INTER-AMERICAN TROPICAL TUNA COMMISSION

WORKSHOP ON USING TAGGING DATA FOR FISHERIES STOCK ASSESSMENT AND MANAGEMENT STRATEGIES

La Jolla, California (USA)
16-19 October 2007

REPORT

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This report is organized into sections corresponding to the topics discussed at the workshop. Under each section, introductory text, taken from the background information provided to participants before the workshop, is given. Then abstracts for each presentation are provided. Finally, the discussions during the workshop about the focus questions are summarized. The report does not represent the consensus of the opinions of the workshop participants.

1. INTRODUCTION

Tagging or mark-recapture experiments have played an important role in fisheries assessment and management. Their use has varied from providing estimates of biological processes to direct input into management strategies. The information derived from tagging data has expanded as the types of data available and the methods to analyze them have become more sophisticated. However, the tagging experiments and analyses still need to be designed appropriately to ensure that assumptions are not violated or, if they are violated, the effects are minor.

In some cases, tagging studies have simply provided qualitative measures of biological processers. For example, maps of release and recapture locations illustrate net movements of individuals. However, these types of maps can be misleading because important factors have not been taken into consideration. For example, the probability of recapture, which is related to the fishing effort, may differ among areas and therefore provide a biased perception of movement (*i.e.* the fish appear to move most often to the areas of greatest effort). Often these maps plot only the individuals that moved long distances, and these individuals may represent a minor proportion of the population, therefore biasing the perception of how much movement is occurring in the population. For these and other reasons, appropriate quantitative analysis of the data is highly desirable.

Unfortunately, quantitative analysis may not be sufficient to extract useful information from the tagging data. For example, if fish are tagged only in a small area relative to that occupied by the stock, the tagging data can provide information only on local abundance or exploitation rates, and will not be useful for assessing the entire stock. Therefore, it is important that tagging studies be designed appropriately so that they achieve the objectives of the experiment. The experimental design should not only consider the objectives, but also the practical constraints of tagging fish and the methods available to analyze the data.

In the last 20 years, there have been numerous developments in the quantitative methods that are available to analyze tagging data. Initially, several approaches have been taken to analyze the data. Advection-diffusion models have been developed to model movement of individuals (Sibert *et al*. 1999). Population dynamics models have been developed to estimate exploitation rates and movement (Ishi 1979; Hilborn 1990; Anganuzi *et al*. 1994). Multinomial likelihood-based models have been developed to estimate survival (Brownie *et al*. 1985; Lebreton *et al*. 1992). Growth increment models used to estimate growth have been improved (Francis 1988). However, in recent years these methods have been converging into a single integrated framework (Maunder 1998, 2001, 2004; Hampton and Fournier 2001; Bentley *et al*. 2001; Besbeas *et al* 2002; Polacheck and Eveson 2006), which attempts to extract all the information about all biological and fishing processes from the tagging data. These analyses are complex, computationally-intensive, and often difficult to diagnose, but provide great potential for providing better assessments of stock status and, consequently, management advice.

In addition to the developments in methods to analyze data, there has been a concurrent increase in the technology used to tag individuals. These methods, such as archival tags, provide larger quantities of much more detailed data. For example, the spatial location (or an approximation based on light) and depth of an individual every 30 minutes for several years. Appropriate methods to analyze this type of data to provide management advice are still being developed. methods are needed to incorporate this information into contemporary stock assessment approaches, or new stock assessment approaches developed.

1.1. Tag types and some applications

Kurt M. Schaefer and Daniel W. Fuller

An overview of various tag types suitable for use on tunas, including conventional plastic dart tags, acoustic tags, archival tags, and pop-up satellite archival tags, and some of their applications for acquiring useful information, along with some pros and cons for each application, is presented.

Large-scale tagging and recapture of tunas with plastic dart tags can provide estimates of movements, stock structure, growth, mortality, and population size, making it one of the most powerful methods for deriving information needed for fisheries management. For each of those applications, the uncertainties and limits of using conventional tag-recapture techniques have been fairly well studied.

Active or passive tracking of tunas tagged with acoustic tags, using research vessels equipped with sonar, echo-sounders, and other oceanographic instruments, can provide useful information on fine-scale horizontal and vertical movements, relative to the tuna's environment. Long-term passive monitoring of tunas equipped with acoustic tags, using acoustic receivers attached to stationary or drifting objects can provide estimates of site-fidelity, associative behavior, and residence times.

The method of tagging and recapture of tunas with archival tags can provide multi-year estimates of daily positions and movement paths. Spatial analyses of such data sets can provide estimates of horizontal dispersion rates, velocities, and utilization distributions. Furthermore, the movement paths can be evaluated relative to regional oceanographic conditions. The additional advantage of archival tags is the corresponding depth data, providing long-term, fine-scale, information on vertical movements and habitat. Various behaviors can be classified and described quantitatively, including frequencies and durations. Estimates of species-specific vulnerability to capture by gear type can be obtained from these analyses. Horizontal and vertical habitat utilization distributions can also be constructed for evaluations of stock structure, and also used for catch-per-unit-of-effort standardization in stock assessments.

