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SIMULATING TAGGING OF TROPICAL TUNA IN THE EQUATORIAL ATLANTIC OCEAN

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SUMMARY

Simulations were conducted to study the bias and precision of estimates of natural mortality and catchability for a hypothetical tagging p rogram of the three species of Atlantic tropical tuna, yellowfin tuna, bigeye tuna and skipjack. Different scenarios of the mix of species and number of tuna released were considered. Scenarios considered whether priority was given to the species of greatest concern regarding stock status, the species of greatest uncertainty in population parameter estimates, whether the species were tagged according to the proportion caught in the Ghana baitboat fleet or whether the same numbers of tuna were tagged for the three species. Results suggest that estimates of these parameters, given model assumptions, would be asymptotically unbiased and relatively precise regardless of the tagging scenario. There is, however, at least a 20% probability that an individual tagging program would result in estimates of bias of about 15% percent of more, even under the strict assumptions considered here. There is a need to investigate the effect on estimates of these parameters caused by the failure of other model assumptions not yet investigated.

RÉSUMÉ

Des simulations ont été réalisées pour étudier les biais et la précision des estimations de la mortalité naturelle et de la capturabilité pour un programme de marquage hypothétique des trois espèces de thonidés tropicaux de l'Atlantique : albacore, thon obèse et listao. On a considéré différents scénarios du mélange des espèces et du nombre de thons remis à l'eau. Les scénarios ont considéré si la priorité était accordée aux espèces dont l'état du stock suscite le plus de préoccupation, aux espèces faisant l'objet de la plus grande incertitude dans les estimations des paramètres de population, si les espèces ont été marquées selon la proportion capturée dans la flottille de canneurs ghanéens ou si le même nombre de thons ont été marqués pour les trois espèces. Les résultats suggèrent que les estimations de ces paramètres, compte tenu des postulats du modèle, seraient asymptotiquement non biaisées et relativement précises indépendamment du scénario de marquage. Il existe toutefois 20% de probabilité qu'un programme de marquage individuel entraîne des estimations de biais d'environ 15% ou plus, même en vertu des stricts postulats examinés dans le présent document. Il faut chercher à déterminer l'effet sur les estimations de ces paramètres causés par la défaillance d'autres postulats du modèle qui n'ont pas encore été étudiés.

RESUMEN

Se realizaron simulaciones para estudiar el sesgo y la precisión de las estimaciones de mortalidad natural y capturabilidad para un programa de marcado hipotético de las tres especies de túnidos tropicales del Atlántico: rabil, patudo y listado. Se consideraron diferentes escenarios de la mezcla de especies y número de túnidos liberados. Se consideraron los siguientes escenarios de marcado: asignar prioridad a las especies que generan más preocupación en lo que concierne al estado del stock, asignar prioridad a las especies para las que existe mayor incertidumbre sobre las estimaciones de parámetros de población, considerar el marcado de especies en función de la proporción capturada en la flota de cañeros de Ghana o el marcado del mismo número de ejemplares para las tres especies. Los resultados sugieren que las estimaciones de estos parámetros, datos los supuestos del modelo, serían asintóticas, no sesgadas y relativamente precisas al margen del escenario de marcado. Sin embargo, existe una probabilidad de al menos el 20% de que el programa de marcado individual tenga como

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resultado estimaciones de sesgo de aproximadamente el 15% o más, incluso bajo los supuestos más estrictos considerados aquí. Es necesario investigar el efecto causado en las estimaciones de estos parámetros por los errores de otros supuestos del modelo que no se han investigado todavía.

KEYWORDS

Abundance, Bait fishing, Exploitation, Fishing mortality, Long lining, Multispecies fisheries, Natural mortality, Population dynamics, Purse seining, Simulation, Stock assessment, Stochastic models, Tagging

1 Introduction

For the last few years, the ICCAT SCRS has been considering the possibility of conducting a large-scale tagging program on tropical tunas (Anonymous 2013) similar to those conducted before in the Western Pacific where 146,000 tunas were tagged and 18,500 recaptured as part of the SPC Regional Tagging Program (SPC 2013) and Indian Ocean where more than 168,000 tunas were tagged and 27,000 recaptured as part of the IOTC Regional Tuna Tagging Program (IOTC 2012). Foremost among the objectives of such program is the goal to improve population parameters that are important for the evaluation of stock status for bigeye tuna (*Thnunnus obesus),* yellowfin tuna (*Thunnus albacores)* and skipjack (*Katsuwonus pelamis)*. Such parameters may include growth, survival and migration rates and the catchability of various fleets. Although, in theory, all these parameters are estimable from tagging data the success of a tagging program largely rests on the combination of 1) having an appropriate methodological design for the goals of the program, 2) properly implementing this design on the field and 3) obtaining the collaboration of the fishing industry for the reporting of accurate information on tag returns.

In this study we aim to develop a simulation tool that can help define selected aspects of the methodological design for the tagging program. This simulation tool addresses the following question: what are some of the tradeoffs that a program like this may have to consider because the three species that are objective of the program are often caught together and thus may be tagged, released and recapture together? More specifically we ask about the ability of such a program to obtain estimates of population parameters for the three species and the uncertainty associated with such estimates. In the study we make the assumption that tag and release will be conducted from baitboat(s) and that the all the recaptures would come from the purse seine fleet. These assumptions reflect the tagging program that was implemented in the Indian Ocean. Furthermore, in the simulations we assume that the tagging would take place in the Eastern Equatorial Atlantic on a survey vessel with similar selectivity to that of the baitboat fleet of Dakar with recoveries been mostly reported by the purse seine fleets from Ghana and the European Union (Gaertner et al. 2004, Hallier and Gaertner 2006).

The simulation model used is a modification of the model proposed by Lauretta (2013) to evaluate estimation bias in a single species framework. The main modifications were 1) change simulation parameters to mirror the scale of abundance of populations of the three species found in the Equatorial Atlantic and, 2) capture and recapture the three species simultaneously. In the study we evaluate the consequences of making different choices on the ratios of tagged animals for the different species caught by the baiboat. Such choices on the number of tuna released with tags from each of the three species are critical to the design of the program, because while migration and growth rates are generally estimable even with few tag returns, much higher numbers of tag returns are necessary to obtain mortality rate and catchability estimates that are relatively precise. By identifying the likely levels of uncertainty of the estimates of these parameters we hope that we can contribute to the design of a more successful tagging program.

