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ESTIMATING SURVIVAL AND RECOVERY PROBABILITIES FOR ARABIAN GULF SAILFISH (*ISTIOPHORUS PLATYPTERUS*) FROM TAG RECOVERY STUDIES

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ABSTRACT

Conventional tagging mark-recovery data for 1686 releases and 85 dead recoveries from Arabian Gulf sailfish [*Istiophorus platypterus* (Shaw in Shaw and Nodder, 1792)] were used to estimate conditional survival (S) and tag recovery (f) probabilities in program mark. An a priori approach was used to construct seven plausible models wherein the S and f parameter probabilities were constrained to be constant or allowed to vary over years. Models were ranked using Akaike's Information Criterion weights (AIC_c) and model probabilities were computed. There was some model selection uncertainty and the best model had a 0.619 probability of being the so-called true model for the parameters estimated. The best model produced the best estimated average annual survival over the 5 yr study at 0.375 (SE = 0.324, 95% CI = 0.252–0.516. A more robust multimodel inference was made by averaging the seven models, producing an estimated average annual survival of 0.382 (SE = 0.068, 95%CI = 0.246–0.518). Post hoc analyses of five additional models incorporating Iranian sailfish catch data as covariates showed no relationship between the Iranian catch and survival probability, but did show a positive relationship between the Iranian catch and recovery probability, suggesting that if catch was high then recovery probability was also high.

Recent reports suggest that populations of large pelagic predators, including billfish (Istiophoridae, Xiphiidae), are decreasing worldwide, primarily as a result of overexploitation (Myers and Worm, 2003). A thorough understanding of population structure, movement patterns, habitat preference, and survival rates is needed in order to manage these species effectively. Mark-recapture techniques have been used widely to study fish movement and date back as early as 1653, when Walton and Cotton (cited in McFarlane et al., 1990) reported the return of Atlantic salmon (*Salmo salar* Linnaeus, 1758) to their natal rivers from the sea. Many early tagging studies were designed simply to establish movement patterns and identify specific stocks. However, there has been tremendous growth in the development of mark-recapture analytical techniques over the last 20 yrs, notably the Cormack-Jolly-Seber approach to resighting and recapture data (Seber and Schwarz, 2002; Barker and White, 2004). An increased use of maximum likelihood methods for estimating population parameters such as survival, mortality, recovery, and abundance is particularly apparent in terrestrial wildlife studies (Morgan and Thompson, 2002).

Advances in computer technology and specialized software programs such as MARK (White and Burnham, 1999), have focused the analysis of mark-recapture data toward model selection and maximum likelihood estimation of parameters (Lebreton et al., 1992). These methods can provide robust estimates of survival and recovery derived from an information-theoretic approach based on Kullback-Leibler information loss (Kullback and Leibler, 1951). The approach ranks various models (hypotheses) to estimate the strength of evidence for the "best" approximating model, or a more robust multimodel inference by averaging the models, (Burnham and

Anderson, 2002). With a set of well developed a priori candidate models, the information-theoretic methods provide a quantitative assessment of the strength of evidence regarding model plausibility. In turn, valid inferences from the sample to the population can be made, based on the strengths of the models (Burnham and Anderson, 2002).

The first practical dart tag for large pelagic fishes, designed by Mather (1963) in the early 1950s, provided an in-water method to tag billfish alongside the vessel. Since that time, several hundred thousand billfish have been tagged and released worldwide with the same basic method (Ortiz et al., 2003). Readers are referred to Bayliff (1996) for a comprehensive bibliography of billfish tagging publications. Published reports from billfish mark-recapture programs have generally been limited to providing the number of releases, recaptures, recapture rates (%), maximum distance traveled, and maximum days-at-liberty; and usually, no distinction is made between live recaptures that are subsequently released and dead recoveries (Mather et al., 1972; Buchanan et al., 1978; Jones et al., 1998; Prince et al., 2001; Ortiz et al., 2003).