The method of tagging tunas with pop-up satellite archival tags also provides the opportunity to obtain estimates of daily positions and most probable movement paths, along with some vertical habitat data, without the necessity for recapture of the tagged tuna. The amounts of data that have been successfully collected to date have most often been limited to about 6 months because of premature tag shedding and data transmission problems. However, if these tags are recovered they provide the same opportunity to download the entire archival tag data record, and thus results similar to those from archival tag data sets can be obtained.

1.2. Introduction to tagging analyses

Mark N. Maunder

A summary of the various tagging analyses was presented. The content of the presentation was similar to that of the introduction section above.

1.3. An overview of different tagging experimental designs for estimating population parameters in commercial fisheries

Tom Polacheck, J. Paige Eveson, and Geoff M. Laslett

The literature on mark-recapture experiments is enormous, with a wide variety of different experimental designs and estimation models. It can be difficult to grasp an overview of the primary features of different approaches and the inter-relationships among them. An overview is important in the initial consideration and design of tagging experiments in order to understand which parameters can be estimated from different experimental designs, the associated data requirements, and the logistical feasibility in any specific situation. We suggest that most mark-recapture experiments in fisheries can be classified into one of three basic types (Petersen, tag attrition, and Brownie) depending upon where the information for estimating the parameters of interest stems from. In this context, we assume that the parameters of primary interest are those related to the population dynamics (*i.e.*, either absolute abundance or mortality rates). We also consider possible integration across these different approaches and the role auxiliary data (*e.g.*, fishing effort; abundance surveys) can have in increasing the information derived from tagging experiments.

A fundamental distinction in the design of a tagging experiment is whether data are collected only on the number of tagged animals that are recaptured or whether, in addition, data are available on the number of animals examined for recaptured tags. In the latter case (*e.g.* Petersen-type experiments), information on the proportion of animals examined that have tags allows estimation of absolute population size. In the former case, which we refer to as "return rate" experiments, mortality rates are the estimable parameters. Within return rate experiments, there is a further distinction, depending on whether the experiment utilizes a single or multiple release events. An experiment with a single release event derives its information on the rate of tag returns over time (tag attrition-type experiments), while an experiment with multiple release events derives its information from the comparison of return rates over time from the multiple release events (Brownie-type experiments). The fundamental distinctions among these different basic experimental designs determines the types of data that need to be collected, the temporal span of the experiment, and, perhaps most importantly, the type and range of population parameters that can be estimated if the experiment is successfully implemented.

2. TRADITIONAL TAGGING

Traditionally, many fisheries tagging experiments were analyzed using the Petersen estimator to estimate stock abundance. The method can be explained based on the assumption that the ratio of marked individuals in the population is the same as in the sample

$$n_1/N = m/n_2$$

and this equation can be rearranged so that the estimated abundance is

$$N = n_1 * n_2/m$$

where

N = estimate of total population abundance,

n_1 = total number of individuals captured on the first visit (the marked individuals),

n_2 = total number of individuals captured on the second visit, and

m = tumber of individuals captured on the first visit that were then recaptured on the second visit (the marked individuals that were recaptured).

The Petersen estimator is simple, based on two samples, and does not incorporate anything about the population dynamics. Often there are additional periods of recapture and important population dynamics processes that should be taken into consideration. Ishii (1979) and Hilborn (1990) developed methods that use population dynamics models to represent the dynamics of the tagged population. The predicted recoveries from the model are then compared to the observed recoveries, using likelihood functions, and the parameters of the population dynamics models are estimated by maximum likelihood. The model with the maximum likelihood estimates of the parameters can then be used to calculate quantities of interest (*e.g.* exploitation rate). Gaertner *et al.* (2004) used this method to test the efficiency of two tag types for tunas. Anganuzzi *et al.* (1994) used this method to incorporate movement among areas.

An alternative approach to the block transfer models used above is to model movement as an advection-diffusion process (Sibert *et al.* 1999; Kleiber and Hampton 1994; Adam and Sibert 2002). This essentially models the movement of tagged individuals as a directed random walk. The spread of the tagged individuals from the point of release can be predicted, and this is compared to the recoveries. The fishing effort levels need to be taken into consideration to ensure that both mortality of tagged individuals and recoveries are appropriately modeled. These models are computationally intensive, and special algorithms are needed to estimate the parameters. In general, the variation in movement should be integrated out of the model. This can be achieved by using a Kalman filter. Other approaches include random effects models or Bayesian state-space models.

2.1. Estimation of natural mortality, using tagging data

M.S.M. Siddeek

Natural mortality (*M*) is an important parameter in all commercially exploitable marine and freshwater animal population dynamics models. Its value is needed to determine appropriate harvest levels; however, even under the assumption of constant *M*, it is a difficult parameter to estimate in heavily-exploited populations. Tag-recapture data provide an opportunity to

estimate this parameter, provided inherent errors are recognized and parameterized in the estimation process. Numerous methods have been developed since the 1950s to analyze fish tag-recapture data for population parameter estimation.