2 Methods

A detailed explanation of the equations used in the single-species model can be found in Lauretta 2013, with a few changes described below to adjust for simulating three species simultaneously (**Table 1**). Assumptions of the simulation presented here are the same as those in Lauretta (2013), however, in this study we explore different scenarios of the number of animals tagged with conventional tags from each species because our focus is on the estimation of mortality rates and catchability. As in Lauretta's (2013), the model also incorporates

PSAT releases and high reward tags to estimate migration and reporting rates, but in this study we do not explore tradeoffs for those other two types of tags. For those interested in such tradeoffs, please see Lauretta (2013). As was done by Lauretta (2013) we ran 10,000 simulations for each test scenario.

Four different tagging scenarios were tested using three different tagging effort levels (**Table 2** and **Table 3**). The 'baitboat' scenario tags fish in the same proportion as they are caught in the baitboat fishery, i.e. every fish caught is tagged regardless of species, based upon the distribution of catch in the Dakar baitboat fishery (Gaertner et al. 2004). The 'even' scenario tags an equal number of all three fish. The 'uncertainty' scenario tags fish based upon the level of uncertainty in population estimates in a ratio of 3:2:1 for SKJ:BET:YFT. This scenario assumes that the highest uncertainty in population parameters is for skipjack, and the least amount of uncertainty is associated with yellowfin tuna. The 'concern' scenario tags fish in a ratio of 1:2:3 for SKJ:BET:YFT. It assumes that ratios of releases should aim to improve population parameters on ratio that reflects the level of concern on stock status for each species because species on a less favorable status would benefit more from improvements in population parameters. In this scenario we assume that the greatest concern is for yellowfin tuna and the lowest concern for skipjack. These scenarios only apply to the usage of conventional tags. The numbers of PSAT and high reward tags are evenly distributed among all three species for all tagging scenarios. The tagging effort level is divided into high, medium, and low, with the high level of effort set equal to the approximate number of fish tagged during the Indian Ocean Tuna Tagging program (Eveson et al. 2012), which at this stage is considered to reflect an optimistic scenario. As a result these simulations represent scenarios where the number of skipjack and yellowfin tuna tagged ranged from 8,350 to 100,000 fish, but the number of bigeye tuna ranged between 11,500 to 66,000 (**Table 3**). Note that the only scenario where the number of tagged bigeye tuna is substantially different to the others is scenario "baitboat".

Catchability and natural mortality rates used in the simulation were those estimated on the latest stock assessment reports for each species (**Table 1**). Catchability estimates reported in stock assessments were from catch in biomass, and so were converted to numbers of fish for the age classes we are most likely to catch and tag using the relative catch in biomass and abundance in numbers of fish. Ages ranges of tuna released and recaptured were assumed to be similar to those tagged in the Indian Ocean Tuna Tagging program (Eveson et al. 2012). Skipjack would be tagged at ages 0-2, yellowfin tuna at ages 1-2, and bigeye tuna at ages 0-2. Given that we assume that the duration of the simulated recapture program is three years, the oldest ages recovered would be age 5. As a result, in the simulation, catchability estimates correspond to ages 0-5.

Fishing effort levels represent a range that would produce levels of fishing mortality similar to those estimated during the most recent stock assessments of each species (Anonymous 2008, 2011, 2012). Tag shedding was assumed to correspond only to type-1 tag loss as estimated from previous tagging studies (BET: Gaertner et al., 2004; SKJ: Kleiber et al., 1987, Adam and Kirkwoor 2001).

The simulation aims to portray populations in two geographic regions. These two regions are both to the east of 30°W, thus only the eastern stock of skipjack is included in this simulation. Region 1 covers the southern equatorial Atlantic area south of 10°N including fisheries in the Gulf of Guinea. Region 2 covers the northeastern Atlantic north of 10°N including fisheries from the Azores, Senegal, and Cape Verde Islands. Migration between the two regions was assumed to be instantaneous and was estimated based upon the relative catch in biomass of each species in the two regions. Yellowfin tuna are primarily caught in the equatorial region with little biomass in the northern region, thus migration rates between the two regions are small. Assuming the majority of all three species spawn in region 1, the majority of the fish caught in region 2 would have migrated there (Pallares et al. 2005, ICCAT 2006-2013). A larger proportion of bigeye tuna are caught in this region than skipjack, however bigeye tuna have a much longer lifespan and thus have more time to build up biomass in the region. Therefore skipjack have the highest migration rate from region 1 to region 2 (m_{12}) estimated as half of the natural mortality rate, followed then by bigeye tuna with approximately half the migration rate of skipjack. The migration rates from region 2 to region 1 (m_{21}) are assumed to be small and were estimated as 25% of m_{12}.

3 Results

For each simulation we calculated the bias as the difference between the value of the parameters used in the simulation and the estimate obtained. Bias was calculated for natural mortality rate and the catchability of the purse seine. From the 10,000 values of bias calculated for each scenario the following statistics are reported: median, 2.5, 10, 25, 75, 90 and 97.5 percentiles. Additionally we report the standard error of the values of natural mortality rate and catchability (**Tables 4-6**).

As expected the standard error of mortality rate and catchability decrease (precision of these estimates increases), as the number of tags increases for an individual species. When all scenarios are considered the maximum standard error in natural mortality are 0.13 and 0.14 for the yellowfin tuna and bigeye tuna respectively when low effort is used and tuna are tagged according to the “uncertainty scenario”. The maximum standard error in natural mortality estimates of skipjack is 0.11 for the low tagging effort and the “concern scenario”. A similar result was obtained regarding the precision of estimates of catchability. Maximum CVs were obtained for yellowfin tuna (0.15) and bigeye tuna (0.14) when the “uncertainty” scenario was used and for skipjack (0.12) for the “concern” scenario.

The median bias in estimates of mortality rates and catchability was low in all scenarios never exceeding more than half a percent. This asymptotic property of the estimator is expected and confirms the estimators are unbiased. Ninety five percentiles of these distributions, however, include some large biases in the estimates reaching +28% to -24% for natural mortality and +36% to -25% in catchability for yellowfin tuna. Similar numbers for bigeye tuna are +28% to -26% for natural mortality and +26% and -20% for catchability. Finally, for skipjack, the numbers are +13% to -13% for natural mortality and +17% and -15% for catchability. As reported above, the less precise estimates are obtained for low tagging effort and the “uncertainty” scenario for yellowfin tuna and bigeye tuna and for the “concern” scenario for skipjack.

It is also important to remember that the median only represents the central tendency of the bias in the asymptotic case; that is if the tagging program was conducted many times. Any single implementation of the tagging program could result in biases within the distributions displayed in **Figures 1-9**. A useful measure of how likely it would be to have a severe bias is to look at the biases for the 90^{th} and 10^{th} percentiles. For yellowfin tuna we see that there is a 20% probability that the bias for a single implementation of the program would exceed about 10%, depending on the scenario of tagging considered. For instance, if the tagging scenario “uncertainty” with low effort was implemented there would be a 20% probability that the bias in natural mortality would exceed ±~15%. Similarly, if the tagging scenario “uncertainty” with low effort was implemented there would be a 20% probability that the bias natural mortality would exceed ±~18% for bigeye tuna. Finally, if the tagging scenario “concern” with low effort was implemented there would be a 20% probability that the bias natural mortality would exceed ±~8% for skipjack tuna.

