A HABITAT-BASED SIMULATION FRAMEWORK TO DESIGN TAG-RECAPTURE EXPERIMENTS FOR TUNAS IN THE INDIAN OCEAN. APPLICATION TO THE SKIPJACK *(KATSUWONUS PELAMIS)* POPULATION.

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ABSTRACT

The IOTC initiated a discussion to organize a large scale tagging program concerning the major tropical tuna species and fisheries. According to the terms of reference for the working party on tagging (Anon., 1999), prospective simulations are needed to help designing tag-recapture experiments. The purpose of this paper is to present the methodology developed to help designing the future tagging program. It is based on three stages: tag recovery simulations with an habitat-based advection-diffusion-reaction model; bootstrapping of the recovery data sets; population parameter estimation and comparison of scenarii. Different scenarii are studied to check the reliability of the method and its ability to compare various tagging experimental designs.

1 INTRODUCTION

Tropical tuna population dynamics is less understood in the Indian Ocean than in the two other oceans. In particular, the basic biological informations needed to conduct reliable stock assessment or to develop spatialized population models (e.g.: stock structure and migration patterns, natural mortality rate *M*, growth curve and associated parameters, ...) are poorly known or missing. Tuna tagging has already been intensively organized and analyzed in the Indian Ocean, but only in Maldivian waters (Waheed and Anderson 1993; Bertignac and Bertignac *et* at., 1993). Those experiments only concerned relatively small-scale fisheries and a single tuna species. skipjack *(Katsuwonus pelamis)*. Given this situation, the IOTC initiated a discussion to organize a large scale tagging program concerning the major tropical tuna species and fisheries. According to the terms of reference for the working party on tagging

(Anon., 1999), prospective simulations are needed to help designing tag-recapture experiments. Such a prospective approach has already proven to be useful in the Pacific Ocean (Bills and Sibert, 1997).

Particularly concerned by the tagging program project, the IRD research project THETIS (Marsac, 1999) initiated the study of such a simulation framework. This work is still under progress. The aim of this paper is to present the methodology developed and the first results concerning the skipjack tuna population.

To design a tagging experiment, we must determine how many fish should be tagged and released, when and where, to achieve a chosen level of precision and accuracy in the key population parameters estimation (Xiao, 1996). Different study have already deal with that complex problem (Bills and Sibert, 1997; Xiao, 1996, 2000). The methodology developed here rely on a three stage simulation framework (Fig. 1):

1. The first stage consists in simulating as realistically as possible tag-recapture experiments of tunas in the Indian Ocean. It is based on a species specific environmentally driven advection-diffusion-reaction model to represent the tagged fish spatial dynamics and their recovery according to a mean fishing effort spatio-temporal distribution. This stage provides spatio-temporal recovery data sets according to various tagging scenarii.
2. The second stage consists in bootstrapping the simulated data set to incorporate stochasticity in the deterministically simulated tag recovery process. It gives a large number of "possible" recapture data set for a given tagging scenario.
3. The third stage corresponds to the assessment process, as it will be done when real tagging data will be available. Each bootstrapped recapture sample is analyzed with an observation model, which provides estimates of the desired population parameters (here, natural mortality, catchabilities and movement rates). Mean biases and standard errors of the parameters estimates are calculated for each tagging scenario studied.

Finally, the whole process enables to compare different possible alternative tagging scenarii to help designing the tagging program.