In the Arabian Gulf (also known as Persian Gulf, hereafter referred to simply as the Gulf) the sailfish, [*Istiophorus platypterus* (Shaw in Shaw and Nodder, 1792)], is the only resident billfish species. It plays an important role in the catch and release recreational fishery of the United Arab Emirates (Fig. 1), where it is a seasonal resident from November through April. A cooperative tagging program established in 1998 enlists the voluntary assistance of recreational fishers and charter operators to tag sailfish, and distributes a monetary reward for tag returns. Sailfish leave the waters of United Arab Emirates in the springtime, undertaking an apparent spawning migration directed northwest, farther into the Gulf (Hoolihan, 2003). From May to July these sailfish are found in Iranian territorial waters of Bushehr province (Fig. 1), where they are susceptible to capture in artisanal gillnet gears. Nearly all tag recaptures have resulted in dead recoveries by gillnet entanglement. Moreover, a high recapture rate (> 5.5%), raises concern that this species may suffer overexploitation due to artisanal fishing activities (Hoolihan, 2004a). Recent electronic tracking studies show Gulf sailfish spend approximately 85% of the time in the upper 10 m of the water column, suggesting a greater likelihood of encountering gillnets (Hoolihan, 2004b). In addition, genetic analysis of mitochondrial DNA indicates that Gulf sailfish form an isolated population living inside the Gulf year-round, with very few individuals mixing with outside populations (Hoolihan et al., 2004). Because the Gulf is comparatively small, these factors imply that total sailfish abundance may be strictly limited. Therefore, an improved understanding of the dynamics and anthropogenic factors influencing this population is needed to develop sound management plans.

Presently, there is a lack of general fisheries data pertaining to Gulf sailfish catch, effort, and size composition over a suitable time series, so it would be useful to extract information on population dynamics from the available mark-recapture data set. Using model-based methods, satisfactory estimates of survival can be obtained from 5 yrs of tagging (Brownie et al., 1985; Williams et al., 2002).

The objective of this study was to further the understanding of Gulf sailfish population dynamics by using a model-based exploratory approach to estimate survival and recovery rates from empirical mark-recapture data, in a way that allows valid inferences to be made from the sample to the population.

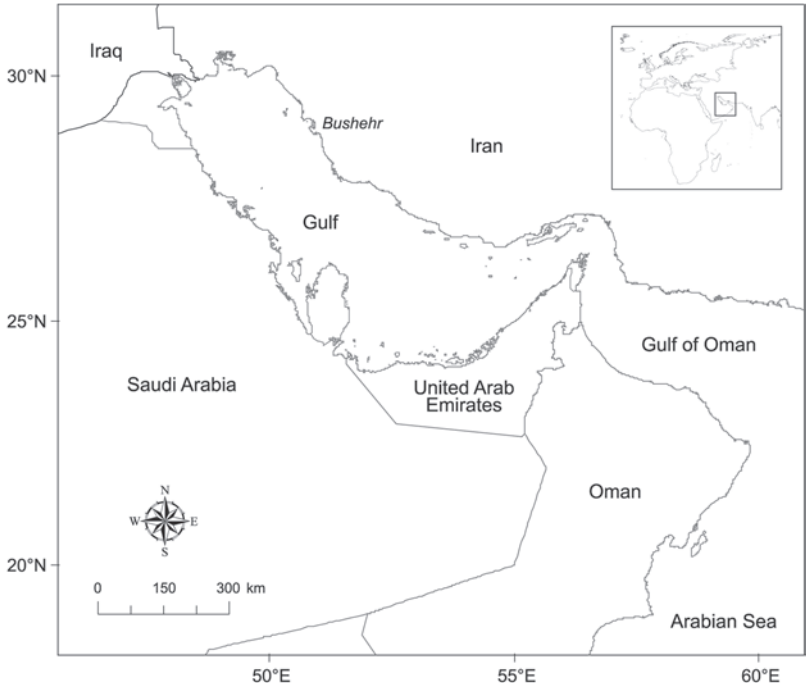

Figure 1. Map of study area.