4 Discussion and limitations of the model

Caruthers et al (2010) used a simulation model to test whether catch per unit of effort (CPUE) data from tropical tuna fleets can be used to estimate relative abundance of bigeye tuna and yellowfin tuna. They suggest that it is challenging to use such data for the purposes of stock assessment because the CPUE data usually available for these two species needs to be aggregated over large spatial scales for analysis and that data imputation may be a better option than aggregation. Their study, however demonstrated the power of simulation modelling as a tool to test the power of current statistical procedures in support of assessments of tropical tunas.

Our paper aimed to used simulation in a similar way than Caruthers et al 2010, but this time to help design and alternative information source for the assessment of tropical tunas, a large tagging program. The results presented suggest that a tagging design in which the proportion of fish tagged from each species is approximately even would result in the lowest bias for natural mortality and catchability estimates for all three species. The baitboat and even scenarios tended to produce smaller median bias for both parameters whereas the less evenly distributed scenarios, “concern” and “uncertainty”, tended to have larger median biases for the species which received fewer tags. Estimates of bias are smallest for skipjack due to the fact that skipjack catchability and natural mortality were assumed to be the highest for the three species.

The model, however, has limitations which may have led our simulations to overestimate tag recovery rates, and therefore underestimate bias. First, the proportion of catch for each species changes between the tagging fleet (baitboats) and the recovery fleet (purse seines) influencing the probability of recapture for each species. The current model assumes that recapture effort is evenly distributed among the three species and that the fishing mortality is therefore simply the product of effort and catchability. Generally, the purse seine fishery in the eastern Atlantic catches a higher proportion of skipjack and fewer yellowfin tuna and bigeye tuna than the baitboat fishery (Fonteneau et al. 2000, Hallier and Delgado de Molina 2000, Gaertner et al. 2004). This is partially due to a vertical stratification of species under FADs, with bigeye tuna often found deepest in the water column (Lennert-Cody et al. 2008). A more accurate estimate may be to set fishing mortality for the recoveries to approximate the fishing mortality generated by the purse seine fleet alone. Although this value is estimated by ICCAT for yellowfin tuna and bigeye tuna because they use fleet and age structured assessment models for these stocks, it is not available for skipjack. It may be possible to calculate this by apportioning mortality of skipjack as a proportion of the catch of each fleet under the assumption that there are no differences in fishing mortality at age.

There is a second reason why our estimates of bias may be inaccurate. Our model does not account for the effects of differential selectivity at age. We expect that the probability of capture decreases with age for bigeye tuna, and to a lesser extent, for yellowfin tuna over the ranges of ages being tagged and recaptured. For example, we know that bigeye tuna generally leave the surface fisheries and are exclusively caught in the long line fisheries when they become adults, or around ages 2-3 (Fonteneau and Pallares 2005). If bigeye tuna are tagged at ages 0-2 we could expect that as fish age over the course of the three-year study their probability of recapture by the purse seine fishery would decrease. This decrease in recapture probability with age causes the simulation to generally overestimate tag recoveries of older fish thus giving an overly optimistic estimate of bias. We would expect some decrease in the probability of recapture of tagged yellowfin tuna, also as they age, although not to the same extent as bigeye tuna.

On the other hand we do not consider at all the possibility of having tag recoveries in the baitboat or longline fisheries. In our model we assume all recoveries come from the purse seine fleet like it was the case in the Indian Ocean. In our model, however, we chose to be conservative in the reporting rate and chose a value of 10%, much lower than the 90% value reported for purse seiners in the Indian Ocean. The result is that simulated recapture rates in our experiments were around 3% (**Figure 10**), much lower than the 15% reported for the Indian Ocean. Although in the Indian Ocean the experience was that the majority of the recaptures were obtained in the purse seine fleet, we would hope that in the Atlantic we would manage to change that and obtain recaptures by these other fleets. If high reporting ratios of recovered tagged fish were achieved from these other fleets estimates of catchability for these fleets could be obtained and the natural mortality estimates could be further improved. More importantly high reporting rates from the longline fleet would ensure that the estimates of natural mortality rates could reflect older age classes, something that could not be obtained if we were to only rely on purse seine recoveries. Such high reporting rates for other fleets may be hard to achieve, especially if the estimates of historic reporting rates for the various Atlantic fleets provided by Caruthers and McAllister (2010) are accurate. In their paper these authors used observer data to calculate reporting rates in Atlantic tuna fleets and estimated, with few exceptions, reporting rates of less than 1.5 % and never greater than 5%. Reporting rates for several important Atlantic longline and baitboat fleets were less than 0.1% suggesting the job of increasing such rate to a meaningful value would be a very challenging one (Caruthers and McAllister 2010) and it may be more useful to focus all the tag recovery effort on the fleets were high reporting rates can be easily promoted with incentives or where reporting rates can be estimated with independent seeding experiments.

In summary, these results suggest that it would be possible to conduct a program for the three species of tropical tuna and obtain rather precise estimates of natural mortality and catchability for young fish (ages 0-5) with the levels of tagging effort considered in the simulation. It is important to remember, however, that these simulations assume some values of percentage of observer coverage and migration rates that have not been estimated for these Atlantic stocks. Moreover, the assumption we make that the probability of recapture is constant with age surely conditions our results. Spatial effects, such as heterogeneous distribution of effort and less than random distribution of release fish would also create departures from the assumption of our model and would have unknown consequences on the levels of bias associated with the estimates. We hope that, at least, this paper elicits discussions on alternative model structures or parameter values that should be investigated and simulated to help in the design of such tagging program, prior to the onset of field operations.

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Table 1. Parameter estimates used for each of the three tropical tuna species.

	Yellowfin Tuna	*Bigeye Tuna*	*Skipjack Tuna*
Natural Mortality (M)	0.7	0.4	0.8
Catchability coefficient (q)	0.0000017	0.0000012	0.0000032
Effort (E)	100000-200000	100000-200000	100000-200000
Fishing Mortality (F = qE)	0.17-0.34	0.12-0.24	0.32-0.64
Migration rate from Equatorial Region (1) to Northern Region (2) (m_{12})	0.05	0.2	0.4
Migration rate from Region 2 to Region 1 (m_{21})	0.05	0.05	0.1
Tagging/handling mortality (T)	0.15	0.1	0.1
Tag Shedding (s)	0.04	0.05	0.01
Observer Coverage/reporting rate region 1 (r_1)	0.1	0.1	0.1
Observer Coverage/reporting rate region 2 (r_2)	0.1	0.1	0.1

Table 2. Break down of tagging effort for each of the three levels, high, medium, and low.