An *M* estimator based on virtual population analysis model (VPA-*M* estimator) for a series of tagging experiments is presented. This estimator assumes that the product of initial survival (due to immediate tagging mortality, immediate loss of tags, emigration from the study area, or unknown reduction in tagged fish population) and the tag reporting rate, *SR* (*S* = initial survival, *R* = reporting rate), has a lognormal distribution. Traditional methods, such as simple regression, were used to constrain the *M* range in the optimization process and to choose appropriate terminal values of fishing mortality (*F*). A multinomial maximum likelihood procedure that could be used to compare *M* and *SR* estimates was also presented.

Tag-recapture data from Irish Sea plaice (*Pleuronectes platessa*), Kuwait shrimp (*Penaeus semisulcatus*), and Aleutian Islands golden king crab (*Lithodes aequispinus*) were used to demonstrate the proposed *M* estimator. Based on 1960s and 1979-1980 tagging data from Irish Sea plaice, the VPA-*M* estimator produced estimates of annual *M* and *SR* of 0.166 (± 0.063) and 0.371 (± 0.007) for males and of 0.108 (± 0.083) and 0.377 (± 0.013) for females. An independent estimate of tag reporting rate from a tag seeding experiment conducted at a fish market was 0.940 (± 0.017). Thus, the initial survival rate (*S*) was approximately 0.40 (= 0.375/0.94). The VPA-*M* estimator applied to 1982 and 1983 tagging experiments on Kuwait shrimp produced an *M* value of 0.131 per 20 days (2.4 per year) with a standard error of 0.013 for males. The point estimate of *SR* at this *M* was 0.3. Based on 1997 tagging data for Aleutian Islands male golden king crab, the VPA-*M* estimator produced point estimates of an annual *M* of 0.375 and an *SR* of 0.398. Based on 1995 tagging data for St. Matthew blue king crab, the maximum likelihood *M* estimator produced a point estimate of annual *M* of 0.188.

One general conclusion can be made from all these results. The magnitude of Ricker's Type A error (1 - SR, immediate mortality due to tagging, immediate loss of tags, emigration from the study area, reduction in tagged population due to other causes, or incomplete reporting of tag recaptures) is similar, and *SR* has a narrow range of 0.3 to 0.4 for the different species considered in the analyses. Consequently, ignoring the *SR* parameter is likely to introduce errors in *M*, *F*, and any secondary parameter estimation that involves initial release number, for example, the harvest rate.

For additional information, see Siddeek (1981, 1989, 1991) and Siddeek *et al*. (2002).

Acknowledgments

I thank Doug Woodby and Jie Zheng of the Department of Fish and Game, Juneau, Alaska, for providing useful comments on this presentation.

FOCUS QUESTION

Is there still a use for traditional methods?

Traditional methods have been well studied, and are generally much less computationally intensive than integrated models. Therefore, traditional methods provide a good tool to investigate the data before they are integrated into a more complex model. When time or computational resources are limited, traditional methods allow a greater number of sensitivity analyses to be conducted. They allow the comparison of the different data sets and aid in identifying inconsistencies in the data. Traditional methods may also allow the use of Bayesian integration when conducting MarkovChain-MonteCarlo methods on the integrated model is computationally infeasible.

Some data (*e.g*. tag shedding from double-tagging experiments) may provide information about quantities for which there is no or little information in other data. These data can therefore be analyzed outside the integrated model, and the estimates and their uncertainty transferred into the integrated model (*e.g.* using a prior). This will reduce the complexity and the computational demands of the integrated model. Care needs to be taken when developing a prior to ensure that it adequately represents the uncertainty. In particular, if two or more parameters are estimated, the correlation among parameters needs to be represented, and it may be difficult to produce the appropriate multivariate distributions (*e.g.* banana shaped distributions are commonly seen in fisheries data).

In general, it is not possible to develop fishery-independent surveys for tunas. Therefore, tagging studies provide one of the few "fishery-independent" approaches to analyzing tuna populations. A management strategy could be based solely on tagging data, using a traditional approach to analyze the tagging data, which eliminates the assumptions required for the other data used in stock assessment models. This could be evaluated, using management strategy evaluation approaches, and compared with current or alternative management approaches.

3. INTEGRATING TAGGING DATA INTO POPULATION DYNAMICS MODELS

Tagging studies are commonly used to assess stock size, growth, natural and fishing mortality, age-specific selectivity, and movement, all of which are important parameters for stock assessment models. However, raw tagging data have only recently been incorporated into stock assessment models. Richards (1991) investigated sharing parameters between a tagging model and a simple stock assessment model for a Canadian lingcod stock. Haist (1998), Punt and Butterworth (1995), and Porch *et al*. (1995) integrated tagging data into catch-at-age analyses with spatial structure. However, none of these models used the size- or age-structured information from the tagging data. Punt *et al*. (2000) integrated age-structured tagging data into the stock assessment model for the southeast Australia stock of school shark, but did not include catch-at-age data. Maunder (1998 and 2001) developed a general integrated tagging and catch-at-age analysis (ITCAAN) that explicitly includes movement and fits to both age-structured tagging and catch-at-age data. Maunder (1998) applied this model to the snapper stock off the northeast coast of New Zealand. A similar method was developed by Hampton and Fournier (2001) for a catch-at-length analysis and applied to yellowfin tuna in the western and central Pacific Ocean. Catch-at-length analysis may be more appropriate for tagging data because it is much easier to measure the length of all the fish released than to age them. Maunder (2001) showed that integrating the tagging data into a catch-at-age analysis can improve the precision of estimates for both productivity and depletion levels.