Methods

Conventional dart tagging with Floy™ FIM-96 small billfish tags (Seattle, Washington) resulted in 2053 releases and 114 recaptures (5.55%) during the period of November 19, 1998–July 31, 2004. No attempt was made to standardize tagging effort from year to year. These data were evaluated for adherence to prerequisite assumptions required for analyses in MARK; a program that computes model parameter estimates using maximum likelihood techniques (White and Burnham, 1999).

One assumption of mark-recapture models is that all releases occur instantaneously, or within a very short period (Smith and Anderson, 1987). Realistically, this is not practical when recreational fishing efforts are targeting a species available in relatively low numbers; however, tagging periods should be as short as possible so as not to confound the tagging and mortality processes. Releases and recaptures were visually assessed in one week bin histograms and a subset of the tagging dataset was selected that confined the release periods to satisfy the model assumption. The selected release period was limited to the 98 consecutive days from January 1 to April 8 (inclusive). All releases and associated recaptures falling outside of this period were excluded from the analyses. As only a few recaptures were re-released alive, it was decided to omit subsequent recaptures of these individuals from the subset and restrict the analysis to a dead recoveries only model, as described by Brownie et al. (1985). Since the first year (1999) of the tagging program had few releases (n = 16), this year was excluded from the analyses. This left a total of 1686 releases and 85 dead recoveries over 5 yrs for the modeling analyses (Table 1). For the recoveries, 72% were made within the same year (season) as released, 23% were recovered after 1 yr, and 8% after 2 yrs.

The "Brownie et al. Recoveries" model class in program MARK (White and Burnham, 1999) was used to estimate probabilities of sailfish survival (S) and tag-recovery rates (f) from the harvest of previously tagged fish. Survival rates are useful in that they often have the greatest impact on population growth rates (Williams et al., 2002). Age and sex could not be deter-

Table 1. Summary of the 1686 sailfish releases and matrix of 85 dead recoveries for years 2000–2004. Releases are restricted to the period January 1–April 8, while recoveries could occur anytime after the period in which fish were tagged.

Year	Releases	2000	2001	2002	2003	2004	Total
2000	322	13	7	3	0	0	23
2001	485		19	7	1	0	27
2002	362			22	2	2	26
2003	297				2	2	4
2004	220					5	5
Total	1,686						85

mined at time of live release and were unavailable at time of dead recovery; consequently, these covariates were not considered in the analyses.

The following notation was used:

N_j = Number of sailfish tagged in year *j*,

S_j = Probability of survival from year *j* to year *j* + 1, conditional on being alive at the beginning of year *j*. The survival interval is defined to be the mid-point of tagging in one year to the mid-point of tagging in the following year, and

f_j = Probability of recovery during the interval *j* to *j* + 1, conditional on being alive at the beginning of year *j*.

Inferences made from the modeled tagging data involve several assumptions (Brownie et al., 1985). These include: no tag loss (shedding); tag or tagging does not affect survival; fate of individuals are independent; fate of a given individual is a multinomial random variable; all individuals have same survival and recovery rates; and annual survival and recovery rates may vary by calendar year.

Models were formulated in program mark that considered both survival and recovery probabilities, while permitting these variables to remain constant or to vary through time. A best-fit model probability was assessed with AIC_c (Sugiura, 1978), a second order version of Akaike's Information Criterion (AIC) adjusted for small sample size (Akaike, 1973),

$$AIC_c = AIC + \frac{2K(K+1)}{n-K-1}$$

where *K* is the number of independently estimated parameters, and *n* is the sample size. In turn, AIC_c was used to compute model probabilities; these are measures of the strength of evidence for the j^{th} model relative to the others (Akaike, 1973; Burnham and Anderson, 2002). The best fitting model is defined by the lowest AIC_c value. Additionally, AIC_c differences (ΔAIC_c) were computed to compare the relative values between models. Models with ΔAIC_c values > 10 generally have little empirical support and might be omitted from further consideration (Burnham and Anderson, 2002).

