability estimates from 100,000 Monte Carlo simulations for releases of 700 floy tags in both the PS and GN fleets, and transmitters applied to 5% (top) and 10% (bottom) of those tagged and released in each fleet.



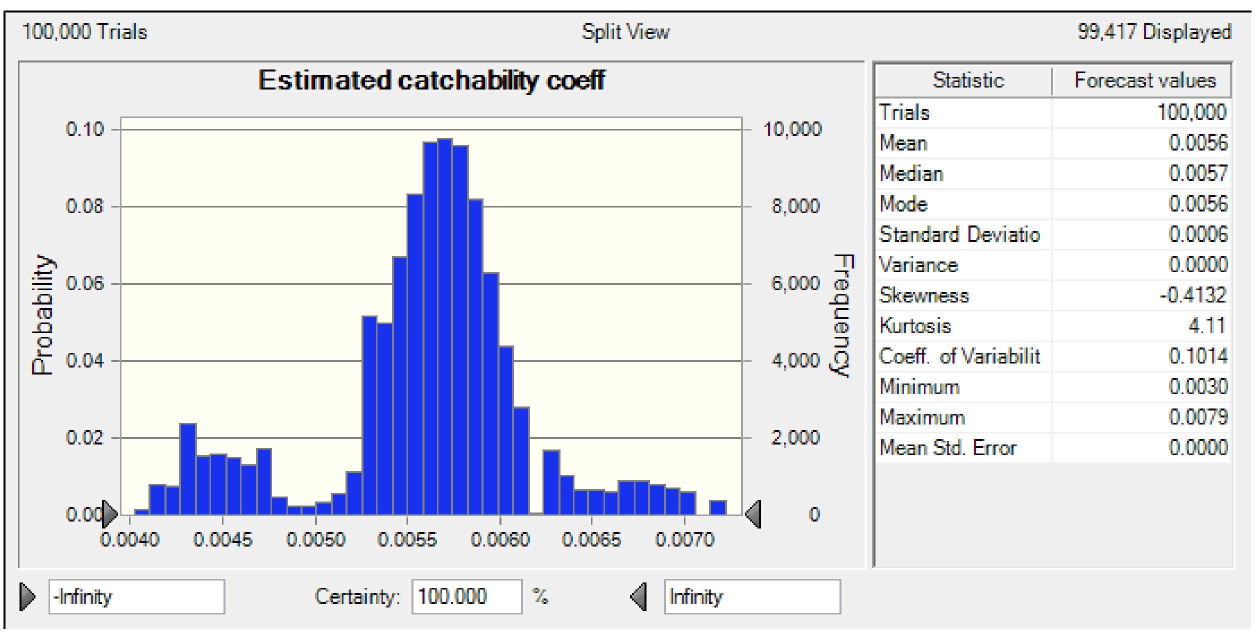
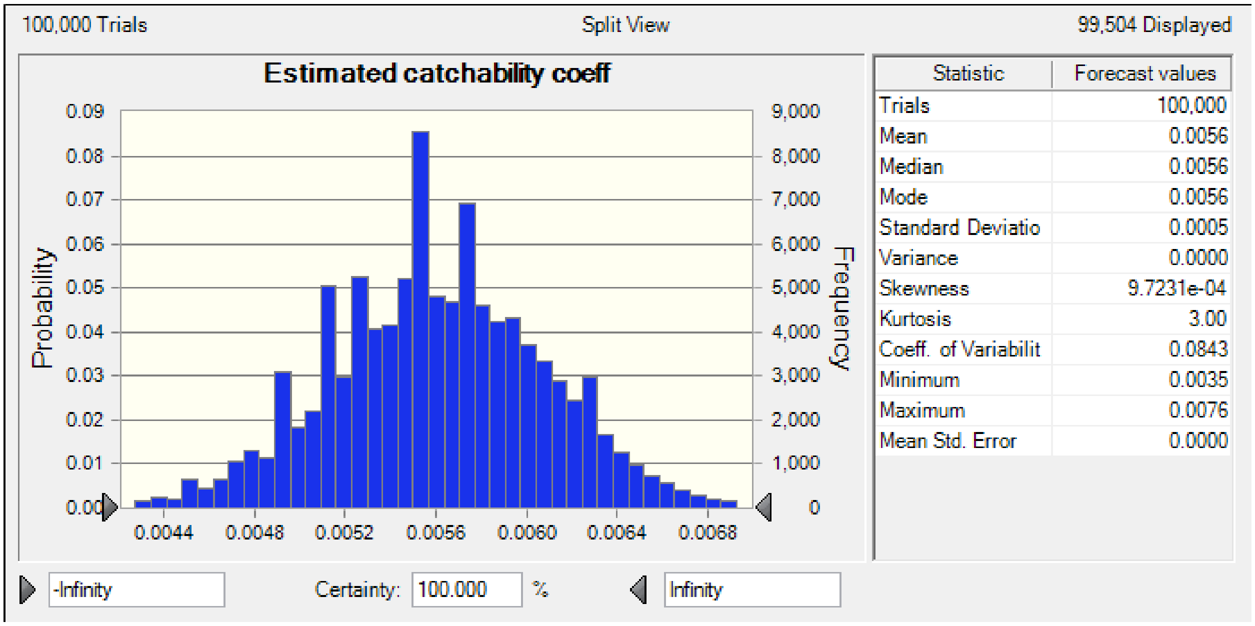
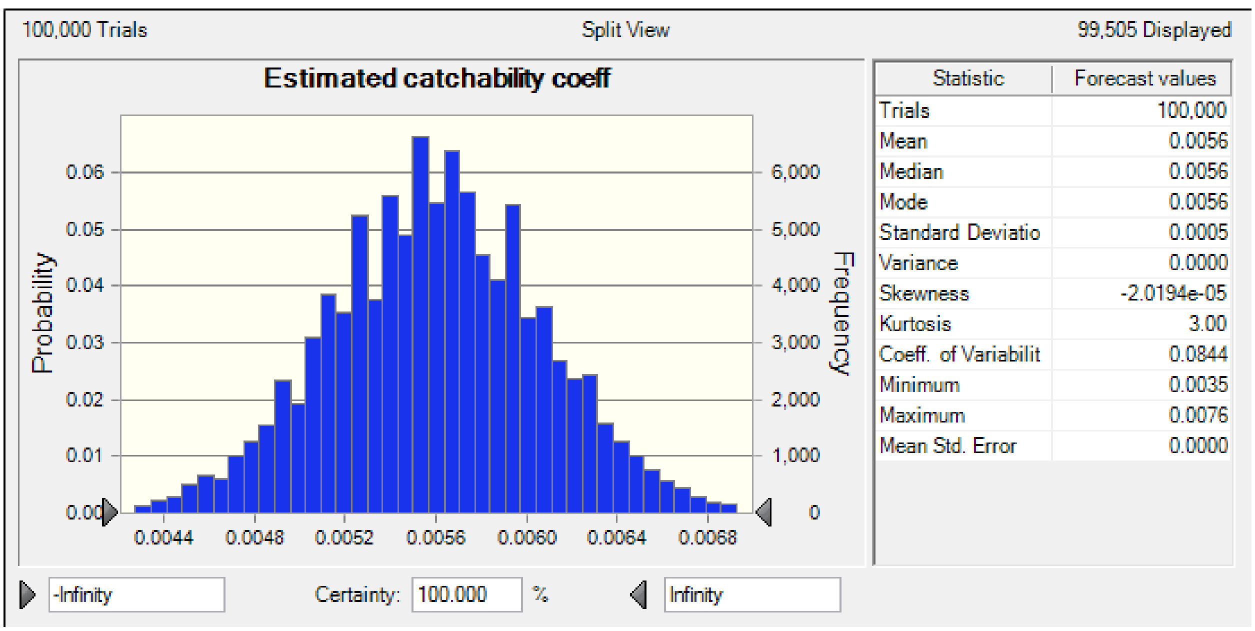