Tagging Effort	*High*	*Med*	*Low*
Total conventional tags	200,000	100,000	50,000
Handling study tags	2000	1000	500
High reward tags/region	2000	1000	500
Electronic tags/Region	1000	500	250

Table 3. Proportion of conventional tags allocated for each species for the four tagging scenarios. In parenthesis number of tags for low and high tagging effort for each species (in thousands).

Tagging Scenario	*Baitboat*	*Even*	*q uncertainty*	*Concern*
SKJ	45% (22-90)	33% (16-66)	50% (25-100)	17% (8-33)
YFT	32% (16-64)	33% (16-66)	17% (8-33)	50% (25-100)
BET	23% (11-46)	34% (17-68)	33% (16-67)	33% (17-67)

Table 4. Biases in estimates of natural mortality and catchability and coefficients of variation for yellowfin tuna.

	Baitboat (23%)			*Even (33%)*			*Concern (50%)*			*Uncertainty in q (17%)*		
	High	*Med*	*Low*	*High*	*Med*	*Low*	*High*	*Med*	*Low*	*High*	*Med*	*Low*
Median % bias M	0.01	0.06	-0.33	0.08	0.13	-0.11	0.05	-0.05	0.11	-0.02	0.13	0.22
2.5 Percentile % bias M	-11.5	-15.2	-20.7	-9.9	-12.8	-17.2	-8.3	-11.1	-14.3	-13	-17.1	-23.8
10^{th} Percentile % bias M	-7.4	-9.9	-13.9	-6.3	-8.4	-11.4	-5.0	-7.2	-9.5	-8.1	-11.2	-16.0
25^{th} Percentile % bias M	-4.0	-5.2	-7.6	-3.1	-4.5	-6.2	-2.6	-3.9	-5.0	-4.3	-5.8	-8.5
75^{th} Percentile % bias M	4.1	5.6	7.5	3.6	4.7	6.3	2.8	3.9	5.5	4.4	6.2	9.2
90^{th} Percentile % bias M	7.8	10.4	14.7	6.8	9.0	12.4	5.3	7.4	10.4	8.5	12.1	17.5
97.5 Percentile % bias M	12.4	16.2	23.4	10.2	14.4	19.5	9	11.4	16	13.9	19.5	28
CV of M	0.06	0.08	0.11	0.05	0.07	0.09	0.05	0.06	0.08	0.07	0.09	0.13
Median % bias q	-0.27	-0.22	-0.24	-0.03	-0.17	-0.36	-0.1	-0.34	-0.27	-0.07	0.08	0.44
2.5 Percentile % bias q	-16.5	-18.5	-22.4	-15	-17.1	-20.4	-14.2	-15.5	-17.9	-16.8	-20.2	-25
10^{th} Percentile % bias q	-10.9	-12.7	-15.5	-10.3	-11.4	-13.9	-7.5	-10.7	-12.4	-9.0	-12.2	-17.5
25^{th} Percentile % bias q	-5.9	-7.0	-8.7	-5.6	-6.4	-7.7	-4.1	-6.0	-6.8	-4.9	-6.6	-9.6
75^{th} Percentile % bias q	5.6	7.1	9.3	5.2	6.3	8.0	4.0	5.6	6.9	5.2	7.8	11.3
90^{th} Percentile % bias q	11.3	14.3	19.07	10.4	12.2	16	8.0	11.2	13.5	10.2	15.0	22.7
97.5 Percentile % bias q	18.1	22.8	30.8	16.6	20.2	25.8	15.5	17.8	22.4	19.7	25.5	36.3
CV of q	0.09	0.1	0.13	0.08	0.1	0.12	0.08	0.08	0.1	0.09	0.12	0.15

Table 5. Biases in estimates of natural mortality and catchability and coefficients of variation for bigeye tuna.

	Baitboat (32%)			*Even (33%)*			*Concern (33%)*			*Uncertainty in q (33%)*		
	High	*Med*	*Low*	*High*	*Med*	*Low*	*High*	*Med*	*Low*	*High*	*Med*	*Low*
Median % bias M	0.03	-0.28	-0.07	0.08	-0.08	0.04	-0.08	-0.01	-0.11	-0.01	-0.11	-0.30
2.5 Percentile % bias M	-14.3	-18.8	-25.8	-14.2	-19.3	-26	-13.8	-18.9	-25.2	-14	-19	-25.5
10^{th} Percentile % bias M	-9.4	-12.8	-17.6	-9.1	-12.4	-17.4	-8.8	-12.2	-16.8	-8.8	-12.0	-17.5
25^{th} Percentile % bias M	-5.0	-6.88	-9.4	-4.8	-6.6	-9.6	-4.7	-6.6	-8.9	-4.7	-6.4	-9.4
75^{th} Percentile % bias M	5.1	6.58	9.4	5.2	6.8	9.0	4.8	6.7	9.1	4.6	6.5	9.4
90^{th} Percentile % bias M	9.7	12.8	18.1	9.7	12.9	17.6	9.0	12.8	17.6	8.8	12.5	18.3
97.5 Percentile % bias M	15	20	28.4	14.8	19.9	27	14.7	20.1	27.9	14.8	19.9	27.7
CV of M	0.08	0.1	0.14	0.08	0.1	0.14	0.08	0.1	0.14	0.07	0.11	0.14
Median % bias q	-0.35	0.34	-0.33	0.13	-0.07	-0.13	-0.20	-0.09	-0.47	0.01	0.1	-0.28
2.5 Percentile % bias q	-14.6	-17.1	-20.5	-14.1	-17.4	-20.3	-14.5	-16.6	-20.6	-14.6	-17	-19.9
10^{th} Percentile % bias q	-9.7	-11.5	-13.9	-10.0	-11.4	-13.7	-8.2	-11.2	-13.9	-7.2	-9.95	-13.9
25^{th} Percentile % bias q	-5.3	-6.45	-7.7	-5.5	-6.2	-7.5	-4.5	-6.2	-7.7	-3.7	-5.45	-7.7
75^{th} Percentile % bias q	5.0	6.1	7.8	5.0	6.2	8.0	4.3	6.2	7.7	4.0	5.7	7.9
90^{th} Percentile % bias q	10.0	12.1	15.8	9.9	12.2	15.9	8.6	12.3	15.6	7.7	10.9	15.8
97.5 Percentile % bias q	16.2	19.4	26.1	15.9	19.6	25.1	16.1	19.3	25.4	15.8	19	25.8
CV of q	0.08	0.09	0.12	0.08	0.09	0.12	0.08	0.09	0.12	0.08	0.09	0.12

Table 6. Biases in estimates of natural mortality and catchability and coefficients of variation for skipjack tuna.