Results

After reviewing the data, a total of seven models were chosen for comparison in program mark, with each representing a hypothesis concerning the parameters of interest and how they might vary or remain constant over time. An a priori approach was used to choose three models to start with: [*S*(.) *f*(t)], [*S*(t) *f*(.)], and [*S*(t) *f*(t)] (Lebreton et al., 1992). The abbreviation *S*(t) denotes that survival is allowed to vary by year (i.e., year-specific), while *S*(.) denotes that survival is constrained to be constant over the years. An additional three models were included to determine potential trends in both survival and recovery probabilities: [*S*(T) *f*(t)], [*S*(t) *f*(T)], and [*S*(T)

f(T)], where T denotes a linear time trend enforced on the parameters. Finally, the model [S(.) f(.)], where both parameters are assumed constant over time, was also included for consideration even though the plausibility of this model was low.

The sparcity of tagging data used in the modeling analyses allowed a standard test statistic to be computed; but because this statistic lacked chi-square distribution, a goodness-of-fit test was not possible. However, examination of the deviance residuals from the seven models exhibited no indication of over-dispersion or other forms of lack of fit; and was taken as a valid assumption that the data met the necessary requirements.

The [S(.) f(t)] model was the best model (in terms of being closest to the truth in a Kullback-Leibler sense), and showed the highest probability (AIC_c weight) of 61.9%, based on measuring the strength of evidence relative to the other six models (Table 2). The best model, [S(.) f(t)], produced the best estimate of average annual survival probability (Table 3) over the 5 yr study at 0.375 (SE = 0.069, 95% CI = 0.252–0.516). No meaningful trend (slope = −0.101, SE = 0.324, 95% CI = −0.736 to 0.534) was evident for the estimated survival probabilities from the best model. Even though the trend was slightly negative (−0.101), precision of the estimate is very low and no inference can be suggested for the trend over the 5 yr study.

Estimated recovery probabilities ranged from 1.0% to 5.5% (Fig. 2) using the better model where f(T) was present (i.e., [S(T), f(T)]; and evidence indicated a negative trend in these recovery probabilities (f) (slope = −0.204, SE 0.103, 95% CI −0.406 to −0.002). A sharp drop was noted between yrs 3 and 4.

There was some model selection uncertainty. Although model [S(.) f(t)] was estimated to be the best with 61.9% of the total probability, two other models, [S(T) f(t)], and [S(t) f(t)], exhibited a reasonably high level of support. The remaining four models showed negligible support for the data. Rather than relying on the inference of the single model [S(.) f(t)], a robust multimodel inference was made by averaging the seven models (Table 4). Because the S and f model formulates survival estimates from one release period to the next, it is not possible to estimate survival for the final or fifth yr; hence there are no values for the final year in Table 4.

The annual sailfish catch by Iranian gillnets has dropped over 95% since year 2000, even though fishing effort has remain fairly constant (N. Niamaimandi, unpubl. data). Simultaneously, there was a noticeable reduction in numbers and age classes of sailfish in the UAE recreational fishery (Hoolihan, pers. obs.).

Table 2. Akaike's Information Criteria (AIC_c) values, AIC_c weights, and number of parameters for seven models tested. S and f are the survival and recovery variables. The notation (.) denotes constrained as constant over years, while (t) allows variation by year, and (T) enforces a time trend on the parameters. Differences between AIC_c values (δAIC_c) > 0 generally have little empirical support.

Model	AIC_c	δAIC_c	AIC_c Weights	No. Parameters
[S(.), f(t)]	784.642	0.000	0.619	6
[S(T), f(t)]	786.563	1.922	0.237	7
[S(t), f(t)]	787.618	2.977	0.140	9
[S(T), f(T)]	794.662	10.021	0.004	4
[S(.), f(.)]	798.749	14.107	0.001	2
[S(t), f(.)]	799.459	14.817	0.000	5
[S(t), f(T)	804.268	19.626	0.000	5

Table 3. Maximum likelihood estimates of parameters for model [S(.)f(t)], where survival (s) is constrained to be constant over years and recovery (f) is allowed to vary by year.