Figure 3. Distribution of catchability estimates from 100,000 Monte Carlo simulations for releases of 2000 floy tags in both the PS and GN fleets, and transmitters applied to 5% (top) and 10% (bottom) of those tagged and released in each fleet.

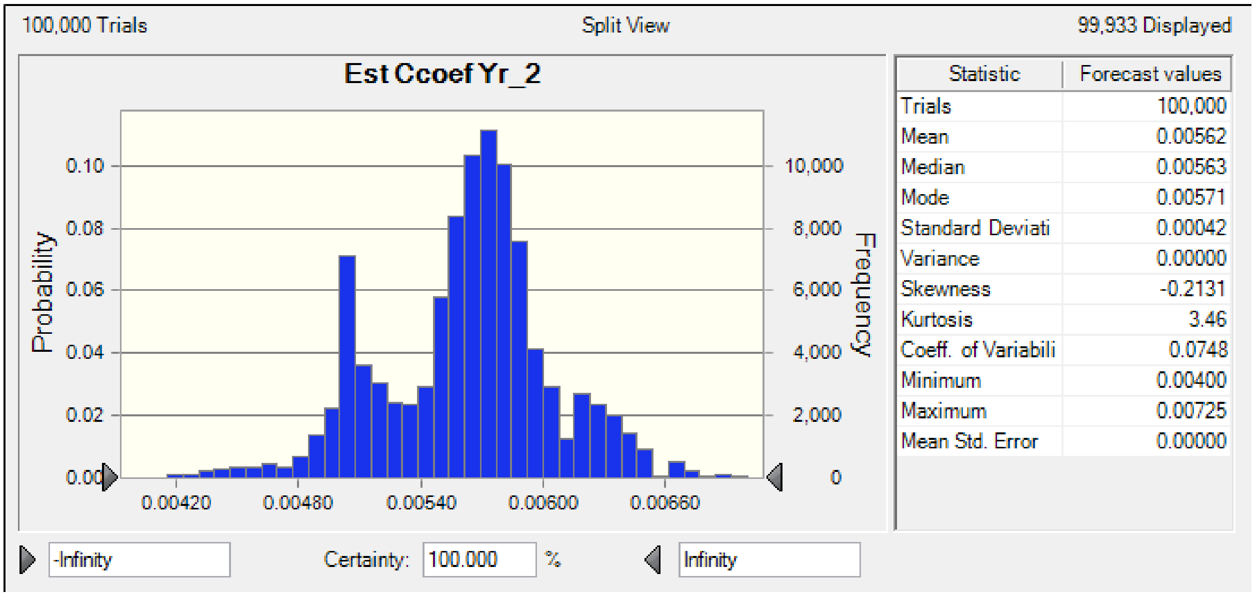


Statistic	Forecast values
Trials	100,000
Mean	0.0056
Median	0.0056
Mode	0.0056
Standard Deviatio	0.0005
Variance	0.0000
Skewness	9.7231e-04
Kurtosis	3.00
Coeff. of Variabilit	0.0843
Minimum	0.0035
Maximum	0.0076
Mean Std. Error	0.0000



Statistic	Forecast values
Trials	100,000
Mean	0.0056
Median	0.0056
Mode	0.0056
Standard Deviatio	0.0005
Variance	0.0000
Skewness	-2.0194e-05
Kurtosis	3.00
Coeff. of Variabilit	0.0844
Minimum	0.0035
Maximum	0.0076
Mean Std. Error	0.0000

Figure 4. Distribution of catchability estimates from 100,000 Monte Carlo simulations after 2 years (top) and 3 years (bottom) whereby 700 floy tags are released in both the PS and GN fleets, and transmitters applied to 5% of those tagged and released in each fleet.



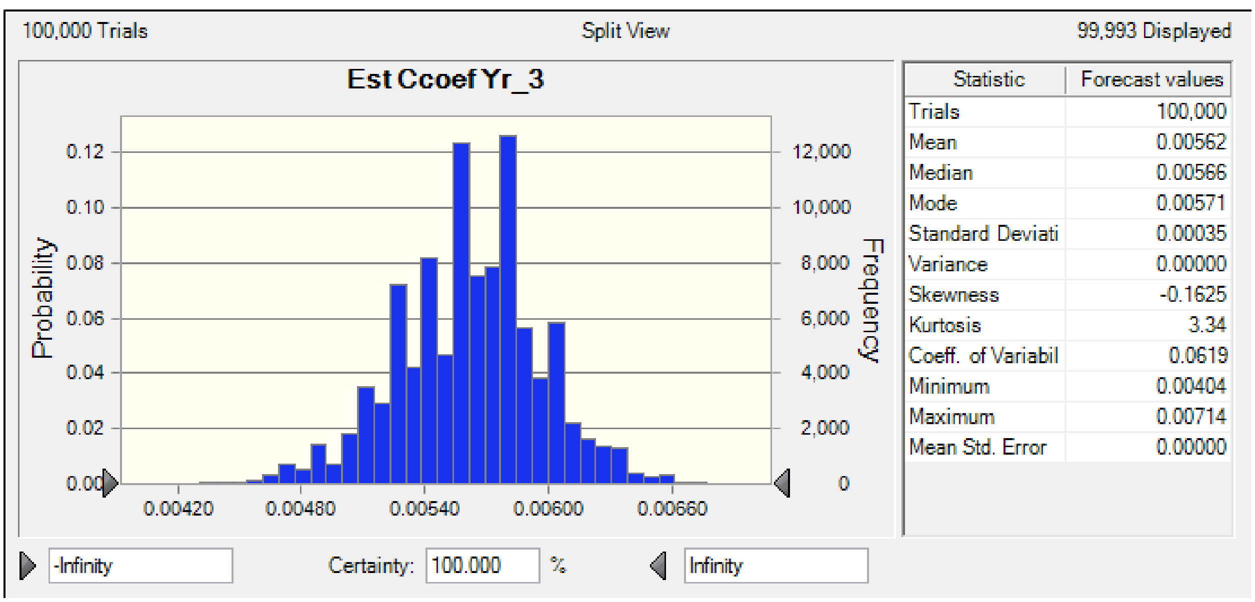


Figure 5. Distribution of catchability estimates from 100,000 Monte Carlo simulations after 4 years (top) and 5 years (bottom) whereby 700 floy tags are released in both the PS and GN fleets, and transmitters applied to 5% of those tagged and released in each fleet.