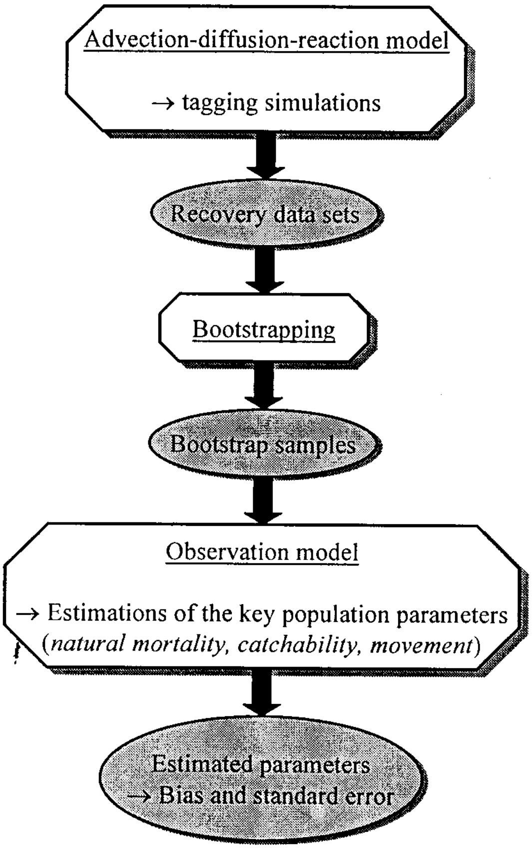

Fig. 1. Synthetic diagram of the method used (see text).

2 THE SIMULATION MODEL

2.1 The simulation model in the general case

An advection-diffusion-reaction model is used to represent the spatial dynamics of tagged tuna population. In such a model, fish movement has two components: a random one, the diffusion term which characterizes « dispersive » movements, and a directed one, the advection term which describes movement directed along a gradient. Both components are included in a partial differential equation (PDE) continuous in time and space (Okubo 1980, Bertignac et al. 1998, Sibert et al. 1999) which represents the spatial dynamics of one cohort of tagged fish:

$$(1)\qquad \frac{\partial N}{\partial t}=D.\left(\frac{\partial^2 N}{\partial x^2}+\frac{\partial^2 N}{\partial y^2}\right)-\frac{\partial\left(\alpha.\frac{\partial(HSI)}{\partial x}.N\right)}{\partial x}-\frac{\partial\left(\alpha.\frac{\partial(HSI)}{\partial y}.N\right)}{\partial y}-(F+M).N$$

With $N=N_{x,\,y,\,t}$ the fish density of the considered cohort at point (x, y) at time t, D the diffusivity coefficient, $HSI=HSI_{x,\,y,\,t}$, the habitat suitability, α a proportionality coefficient, M the natural mortality rate and $F=F_{x,\,y,\,t}$ the local fishing mortality rate.
Such models have a long history in ecology (Skellam 1951, Okubo 1980, Holmes 1994) but their use in fishery science has grown recently, particularly for tuna population modelling purposes (MacCall 1990, Sibert and Fournier 1994, Sibert *et al.* 1996, Bertignac *et al.* 1998, Maury and Gascuel, 1999, Maury *et al.*, 1999, Sibert *et al.* 1999). To be realistic in our case, they must reflect the heterogeneous distribution and movement of the fish population linked to the environment heterogeneity. Thus, in equation (1), the advective component of the model is related to the local gradient of a habitat suitability index (*HSI*). According with Hutchinson (1957) niche definition, the *HSI* is defined as an hypervolume whose n dimensions corresponds to the n environmental factors considered to determine fish habitat:

$$(2)\qquad HSI=\prod_{i=1}^{n}(ba_i)^{p_i}\quad\text{with}\quad\begin{cases}ba_i=f_i(e_i)\\ R\xrightarrow{f_i}[0,1]\end{cases}$$

With ba_i the biotic affinity for the environmental factor e_i, p_i its associated weight and f_i the functional response (non-linear in the general case) of tuna to the environmental factor e_i. Then, due to its environmental forcing, the model transports the tagged fish population towards the most suitable places for fish living, according to the habitat temporal evolution.
A numerical solution of equation (1) is obtained using an « alternating-direction implicit method » (Press et al. 1994) with a one day time step on a 1°x1° square grid which lay from 19°west to 130°west (longitude) and 41°south to 30° north (latitude) (Fig. 2). Closed reflective boundaries (Neumann conditions: $\frac{\partial N}{\partial x}=\frac{\partial N}{\partial y}=0$ at boundaries) are used to model impassable frontiers and shores. The initial tagged population distribution (the time and place of the fish release) is user defined and can be chosen everywhere in the grid.