Parameter	Estimate	SE	95% Confidence interval
S	0.375	0.069	0.252–0.516
f	0.041	0.011	0.024–0.069
f	0.043	0.008	0.029–0.062
f	0.055	0.010	0.037–0.079
f	0.010	0.004	0.004–0.024
f	0.022	0.008	0.011–0.044

To consider the effect of the Iranian catch data, a post hoc analysis was done incorporating this data as a covariate for survival and recovery probability (two separate analyses). The forms of the model were:

$$S_j = \beta_0 + \beta_1(C_j), \text{ and } f_j = \beta_0 + \beta_1(C_j),$$

where C_j = Iranian sailfish catch in year j, β_0 is the intercept, and β_1 is the slope in the relationship. There was no evidence of a relationship between the Iranian catch data and survival probability, however a positive relationship was apparent between the Iranian catch data (C_j) and the estimated recovery probabilities (f_j). This was based on the data available (slope = 0.002, 95% CI = 0.000–0.004), and suggested that if catch was high, then recovery probability was high also.

Discussion

Model Assessment of Survival and Recovery.—The estimated average annual survival probability (S = 0.375, SE = 0.069) for the best model [S(.) f(t)] and the model averaged estimate (S = 0.382, SE = 0.068) seemed low. For comparison, Smith et al. (2000), reported estimates of annual survival probability for mark-recaptured Atlantic striped bass (*Morone saxatilis* Walbaum, 1792) ranging from 0.63 to 0.90 over a 10 yr study period. Rodriguez-Marin et al. (2005), using a similar modeling approach to the present study, estimated annual survival at 0.28 for bluefin tuna (*Thunnus thynnus* Linnaeus, 1758) in the Mediterranean. Low estimates of survival probability may be a result of overexploitation, lack of suitable time series of data, failure to meet the basic model assumptions, or a combination of these factors. An important consideration is that the information criteria can only select the best model from the candidate models available; therefore, if a better model exists, but is not offered as a candidate, the information-theoretic approach cannot be expected to consider it (Burnham and Anderson, 2002).

Table 4. Multi-model weighted average estimates of survival probablities for Gulf sailfish (yrs 2000–2004), where j denotes year and S_j is the mean survival estimate.

j	Estimate S_j	Standard error	95% Confidence interval
1	0.407	0.110	0.220–0.626
2	0.355	0.083	0.213–0.529
3	0.418	0.157	0.168–0.718
4	0.349	0.112	0.169–0.585

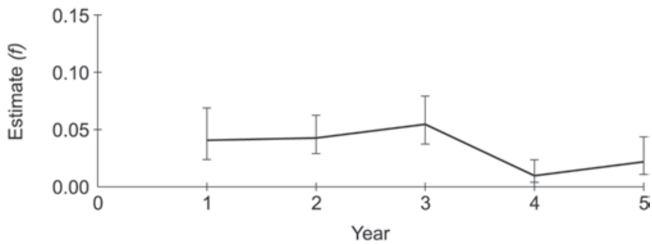

Figure 2. Estimated recovery probability *(f)* that a tagged sailfish is harvested and reported, derived from the best model, [*S*(.) *f* (t)]. Y bars represent 95% confidence intervals.

Bias on Survival Estimates.—The Brownie et al. (1985) dead recoveries model assumes no tags are lost or shed after release. During this particular study, no attempt was made to double-tag fish for the purpose of estimating tag loss. However, some tag loss is to be expected, which will accordingly bias the estimates of annual survival (Nelson et al., 1980). Tag loss can result from improper placement, innate immune response to expel a foreign object or mechanical removal including breakage. Non-reporting of tag recoveries can also bias survival estimates. In the present study, tag rewards were high (US$50/tag) and program awareness was directed at fishermen. For these reasons, and the evidence suggesting the study population remains inside the Gulf year-round (Hoolihan et al., 2004), the failure to report tag recoveries was presumed negligible.