The need for an integrated approach can be illustrated using the Petersen estimator. The Petersen estimator is based on a closed population (*i.e.* no individuals entering or leaving the population). However, the recoveries often occur after a substantial time period (*e.g.* one year). During this period some individuals may be recruited to the population. The addition of catch-at-age data allows for the estimation of annual recruitment, which can be used to adjust the Petersen estimator for the recruiting individuals.

Integrating tagging data into the stock assessment model is simple if no spatial structure is assumed, but becomes more complex if the movement of individuals among sub-populations is modeled. When interactions among multiple sub-populations are included, each tag release group must be modeled, using the same equations used for the total population. The tagged population is modeled, assuming the same dynamics and parameters as the total population, with the only difference being that recruitment to the tagged population occurs through releases, and can therefore occur at any age. Each set of releases (a release group) that can be uniquely identified in the recoveries (*e.g.* different area/time of release) is modeled as a separate population. The most common likelihood function used is the multinomial, as it is suitable for modeling multiple outcomes. There may be more variation in the recaptures than described by the multinomial, so other likelihood functions may be more appropriate. For example, Hampton and Fournier (2001) used the negative binomial. Many modifications can be included in the analysis. For example, adjustments for mixing rates of tagged with untagged fish, reporting rates, tag loss, and mortality due to tagging and handling (Hampton 1997; Hampton and Fournier 2001) can be incorporated.

The general stock assessment models MULTFAN-CL and CASAL both integrate tagging data into the assessment model. These models have been used for several different species.

3.1. Introduction to integrated analysis

Alexandre Aires-Da-Silva and Mark N. Maunder

Traditional stock assessment analysis has relied mainly on a two-step analytical procedure. First, a summarized version of some type of raw data is produced in a first analysis. The summarized data are then provided as input for a second analysis. One example is the use of raw tagging data to obtain a Petersen estimate of stock size (first step), which is then used in the fitting procedure of a population dynamics model (second step). The traditional approach brings some disadvantages, including loss of information in the summarization process, inconsistencies between the assumptions for the two analyses, difficulties in determining the error structure and in including uncertainty, and reduced diagnostic ability.

The development of modeling and statistical approaches to assimilate large and diverse data sets is now a very active field. This is strongly motivated by recent developments in computer technology, allowing analyses that were not possible until very recently. Within this context, the "integrated analysis" approach has recently emerged. Basically, it consists of combining the first analysis (*e.g.*, estimating stock size from tagging data) and the population dynamics modeling into a single analysis, instead of the traditional two-step process. Data and parameters are thus shared in this one-step process. All the information contained in the raw data is now available to the stock assessment, and conflicting assumptions are avoided within this framework. Uncertainty is propagated throughout the analysis, and correlation among parameters is automatically considered. Diagnostics ability is greatly enhanced within the integrated approach.

The different of types of integrated analysis are reviewed, with emphasis on integrating tagging and population dynamics models in fisheries stock assessment. The challenges presented by integrated analysis are identified.

3.2. Estimating fishing mortality and movement rates for the blue shark in the North Atlantic Ocean from tag-recovery data

Alexandre Aires-Da-Silva

Large numbers of blue sharks are taken as bycatch in pelagic longline fisheries of the North Atlantic Ocean, and this species has even become a target of those fisheries. The status of the stock is ambiguous due to the limitations of the fishery-dependent data. Paradoxically, the tagging data for North Atlantic blue shark is superior to tagging data for any other species of pelagic shark. This study presents a spatially-explicit tagging model to estimate blue shark movement and fishing mortality rates in the North Atlantic. The model uses the blue shark tag-recovery data of the Cooperative Shark Tagging Program (1965-2004 of the U.S.-National Marine Fisheries Service. Four major geographic regions (two on each side of the ocean) were assumed, and annual rates of mixing between regions were estimated. In general, the proportions of blue sharks staying in a region each year exceeded the proportions moving to other regions. The fishing mortality rates (*F*) were found to be heterogeneous across the four regions. While the estimates of *F* obtained for the western North Atlantic were less than 0.1, those in the eastern North Atlantic rapidly approached 0.02, the estimated reference point corresponding to the maximum sustainable yield, during the 1990s. These results suggest that careful monitoring of the exploitation of blue sharks is in order, especially since the juvenile and pregnant female segments of the stock are highly vulnerable to the fisheries in the eastern North Atlantic.

3.3. An integrated model for spiny dogfish in the northeastern Pacific Ocean: how much should tagging data influence estimates of abundance?

Ian Taylor

An age- and spatially-structured population dynamics model was developed for spiny dogfish (*Squalus acanthias*) in the northeastern Pacific Ocean. This model integrates data from three historical tagging experiments. The estimates of initial abundance were found to be more influenced by the contributions of the tagging data than by the indices of abundance. As an alternative, a two-part likelihood for the tagging data was used, with a multinomial distribution applied to the proportions of recaptures by area and a negative binomial distribution for the total number of recaptures across all areas. The overdispersion parameter in the negative binomial allowed an examination of the impact of adjusting the importance of the total tagged fish recaptures relative to the other data sources.