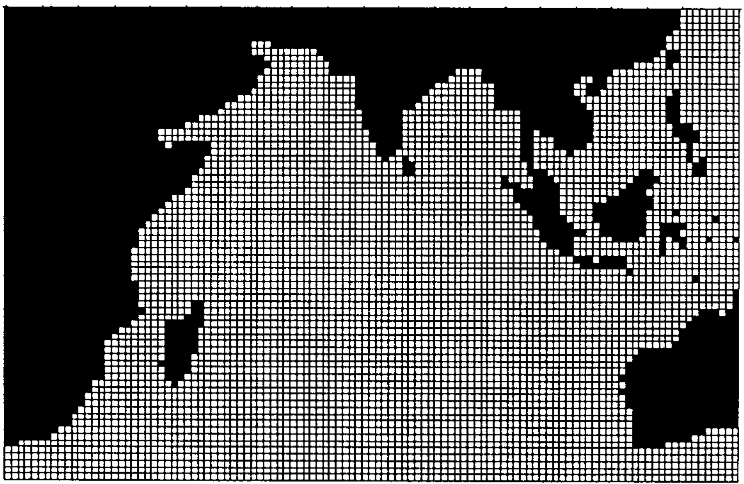

Fig. 2. Numerical grid used to integrate the spatial population dynamics model.

2.2 Habitat parameterization for the skipjack population

The model as formulated is generic enough to be used for the three main tropical tuna species (bigeye, skipjack, yellowfin) only by specifying *ad hoc* functional response to the environment (functions f_i). In this paper, we particularly focus on skipjack tuna because the important amount of information related to its dynamics available in the Pacific facilitates our analysis. To characterize the skipjack habitat, we assume that the sea surface temperature (*SST*) is the main parameter to be taken into account. The concentration of preys abundance (the tuna forage) is also probably an important determinant of skipjack distribution as Bertignac (1998) has shown. Nevertheless, such data can't be used here because they are not yet available in the Indian Ocean.

A dome shaped function allowing the definition of an optimal temperature and a lethal temperature is used (Fig. 3):

$$
\begin{aligned}
ba_{SST} &= 1 - \frac{\left|sst - sst_{opt}\right|^{\gamma}}{\left|sst_0 - sst_{opt}\right|^{\gamma}} && if\ sst > sst_0 \\
&= 0 && if\ sst < sst_0
\end{aligned}
$$

With *SST* the sea surface temperature, SST_{opt} the optimal *SST* fixed at 28°C, SST_0 the lethal *SST* fixed at 16°C and γ a dimensionless parameter arbitrarily fixed at 2.

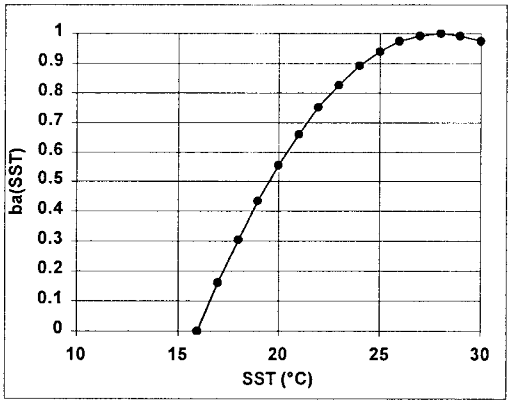

Fig. 3.: Functional response to the SST used in the case of the skipjack population.

As defined and parameterized, the skipjack habitat only constrains the fish population to stay in its large-scale home range. In this prospective study, as we do not know the exact values of parameters, the goal is simply to limit the skipjack distribution and movements to realistic spatial ranges. In the current version of the simulation model, two environmental parameterizations are possible. From the one hand, climatological environmental data may be used to force the spatialized tagged population model. From the other hand, because the Indian Ocean is regularly subject to strong large scale environmental anomalies (Anderson, 1999, Saji *and al.*, 1999), an environmental forcing typical of extreme events is also proposed.

In the present study, monthly SST Levitus data are used at a 1° x 1° spatial resolution.

2.3 Fishing mortality parameterization for the skipjack stock

Fishing mortality parameterization is a key point to obtain realistic tag recovery simulations. To get an estimation of the total annual fishing mortality applied to the stock, a length-based VPA was conducted (Fonteneau, com pers) on mean catch at size data (on the 1994-1998 period). The estimated total annual fishing mortality applied to recruited fish fluctuates between 0.5 and 1.7 yr^{-1} (Fig. 4). Because most of the skipjack caught have a length comprised between 45 and 55cm, the total fishing mortality is assumed to be equal to 2 yr^{-1}.