	Baitboat (45%)			*Even (34%)*			*Concern (17%)*			*Uncertainty in q (50%)*		
	High	*Med*	*Low*	*High*	*Med*	*Low*	*High*	*Med*	*Low*	*High*	*Med*	*Low*
Median % bias M	0.01	0.04	0.12	-0.03	0.03	0.06	0.03	-0.09	-0.35	-0.004	0.04	0.04
2.5 Percentile % bias M	-8.6	-10.7	-13.3	-9.2	-11.5	-15	-11.6	-15.2	-21	-8.3	-10	-12.9
10th Percentile % bias M	-5.5	-6.8	-8.9	-5.9	-7.5	-9.7	-7.0	-9.9	-13.8	-4.2	-6.0	-8.4
25th Percentile % bias M	-2.9	-3.6	-4.7	-3.0	-4.0	-5.2	-3.7	-5.2	-7.4	-2.2	-3.1	-4.4
75th Percentile % bias M	3.0	3.6	4. 6	3.2	4.1	5.3	3.8	5.2	7.1	2.3	3.2	4.5
90th Percentile % bias M	5.7	6.9	8.9	6.1	7.7	10.4	7.3	10.4	14.1	4.3	6.1	8.7
97.5 Percentile % bias M	8.6	10.7	14.2	9.2	11.7	15.7	12	16.1	21.8	8.5	10.6	13.4
CV of M	0.04	0.05	0.07	0.05	0.06	0.08	0.06	0.08	0.11	0.04	0.05	0.07
Median % bias q	-0.27	0.03	-0.003	-0.02	-0.43	-0.22	-0.04	0.10	0.29	0.06	0.06	-0.25
2.5 Percentile % bias q	-11.2	-12.5	-14.9	-12	-13.4	-16.4	-13.6	-16.3	-21	-11.2	-12.2	-14.6
10th Percentile % bias q	-7.5	-8.4	-10.0	-7.8	-9.0	-11.1	-8.1	-11.0	-14.3	-5.0	-7.0	-9.9
25th Percentile % bias q	-4.0	-4.6	-5.4	-4.3	-5.2	-6.2	-4.4	-6.1	-7.9	-2.7	-3.8	-5.6
75th Percentile % bias q	3.9	4.6	5.7	4.1	4.8	6.1	4.	6.3	8.8	2.7	3.9	5.3
90th Percentile % bias q	7.7	9.0	11.2	7.8	9.5	12.3	8.7	12.5	17.3	5.2	7.7	10.7
97.5 Percentile % bias q	11.8	14.3	17.7	12.4	15.5	20.4	15.4	20.3	27.7	11.9	14	17.1
CV of q	0.06	0.07	0.08	0.06	0.07	0.09	0.07	0.09	0.12	0.06	0.07	0.08

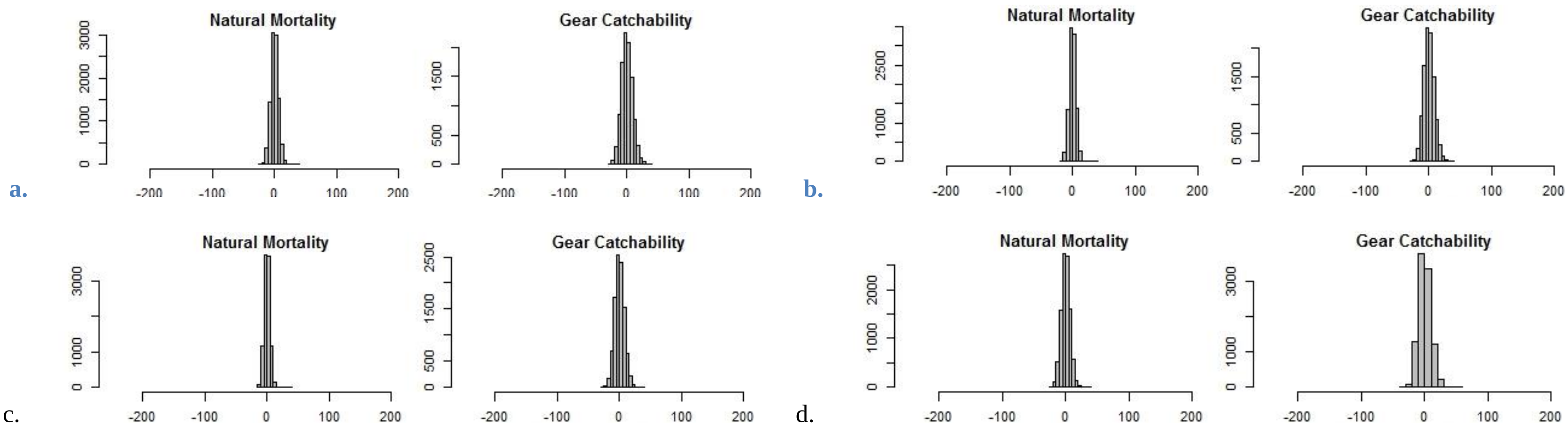

Figure 1. Percent bias of parameter estimates for the high tagging effort for yellowfin tuna for each scenario: a. batiboat; b. even; c. concern; d. q uncertainty.