3.4. Estimates of fishing mortality rates for Atlantic bluefin tuna in 1990-2006 from Bayesian statistical analysis of three kinds of tag records

Hiroyuki Kurota, Murdoch McAllister, Barbara Block, Gareth Lawson, Jake Nogueira, Steven Teo, and Nathan Taylor

Fishing mortality rates of western and eastern Atlantic bluefin tuna are estimated from mark-recapture data by using a Bayesian spatially-structured model. We analyzed the recapture data from pop-up and archival tags released in the western Atlantic by the TAG-A-GIANT program (1996-2006), and the conventional tag data provided by US National Marine Fisheries Service (1990-2006). The model is a cohort-based, age-structured model considering two spatial areas (west and east of 45°W). The model does not account for stock mixing, since it does not yet incorporate data on stock of origin. A sequential Bayesian approach, in which the key components of the model are separated and fitted sequentially to data sets pertinent to each component with the posterior from one analysis serving as the prior for the next, is applied. In this study, we first estimate movement rates from pop-up satellite tag data, then estimate fishing mortality rates using archival tag data, and finally update them with conventional tag data.

Statistical estimates of movement rates from the west to the east are mostly consistent with the general conclusion reached previously that cross-over rates are higher for larger fish (Block et al. 2005).

Estimates of recent fishing mortality rates (*F*s) are higher in the east than in the west and on the order of 0.15-0.4 for the medium and large sized fish. Estimates of *F* in the east from tag analyses suggest values higher than 0.14 per year, the rate of natural mortality (*M*) presumed for bluefin tuna in stock assessments of the International Commission for the Conservation of Atlantic Tunas (ICCAT), and are thus unlikely to be sustainable. These estimates show an increase since the late 1990s. In the west, no distinct time trend in estimated values for *F* has been found and estimates remain high. In most of the scenarios investigated, 80% probability intervals for *F* for medium and larger sized fish in the west overlap with *M* over the full time series up to 2006. These estimates of *F* for Atlantic bluefin tuna are as high as those obtained from recent ICCAT stock assessments, and highlight the need for fishing effort reductions in both the western and eastern Atlantic Ocean to prevent further population declines.

3.5. Integrating tagging data into assessments, using MULTIFAN-CL

Adam Langley

MULTIFAN-CL (MFCL) is a spatially-disaggregated, age-structured population model principally developed for the stock assessment of tunas, and routinely used in the assessments of yellowfin, bigeye, skipjack, and albacore tuna in the western and central Pacific Ocean. MFCL integrates catch, effort, fish size (length- and weight-frequency data), and tagging data. For tropical tunas, tag release and recovery data are available from a number of large-scale tagging programmes conducted during the early 1980s and early 1990s. These data potentially inform the model about fishing mortality rates, movement rates among regions, and, when sufficient data are available, age-specific natural mortality rates. The observational model for the tagging data predicts the number of tagged fish returned from each fishery and time-step as a function of the fishery-specific selectivity, catchability, fishing effort, and tag reporting rate. Independent estimates of fishery-specific tag reporting rates are included in the model as a prior. The objective function of the MFCL model includes a tagging component to minimize the deviation between the observed and predicted number of tag returns for each fishery (and additional penalties for deviation from the fishery-specific reporting rates). A negative binomial error structure is usually assumed for the observed tag recoveries. A range of diagnostics is reported to assist in the assessment of the overall fit to the tagging data.

3.6. A spatial model (CASAL) integrating two tag-recapture experiments: high model complexity and computational limitations

Jeremy McKenzie and Nick Davies

A case study is presented for the northeastern New Zealand snapper (*Pagrus auratus*) stock (SNA 1) for which a spatially and temporally disaggregated model is being developed that integrates tag recapture data. The CASAL generalised modelling software, which includes desirable features for multiple stocks and partitioning of tagged/untagged populations, has been used. SNA 1 is reasonably data rich, with time series available for catch-at-age (up to 15 years), catch-at-length (up to 9 years), catch per unit of effort (15 years), trawl surveys (11 years), and tag-recapture experiments (1985 and 1994). The total numbers of tagged fish released and recaptured in 1985 and 1994 were: 18 800 and 25 300; and, 1 093 and 521, respectively. These data, and other historical evidence, indicate the three component substocks are reasonably discrete, with limited mixing occurring mainly around the time of spawning, so a multiple-substock model was constructed, with spatial partitions for each. The model was age-structured, and with multiple fisheries. Three stages of model development are presented: 1) excluding tagging data; 2) including tagging data, with no movement parameters; and, 3) including tagging data and estimating movement. Computational limitations were experienced in stages 2) and 3), illustrating a problem in using generalised software when integrating tagging data in this instance.

FOCUS QUESTIONS

Is it practical to integrate all available data into the assessment model, or should separate analyses be carried out?