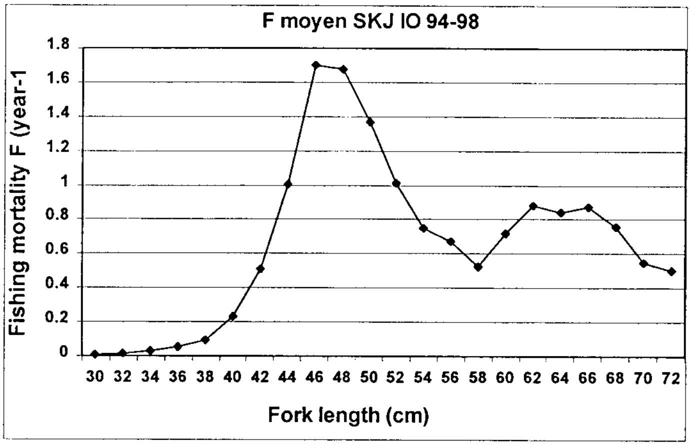

Fig. 4.: Fishing mortality applied to the skipjack stock estimated with a length-based VPA (Fonteneau com pers).

Because stocks[1] have no clear boundaries, stock surface S_T is mostly a theoretical concept. Here, we defined it as the surface where 95% of the catches occurred (Marshall and Frank, 1994; Swain and Sinclair, 1994). To get an estimation of that surface, mean monthly catches by 1° square were sorted and their cumulative distribution was drawn as a function of the corresponding number of fished square (Fig. 5a). The obtained monthly stock surface is represented Fig. 5b.

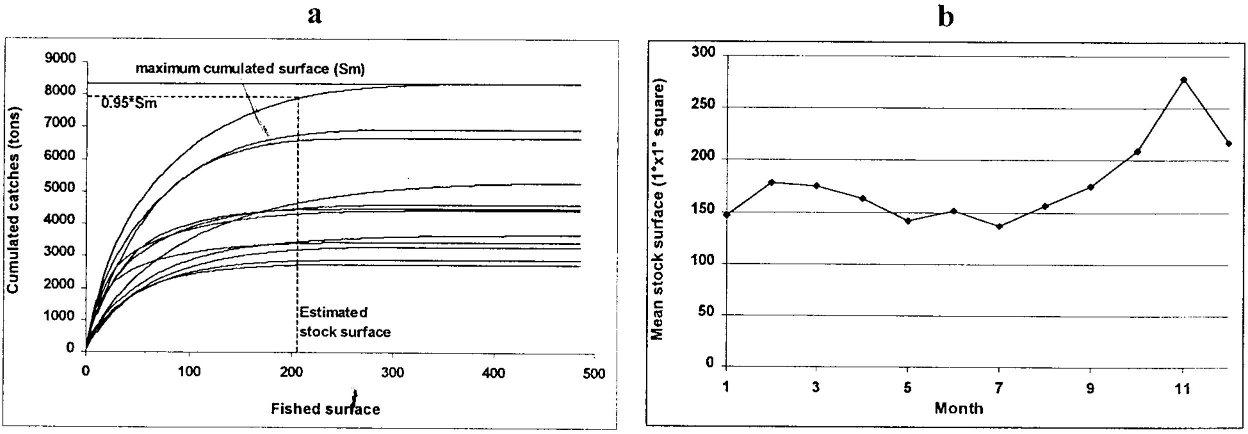

Fig. 5. a, the cumulative distribution of catch versus surface for 12 mean months. b, the estimated monthly stock surface.

The local catchability q_s is then calculated using the following equation (Maury, 1998)[2]:

$$q_s = \frac{F_T \bar{S}_T}{f_T S_s} = \frac{2*177}{149155*1} = 0.0024 \quad searching \quad hours^{-1}$$

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[1] In the present work, the stock is defined as the exploited fraction of the population.

[2] If we assume that the stock (not the population) has an homogeneous density, the CPUE calculated locally $U_s = \frac{C_s}{f_s} = q_s N_s = \frac{q'}{S_s} N_s$ equals the CPUE calculated at the whole stock level $U_T = \frac{C_T}{f_T} = q_T N_T = \frac{q'}{S_T} N_T$ with q', a constant. Then,. $F_s = \frac{f_s S_T}{f_T S_s} F_T \Leftrightarrow q_s = \frac{F_T S_T}{f_T S_s}$.