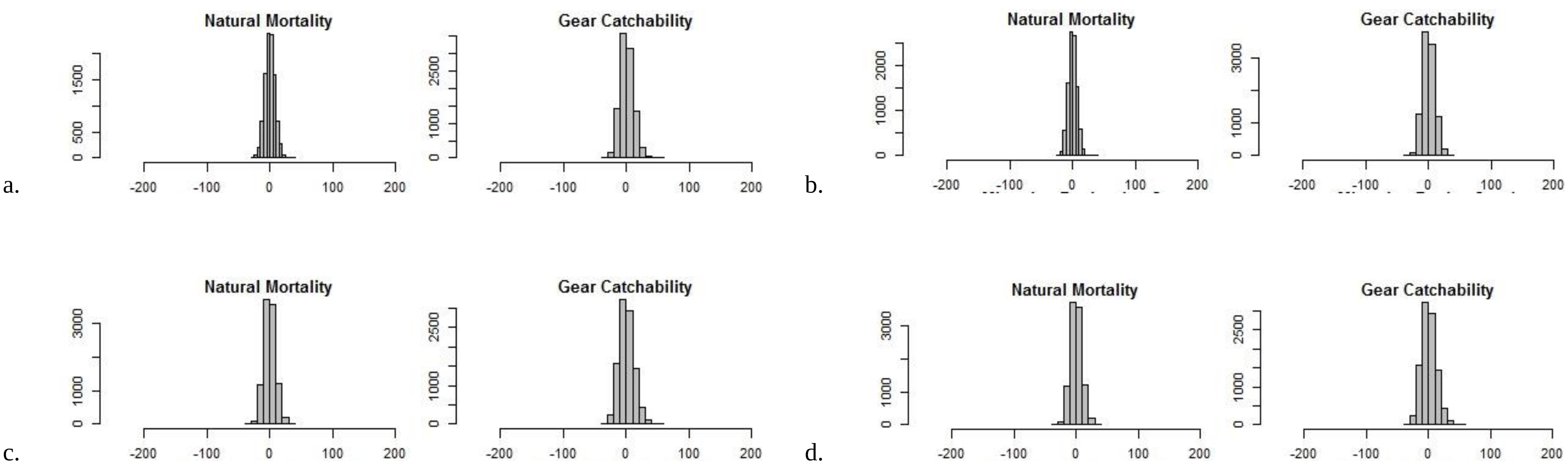

Figure 2. Percent bias of parameter estimates for the medium tagging effort for yellowfin tuna for each scenario: a. batiboat; b. even; c. concern; d. q uncertainty.

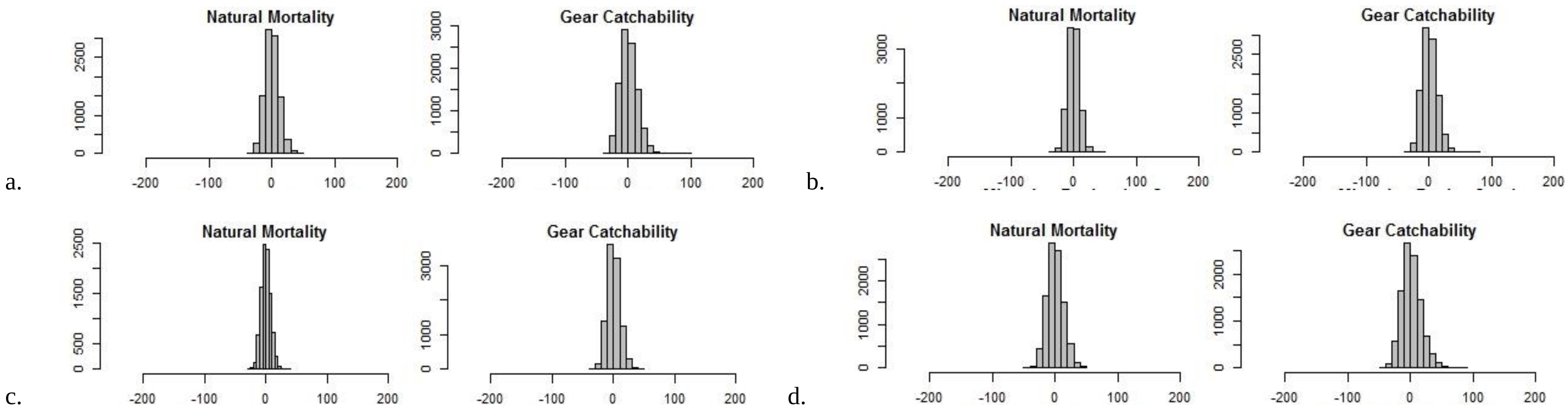

Figure 3. Percent bias of parameter estimates for the low tagging effort for yellowfin tuna for each scenario: a. batiboat; b. even; c. concern; d. q uncertainty.

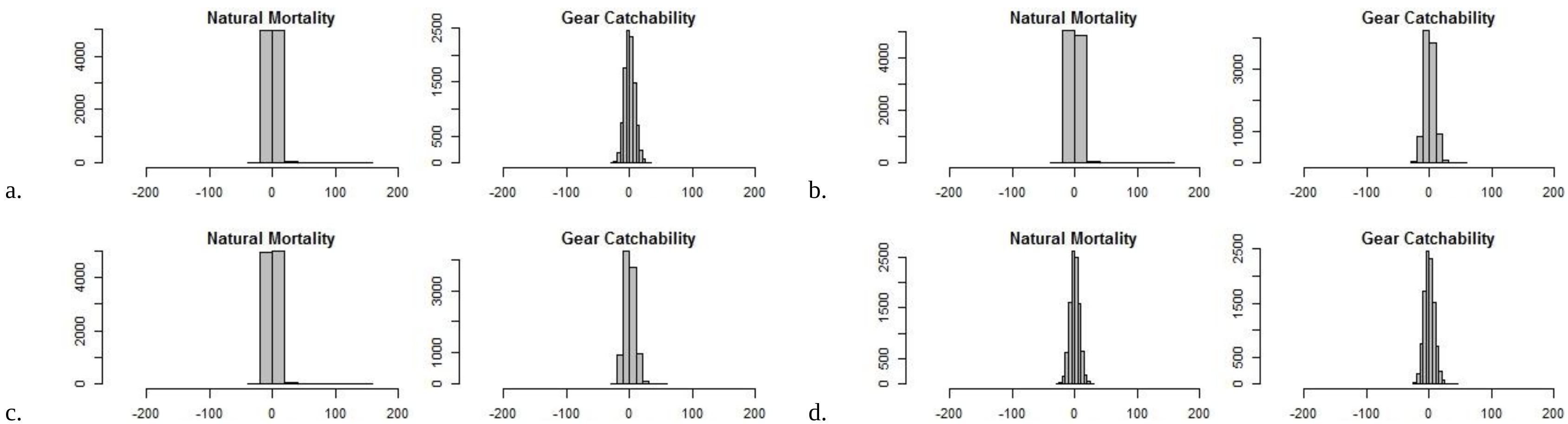

Figure 4. Percent bias of parameter estimates for the high tagging effort for bigeye tuna for each scenario: a. batiboat; b. even; c. concern; d. q uncertainty.