It is not possible to use an integrated model for all applications. For example, the CASAL application applied to the SNA 1 stock in New Zealand was too computationally intensive when movement was allowed among populations. This was the case because a large number of partitions are created for the whole time period to represent the tagging data in each area. The use of length-frequency data greatly increases the computational and memory demands of integrated models, and this may be a contributing factor in this application. Maunder (1998) applied an integrated model to the same data, but converted the lengths into ages outside the model, which greatly reduced the computational burden.

There have been several MULTIFAN-CL applications that have successfully integrated tagging data. However, the computational requirements often restrict certain aspects of the modeling. For example, full Bayesian analysis using Markov Chain-Monte Carlo integration is often not possible.

It may be necessary to limit the integrated analysis to over the time frame of the tagging analysis, or to just examine the tagging data with auxiliary information to reduce the computational demands.

Integrated analysis eliminates the need to provide complex multivariate distributions that would be required in some applications of sequential Bayesian updating.

A cost-benefit analysis should be conducted to determine if conducting an integrated analysis or adding a particular data set adds substantially to the quantity of the analysis versus being able to estimate uncertainty, interpret results, provide goodness-of-fit tests, and conduct sensitivity analyses.

Model misspecification in integrated analysis often causes the data to force some of the model parameters toward unrealistic values. This characteristic informs the analyst about problems with the model. However, in some cases this may not be apparent, in which case biased results would be used for management advice.

One of the major issues in integrated assessment is the development of weighting factors for each data set. These weighting factors are determined by the standard deviations and sample sizes used in the likelihood functions. The appropriate weighting factors are also influenced by how much process variability is modeled. Maximum likelihood estimation of the weighting factors is possible, but many applications fix the weighting factors. The results are often very sensitive to the values assumed.

More information on stock assessment models and integrated analysis can be found in the report of the Inter-American Tropical Tuna Commission (IATTC) workshop on stock assessment methods (http://www.iattc.org/PDFFiles2/Assessment-methods-WS-Nov05-ReportENG.pdf)

What is the appropriate grouping level for tags in an integrated model?

MULTIFAN-CL has the capacity to group tagged fish from different tag groups when they reach a given age to decrease the computational demands of modeling tag data. However, no analyses have been performed to determine how this influences the results or how much it reduces computation time.

Some models recruit tagged fish to the tag group each year, rather than treating each year of release as a tag group. These methods lose information about natural mortality that are contained in multiple releases.

The rules for grouping should be based roughly on how much information is lost by grouping. This may be related to how much the dynamics of the individuals differ among groups.

Another aspect of grouping is how to group tags to perform diagnostics. Not grouping creates so many diagnostics that it is often impossible to get anything from the diagnostics. Too much grouping may hide problems.

Grouping can also be used to improve the statistical properties of the likelihood functions. For example, zeros or small values may cause problems in some likelihood functions.

Can tag reporting rates (i.e. probability that a recaptured tagged fish will be reported to the tagging organization) and/or tagging-related mortality be estimated reliably in an integrated model? Or are reporting rates highly confounded with other estimated parameters, e.g. F, M, selectivity, etc.

Reporting rate is one of the most important pieces of auxiliary information needed for tagging studies. It can be estimated within an integrated analysis, but confounding with other parameters, especially fishing mortality, often makes the estimates very imprecise and eliminates information in the tagging data about the desired quantities.

It is important to consider whether the removals of tags by all fisheries are important, even if some fisheries data are not used in the analysis, so as to ensure that the recaptures from those fisheries do not bias the results.

It may be useful to investigate tagging designs that can improve the estimation of reporting rates. For example, a fleet for which the catchability is constant over the entire time period or stock may provide estimates of (relative) reporting rates for different tagging programs.

Estimation of initial tagging mortality can be estimated from the tagging data. However, it is confounded with reporting rates and initial tag loss. If independent estimates of reporting rates and tag loss are available, good estimates of initial tagging mortality may be possible. Alternatively, initial tagging-related mortality can be estimated with net enclosure experiments. Other aspects, *e.g.* trap shyness, may bias the estimates as well.

How can tagging data be used to better inform the model about certain parameters? For example, length-frequency data provide too much information about movement.

In the MULTIFAN-CL applications that use tagging data, the tagging data are overwhelmed by the length-frequency data. This results in movement parameters being estimated by temporal or spatial variations in the length frequencies, and the estimates of movement contradict those from tagging data. It would be useful to increase the influence of tagging data on the movement estimates and reduce the influence of the length-frequency data.

The length-frequency data provide information on the other population dynamics processes, so down-weighting the length-frequency data is probably not an appropriate solution. The variations in length-frequency distributions are probably caused by variations in other population dynamics processes (*e.g.* growth and selectivity), and modeling these variations may reduce the influence of the length-frequency data on movement.

The influence of the length-frequency data on movement could be reduced by fitting to the length frequencies combined across all regions.

The tagging likelihood could be modified to increase the emphasis on the movement.

4. AUXILIARY INFORMATION

In addition to the main objectives of tagging studies (*e.g.* estimation of biomass, natural and fishing mortality rates, growth rates, and movement), there is auxiliary information that is required to remove biases from the analysis. This auxiliary information includes reporting rates (Hearn *et al.* 1998), tag shedding (Xiao 1996; Hampton 1997; Adam and Kirkwood 2001), and tag-related mortality. Estimation of these parameters should be included as part of the tagging experiment.