Another underlying model assumption is that survival rates are not affected by the tag or tagging procedure. However, the actions of capturing, tagging, and releasing a sailfish with recreational fishing gears can induce a great amount of physical stress on the animal. This is potentially life threatening, by causing death as a direct result of exhaustion or injury, or increasing the animal's vulnerability (at least temporarily) to predation. For example, shark attack has been implicated in the mortality of billfish released with electronic tags (Jolley and Irby, 1979; Pepperell and Davis, 1999). Generally, post-release survival of tagged and released billfish is thought to be high, based on results of electronic tracking studies (Jolley and Irby, 1979; Holland et al., 1990; Holts and Bedford, 1990; Brill et al., 1993; Pepperell and Davis, 1999; Hoolihan, 2004b); however, it does not meet the model's assumption that survival rates are unaffected by tagging, therefore biasing the estimated survival and recapture probabilities. For tagging mortalities, deaths go unreported, causing survival estimates to be biased downward. Also, in the case of tag shedding, a percentage of these unmarked fish would presumably still be captured but not identified, therefore resulting in a downward bias for recapture rate.

A low survival rate would be expected in an overexploited population. The Iranian catch data suggested that as overexploited populations decline in abundance, the probability of recovery (*f*) also declines. This may explain the sharp decrease in *f* between the third and fourth years. At present, the total tag encounter rate (5.64%) for Gulf sailfish remains high (Hoolihan, unpubl. data), in comparison to other sailfish tagging programs (Table 5).

The total number of tagged and recaptured sailfish available for model-based analysis in the present study was comparatively low, and this is reflected in the somewhat poor precision of survival estimates. More importantly, the low total recovery probabilities (*f* ranging from 0.010 to 0.055) suggest a cautious interpretation of the derived estimates. Modeling analysis provides survival and recovery rates that are

Table 5. Total tag encounter rate comparison for sailfish tagging programs.

Program (region)	Period	Number tagged	Recapture rate (%)	Study
Environment Agency–Abu Dhabi (Arabian Gulf)	1998–2005	2,073	5.64	Hoolihan (unpubl. data)
The Billfish Foundation (Atlantic, Indo-Pacific)	1990–1996	14,746	1.97	Peel, 1996
National Marine Fisheries Service (Atlantic)	1954–1995	61,428	1.70	Jones and Prince, 1996
National Marine Fisheries Service (Indo-Pacific)	1963–1998	7,749	0.58	Holts and Prescott, 2001
Oceanographic Research Institute (Indian Ocean)	1976–2004	2,462	1.14	Bullen et al., 2005
Major constituent-based programs (global review)	1954–2001	126,716	1.52	Ortiz et al., 2003

model-based estimates only; therefore, the results should be considered exploratory, rather than confirmatory. A larger data set would better support the models, as well as allowing more complex models to be assessed (Burnham and Anderson, 2002). The capture methods and low number of sailfish available on any given occasion presents an obstacle to fulfilling the model assumption of an instantaneous release period. However, by extracting subsets of data that narrow the release period, as shown in this study, this assumption can be met satisfactorily to allow valid statistical inferences of population parameters. (Brownie et al., 1986; Burnham et al., 1995; Schwarz and Arnason, 1996; Barker, 1997; Pine et al., 2003).

Most of the tag recoveries (72%) occurred within 6 mo of release (in the same season). Just 8% reached the second year, and none after that. This might suggest that Gulf sailfish are short-lived, or may be affected by overexploitation (i.e., decrease in abundance of adult population). Sailfish are known to mature around 2–3 yrs and can reach much higher maximum ages, therefore overexploitation is a more plausible reason for the lack of older tag recoveries (Hedgepeth and Jolley, 1983; Prince et al., 1986; Alvarado-Castillo and Félix-Uraga, 1996; Chiang et al., 2004).

The utility of model-based analysis for mark-recapture data is apparent, however, the results from the present study should be considered exploratory. Further analysis, using model-based methods, for the substantial billfish tagging data sets dating back to the 1950s may provide greater insight into billfish population dynamics. Additionally, inclusion of the information-theoretic approach to mark-recapture analyses in the planning and design stages for tagging studies would be beneficial. This pertains not only to conventional tagging studies, but also to electronic tagging which has gained widespread popularity with billfish investigators. Staggered entry design models developed for telemetry studies (Pollock et al., 1989) allow for "new" (i.e., electronically tagged) animals to enter the population over time, as well as accounting for animals being lost due to radio failure, radio loss, or emigration.

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