The monthly fishing mortality distribution is calculated in each 1° square s ($F_s = q_s f_s$) using the mean fishing effort distribution for purse seiners (which represent the major part of skipjack catches). The considered period ranges from 1991 to 1999 without the two anomaly years 1994 and 1997.

2.4 Generating recovery samples

The tag recoveries generated by the simulation model are perfectly deterministic. In reality, tag recovery exhibits a high stochasticity. Consequently, bootstrap samples are calculated for each simulated recovery data set by assuming that the monthly observed tag recovery are Poisson random variables whose expected values are given by the simulated number of skipjack tags returned during one month. This distribution is appropriate for an observation of a rare event such as a tagged fish return (Hilborn, 1990, Sibert and al., 1999).
In the present paper, each sample contains 50 data sets.

3 THE OBSERVATION MODEL

3.1 Model structure

Our habitat based advection-diffusion-reaction simulation model could be used for population parameter estimation purpose. Nevertheless, for computing time reasons, a simpler compartment model was preferred. Assuming a constant natural mortality rate for tagged fishes and a constant catchability coefficient in each spatial compartment, the observation model is based on the following equations, which take into account movement between homogeneous zones:

$$\text{(3)}\quad \begin{cases} \dfrac{dN_{1,t}}{dt} = \sum\limits_{i=2}^{n} T_{i\to 1,t} N_{i,t} - (q_1 f_{1,t} + M + \sum\limits_{i=2}^{n} T_{1\to i,t}) N_{1,t} \\ \vdots \\ \dfrac{dN_{j,t}}{dt} = \sum\limits_{i=1,i\neq j}^{n} T_{j\to i,t} N_{i,t} - (q_j f_{j,t} + M + \sum\limits_{i=1,i\neq j}^{n} T_{j\to i,t}) N_{j,t} \\ \vdots \\ \dfrac{dN_{n,t}}{dt} = \sum\limits_{i=1}^{n-1} T_{i\to n,t} N_{i,t} - (q_n f_{n,t} + M + \sum\limits_{i=1}^{n-1} T_{n\to i,t}) N_{n,t} \end{cases} \qquad \begin{cases} \dfrac{dC_{1,t}}{dt} = q_1 f_{1,t} N_{1,t} \\ \vdots \\ \dfrac{dC_{j,t}}{dt} = q_j f_{j,t} N_{j,t} \\ \vdots \\ \dfrac{dC_{n,t}}{dt} = q_n f_{n,t} N_{n,t} \end{cases}$$

With $N_{i,t}$, the number of tagged fish in zone i at time t, $T_{i\to j,t}$, the transfer rate from zone i to zone j at time t, q_i the catchability coefficient in zone i, M the natural mortality rate and $f_{i,t}$ the fishing effort in zone i at time t.

The system (3) is integrated numerically using a semi-implicit scheme on a 10 days time basis. Given the short time basis used, we restricted fish movement during one time step to occur only between spatially adjacent zones. The spatial zonation used is represented Fig. 4 with the tagged fish transfer rates between zones.