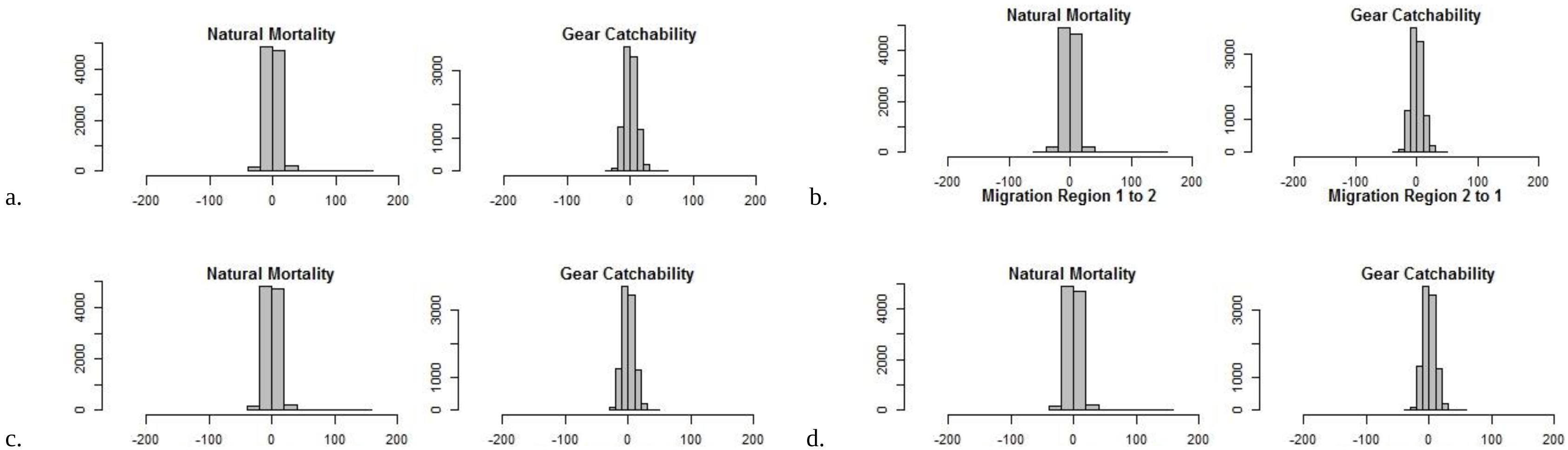

Figure 5. Percent bias of parameter estimates for the medium tagging effort for bigeye tuna for each scenario: a. baitboat; b. even; c. concern; d. q uncertainty

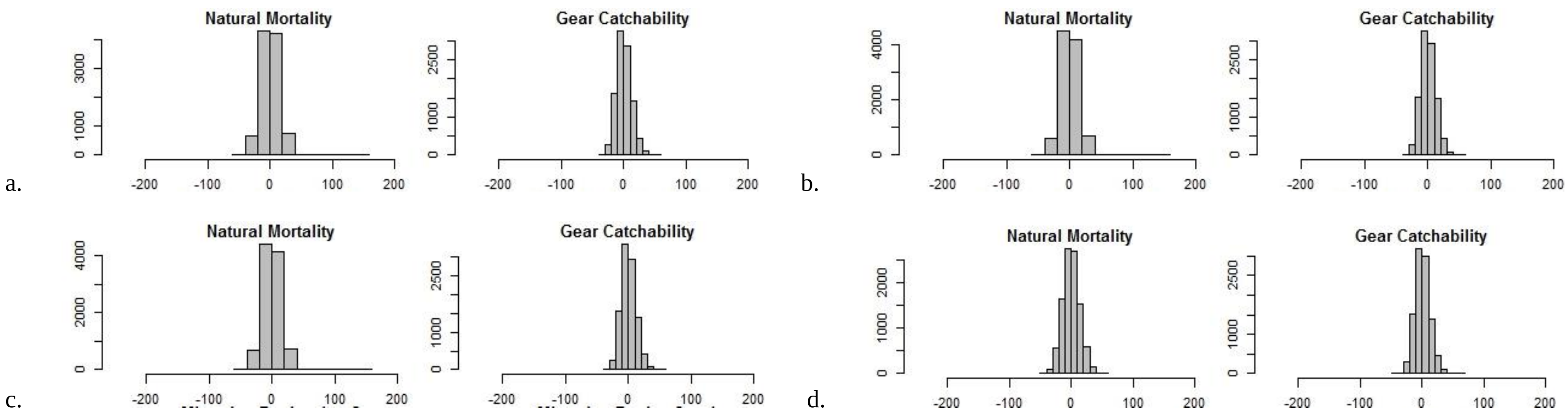

Figure 6. Percent bias of parameter estimates for the low tagging effort for bigeye tuna for each scenario: a. batiboat; b. even; c. concern; d. q uncertainty.

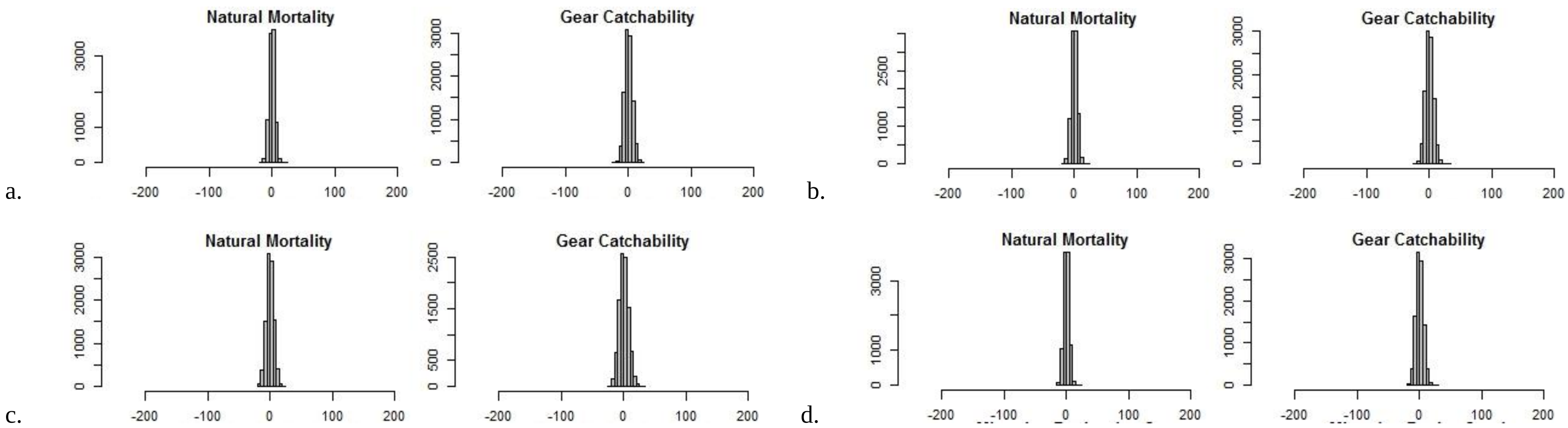

Figure 7. Percent bias of parameter estimates for the high tagging effort for skipjack tuna for each scenario: a. batiboat; b. even; c. concern; d. q uncertainty.