If the reporting rate is not 100%, and it is not compensated for in the analysis, fewer recovered tags than there actually were will be used in the analysis. This will cause a positive bias in the biomass estimates and a negative bias in the exploitation rates. Tag seeding experiments can be conducted to estimate reporting rates. These experiments involve clandestinely putting tags on fish caught by a vessel to determine if they are reported. However, this type of analysis determines reporting rates for only the part of the recovery phase after the tag was seeded, and due to logistics of tag seeding may miss some of the recovery phase. Reporting rates may differ among vessels, fisheries, ports where the fish are landed, *etc*. Statistical analysis of the tag seeding data (*e.g.* general linear modeling) may help define the factors that influence the reporting rate, and this might then be applied to the components of the catch for which tag seeding experiments were not carried out.

Reporting rates can also be estimated by having different rewards, the assumption being that tags with high rewards are fully reported; this information can then be used to determine the reporting rate for tags with the standard reward. However, caution must be taken in designing this type of program so that the information obtainable from tags with the standard rewards is not lost in estimating the reporting rate.

Tag shedding has similar consequences similar to those due to non-reporting of tags. Tag shedding rates are typically estimated from double-tagging experiments. The amount of tag shedding can be estimated from the number of double-tagged fish that are returned with only a single tag. The analysis should take into account the fact that some double-tagged fish that are recaptured will have lost both tags, and will therefore not be reported. One problem with double-tagging studies is that the loss of the tags may not be independent, so if one tag is lost, there is a greater probability that the other tag will also be lost. Tag shedding may also be correlated with factors such as the person who applied the tag, and these covariates should be considered in the analysis of tag shedding data.

Tag-related mortality has similar consequences as shedding and non-reporting. Tag-related mortality can be separated into 1) immediate mortality occurring soon after tagging the fish and 2) long-term mortality due to having the tag (*e.g.* infections, greater vulnerablity to predators). Tagging mortality can be evaluated by confining tagged fish in pens or large tanks such as those at the IATTC's laboratory at Achotines, Panama. However, it may be infeasible to hold tagged fish in pens for long periods of time, and holding experiments in either pens or tanks may be confounded by the effect of the pen or tank. Tag–related mortality rates can be included in the models used to analyze the data. It is possible that tag-related mortality may be greater for double-tagged fish than for single-tagged fish.

4.1. Estimating tag reporting and tag shedding for tunas in the EPO

Mark N. Maunder, Kurt M. Schaefer, Daniel W. Fuller, and Ernesto Altamirano Nieto

A tag seeding experiment was carried out to obtain data with which to estimate tag reporting rates. Observers aboard purse-seine vessels surreptitiously placed conventional plastic dart tags in skipjack, yellowfin, and bigeye tuna before they were put into the wells. Three tagged fish, preferably one of each species, were tagged per well. Half of the fish were double tagged. The data were analyzed, using a logistic regression programmed in AD Model Builder. Species and tag type were included as categorical variables and length was included as a continuous variable. We intended to include tagger as a random effect, but this was not included in the analysis. Length, species, and tag type were all significant, and were included in that order. Larger fish were less likely to be reported. These results suggest that the fact that not all the seeded tagged fish were returned was due to tag loss, rather than to failure to detect of the tags. The observers were apparently not well trained in the proper techniques for the placement of the tags at the base of the second dorsal fin of the fish between the pterygiophores. (It is more difficult to properly tag larger fish due to their greater muscle mass.)

Tag loss was estimated by analyzing data for double-tagged fish released at sea. A logistic regression was combined with a tag attrition model and programmed in AD Model Builder. The explanatory variables were applied to both immediate and continuous loss. Species and tagger were included as categorical variables, and length was included as a continuous variable. The tag loss rate was not strongly correlated with time at liberty. There was a large tagger effect on initial tag loss, due to the fact that fish tagged by one tagger experienced a much higher loss than those tagged by the other taggers. The tagger effect may have been confounded with species (*e.g.* skipjack), but not enough data were available by tagger and species to determine this. Tag loss estimates from double-tagging studies will be influenced by the difference in detection rates between single- and double-tagged fish, but inclusion of this effect was not possible due to the problems with the tag reporting analysis.

4.2. Analysis of a tag-seeding experiment initiated in the Indian Ocean

Julien Million

The Indian Ocean Tuna Commission (IOTC) has been conducting a series of large- and small-scale tuna tagging experiments in the Indian Ocean since 2002. So far, more than 170 000 fish have been tagged, with more than half of these being yellowfin and bigeye tuna. To date, more than 21 000 fish have been recovered and reported, 97% from the catches of European purse-seine vessels based in the Seychelles that operate mainly in western Indian Ocean. In 2006 this fleet consisted of 52 vessels, which caught 389 935 mt of tunas.

A tag-seeding experiment was initiated on purse-seine vessels of the Seychelles fleet in 2004. A maximum of 15 tags are seeded aboard a vessel by either the observer or the captain. The tags are applied to different species of different sizes and dispersed to different wells. The method of attachment method of the tags is slightly different from the method of attachment of the tags applied to living fish, in order to ensure that the tags are firmly attached to the dead fish, but the streamers are the same color and size as the streamers on the tags that are applied to living fish. The recoveries of the seeded tags are processed the same way as those of the tags that had been applied to living fish, and the rewards are the same.