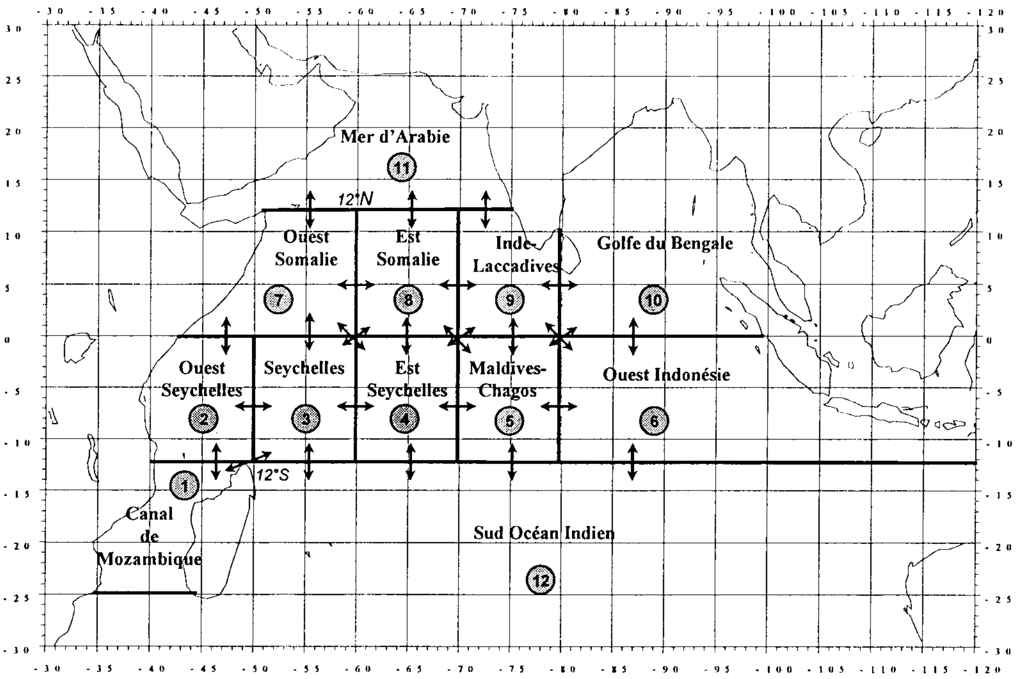

Fig. 6. Spatial structure of the assessment model used. 12 compartments and 54 transfer rate are implemented.

12 spatial zones are distinguished in the case of the skipjack tuna population. Given this spatial division, 661 parameters are defined (54x12 transfer rates, 12 catchability coefficients and one natural mortality rate) and must be estimated. Other species such as bigeye or yellowfin exhibit wider distribution range and migration movements than skipjack do. Using the model for such species will require a more complex spatial division to be defined. In particular, zones 6, 10 and 12 will need to be splitted in several smaller compartments.

3.2 Fitting the observation model to simulated data

Observed (simulated) numbers of tag returns are related to predicted numbers of tag returns by a Poisson likelihood function:

$$(4)\qquad L \stackrel{!}{=} P\left({C_{g,z,m}} \middle/ {\hat{C}_{g,z,m}, f_{z,m}} \right) = \prod_{g}\prod_{z}\prod_{m}\left(\frac{\hat{C}_{g,z,m}^{\,C_{g,z,m}} . e^{-\hat{C}_{g,z,m}}}{C_{g,z,m}!} \right)$$

With C the observed recovery, $\hat{C}$ the predicted recovery, f the fishing effort (fixed), g the tag group, z the zone and m the month.

Maximum likelihood parameter estimates are obtained by minimizing the negative loglikelihood with the ADMB software (©Otter Research, 1996):

$$(5)\qquad -\log(L) = \sum_{g}\sum_{z}\sum_{m}\left[\hat{C}_{g,z,m} + \sum_{i=1}^{C_{g,z,m}} \ln(i) - C_{g,z,m} \ln\left(\hat{C}_{g,z,m}\right) \right]$$

3.3 Synthesizing the results

Relative bias and relative standard error of the estimated parameters can be used to measure the accuracy and precision to be expected from a given tagging scenario (Xiao, 1996, 2000).

For each parameter p, relative bias RB and relative standard error RSE are computed as follows:

$$(6)\qquad \begin{cases} RB_{\hat{p}} = \frac{1}{p}\left[p-\mu_{\hat{p}}\right] = 1-\frac{1}{np}\sum_{i=1}^{n}\hat{p}_i \\ RSE_{\hat{p}} = \frac{1}{p}\sqrt{\sigma^2_{\hat{p}}} = \frac{1}{p}\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\hat{p}_i-\frac{1}{n}\sum_{j=1}^{n}\hat{p}_j\right)^2} \end{cases}$$

4 RESULTS

The whole process (simulation, bootstrapping, estimation) is used to study a tagging scenario where tagging occurs in January, simultaneously in all zones excepted in the zone n°12 where skipjack are very scarce. The spatio-temporal localization of tagging in each zone is given in table 1. This scenario is perfectly unrealistic. Its purpose is to check the reliability of the method and its ability to compare various tagging scenarii.

Table 1: scenario of tagging used in the present work.