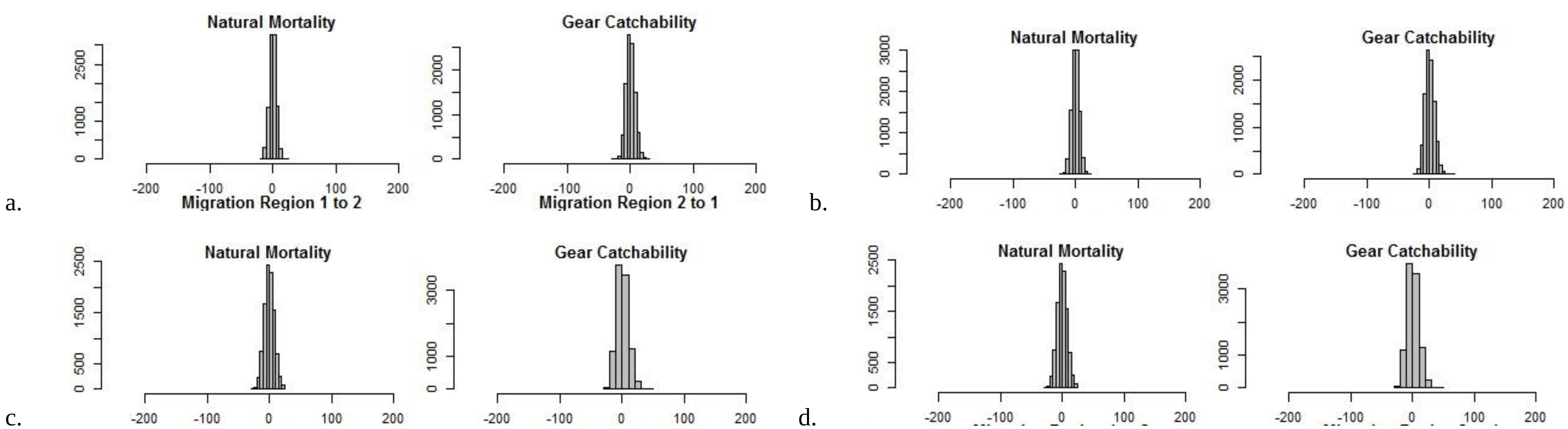

Figure 8. Percent bias of parameter estimates for the medium tagging effort for skipjack tuna for each scenario: a. batiboat; b. even; c. concern; d. q uncertainty.

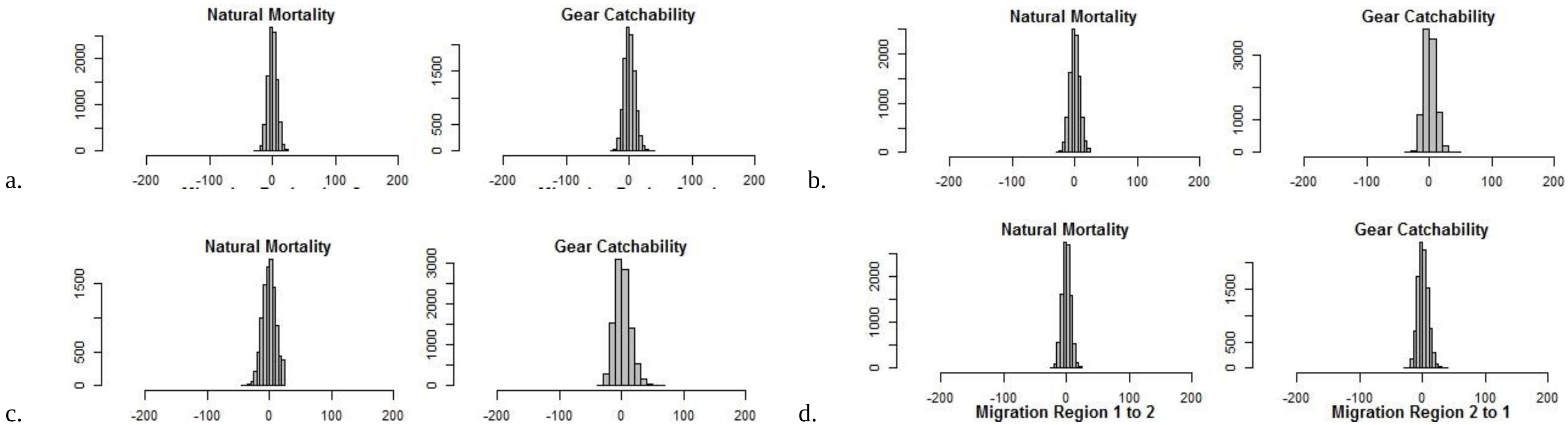

Figure 9. Percent bias of parameter estimates for the low tagging effort for skipjack tuna for each scenario: a. batiboat; b. even; c. concern; d. q uncertainty.

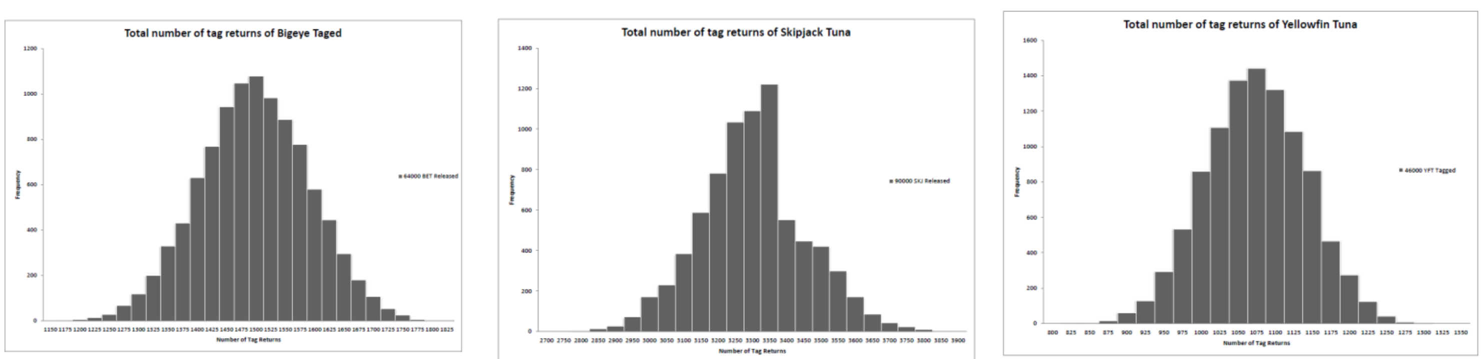

Figure 10. Simulated numbers of recaptured bigeye tuna, skipjack and yellowfin tuna for the “baitboat” scenario and high tagging effort.