ZONE	TAGGING COORDINATES	MONTH OF TAGGING
1	15°S – 43°W	January
2	5°S – 45°W	January
3	5°S – 55°W	January
4	5°S – 65°W	January
5	5°S – 75°W	January
6	5°S – 85°W	January
7	5°N – 55°W	January
8	5°N – 65°W	January
9	5°N – 75°W	January
10	5°N – 85°W	January
11	15°N – 60°W	January
12	/	/

Eight scenarii are compared in the present work with 500, 1000, 1500, 2000, 3000, 4000, 5000 or 10000 fishes tagged in each zone. For illustrative purpose, the fit of the observation model to simulated data is presented Fig. 7 for the group tagged in zone 2 for two different scenarii.

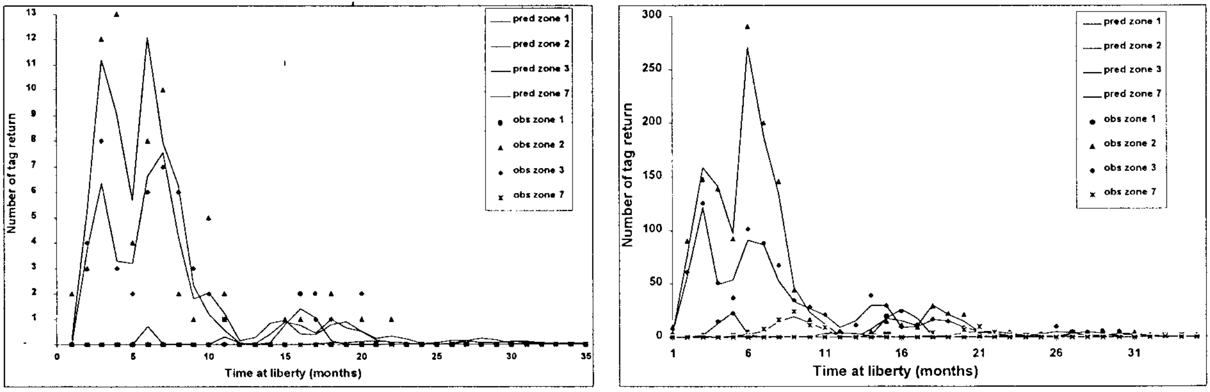

Fig. 7.: Predicted recovery of fish tagged in zone 2 (straight lines) and observed one (dashed lines). On the left, 500 fishes were tagged in zone 2 and on the right, 10000 were tagged in zone 2.

For each of the 661 parameters, the mean estimated value, its relative bias and relative standard error are calculated. Fig. 8 presents the results as a function of the number of fish initially tagged in each zone for natural mortality and for catchability in each zone. Results concerning the 648 movement rates are not presented here for simplicity but they exhibit very similar patterns.

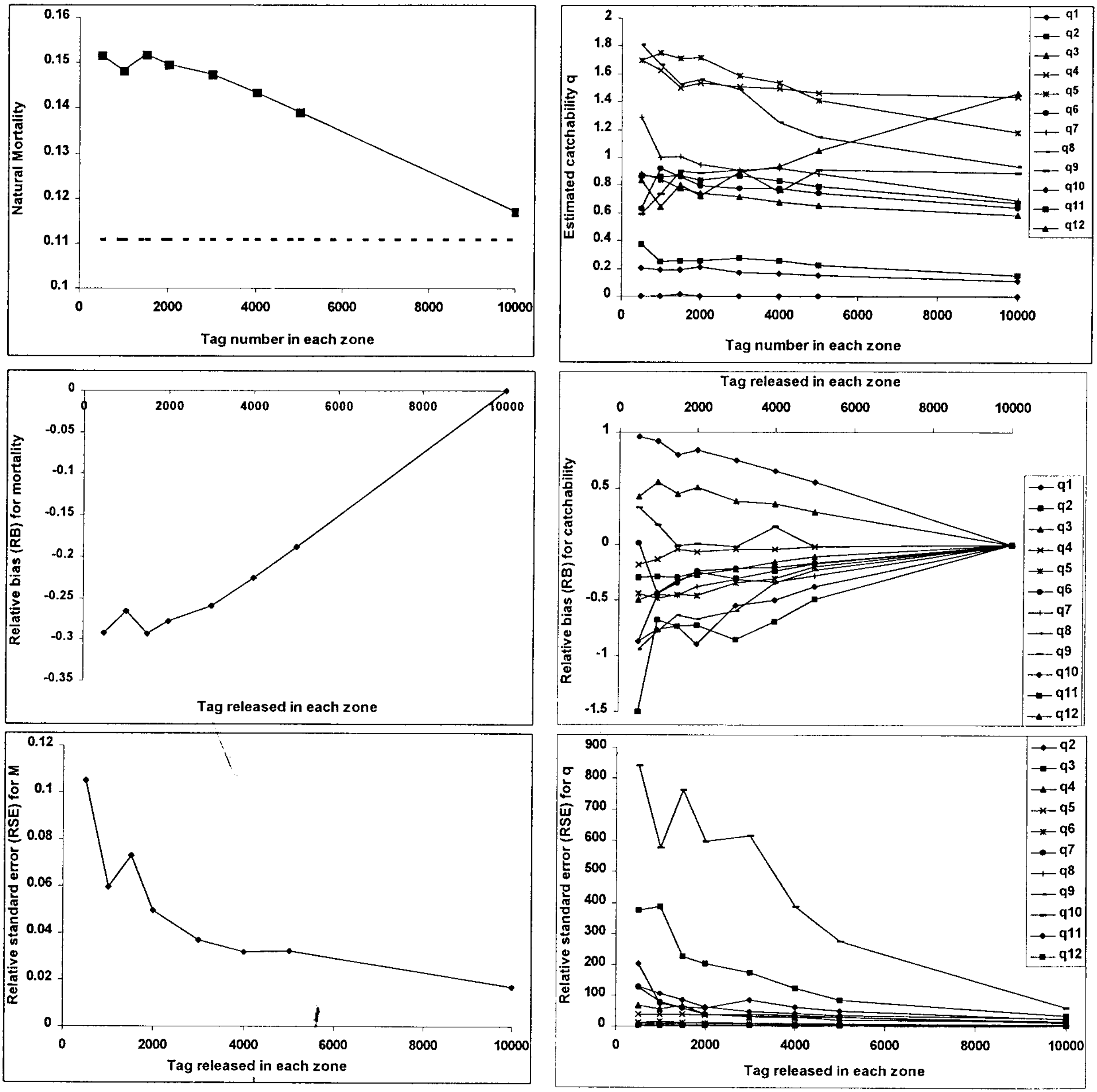

Fig. 8.: Results of the parameter estimation for natural mortality M (left) and for catchability q (right). First line, estimated parameter mean value. Second line, parameter relative bias (RB). Third line, parameter relative standard error (RSE).

When the total number of fish tagged in each zone is low (<1500), the simulated recovery data sets are dominated by a strong stochasticity and, consequently, the parameter estimates are highly biased and their relative standard error is high. On the contrary, when the total number of fish tagged in each zone increases, the relative bias tends linearly to zero and the relative standard error decreases exponentially.

Given these tagging scenarii, the natural mortality is the most precisely estimated parameter. Without surprise, the most precisely estimated catchabilities and movement parameters corresponds to the zones where a high fishing mortality is exerted.

Concerning catchabilities and movement rates, the biases in parameter estimation are either positive either negative, depending of the zone considered.

The coherence of the results obtained should not hide their strong dependance on the observation model used. If the observation model is a habitat-based advection-diffusion-reaction model instead of a compartment model, the advection term will be more precisely estimated in a region of high habitat gradients when the diffusion term will be more precisely estimated in regions of low habitat gradient. This should be taken into account in the design of future tagging scenarii.

5 CONCLUSION

This work is still under progress. Several improvements of the model should be undertaken. The first one is to incorporate estimations of "tuna forage" in the habitat model to improve simulated fish distribution, especially around the Somalian upwelling. The next step is to test realistic environmental parameterizations for the two others tropical tuna species considered in the future IOTC tagging program (yellowfin and bigeye tuna) and to parameterize various hypotheses for their fishing mortality, considering both purse seiners and longliners fleets. Nevertheless, despite those necessary future improvements, the simulation framework presented is now operational and should be used by the IOTC Working Party on Tagging to test and compare various alternative realistic tagging scenarii. Such alternative scenarii should be defined precisely during the present WPT meeting.

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