Since 2004, 1935 tags (942 on yellowfin, 813 on skipjack, and 180 on bigeye) have been seeded. The reporting rate for all species combined has increased from 47% in 2004 to 90% in 2007. This shows the effectiveness of the publicity campaigns, which were not fully implemented until 2005. The IOTC will continue its seeding experiment until recoveries are no longer reported for tags placed on living fish. Reporting rates will be estimated for the three species of fish, for different sizes of fish, and for different unloading ports. The experiment will be improved by double tagging to estimates the shedding rates of the seeded tags and by seeding on freezer ships and in canneries, in addition to fishing vessels.

FOCUS QUESTIONS

What type of auxiliary information is required for interpreting tagging data, and how should it be obtained?

Reporting rates are one of the most important pieces of auxiliary information needed for analyzing tagging data. In general, there is little information in the tagging data about reporting rates because they are confounded with other parameters. If they are estimated without auxiliary information this removes information about the quantities of interest. Substantial effort should be made to provide auxiliary information on reporting rates. Money may be better spent by determining reporting rates rather than increasing numbers of releases or recapture rates.

If catch data are good for all fleets and reliable estimates of reporting rates are available for at least one of the fleets, then the reporting rates for the other fleets can be estimated from the tagging data within the assessment model. However, by estimating these reporting rates, the information in the tagging data from these fleets may provide little information about the quantities of interest.

Tag recoveries are not required from the entire catch. Therefore, recovery effort can be focused on a component of the catch for which the reporting rates are very high or for which reliable estimates can be calculated. The spatial and size-frequency coverage of the catch examined for tags should be broad enough to provide information on all components of the population. For example, the use of Passive Integrated Transponder (PIT) tags and installation of tag scanners at locations at which large portions of the catch are landed may provide better tagging results than voluntary recoveries. Experiments with seeded PIT tags will provide reliable estimates of the efficiencies of the scanners. An important component of tagging programs is recording the amounts and length structures of the fish that are examined for tags. This is linked to the estimation of the reporting rates. However, if not all the catch is used in the analysis of tags the information on fisheries interactions may be lost.

The recovery rates and quality of data from recoveries are greatly improved by having people at the ports to collect the information and pay the rewards. This also raises awareness of the program.

The success of tag-seeding programs to estimate reporting rates has been mixed. Efforts at the IATTC have encountered biases due to tag loss. The use of intra-muscular tags may improve these results.

Tag shedding rates can be estimated from the results of double-tagging experiments. Tag shedding can be divided into initial loss and long term sytematic loss. The dependence between the two tags may bias the results.

Tag-related initial mortality can be estimated from tagging data. However, it is confounded with reporting rate and tag shedding. If auxiliary data are available for these other factors, a reasonable estimate may be obtained from the tagging data. Tag-related mortality can be divided into initial loss and long-term systematic loss. Tag-related mortality is dependent on several factors, such as size of the fish and method of capture. Auxiliary data from net experiments may be informative, particularly if the survival rate is high.

Tagging may have an impact on growth, and auxiliary information on this may be useful in interpreting data. This information could come from comparing the growth increment data from tagging data with growth increments data from otoliths or other hard parts or from length-frequency data. There is some indication that tagging affects the growth rates of tuna. Comparison of the growth rates of single- and double-tagged fish might indicate whether this is the case.

Other auxiliary data that may be useful in interpreting tagging data are the age, length, sex, and maturity of the fish, which may help interpret movement. The microchemistry of the otolith may also be useful for estimating movement.

There is a need to conduct simulation analyses to determine which parameters can be estimated from tagging studies and which parameters need auxiliary information to improve the estimates of the quantities of interest.

Should these data be analyzed separately or integrated into the assessment model?

This question is addressed in the section on integrated analysis.

5. ADVECTION-DIFFUSION MODELS

Tagging data provide a wealth of information on the spatial distribution of fish and the exchange of fish among spatial strata. Most stock assessment models ignore the spatial distribution of the fish. The most common approach to incorporate spatial distribution is to treat fisheries in different areas, but fishing with the same gear, as different fisheries (*e.g*. the IATTC tuna assessments using A-SCALA). This allows the fish and/or fisheries in different areas to have different characteristics. For example the selectivity curves and catchability coefficients may differ among areas. A few assessments explicitly model spatial structure in the population dynamics (*e.g*. Maunder 1998, 2001; Hampton and Fournier 2001; see above). Population dynamics models with a finer spatial stratification (*e.g.* SEAPODYM, http://www.seapodym.org/) might be able to take advantage of the finer spatial resolution of archival tag data.

Advection-diffusion models are widely used in animal ecology (*e.g*. Skellam 1951 and Okubo 1980) and have been applied in population models of fish movements (*e.g.* Sibert and Fournier 1994; Sibert *et al*. 1999; Adam and Sibert 2002). The time development of the density of the tagged population is assumed to follow the advection-diffusion-reaction (ADR) equation. The ADR equation is solved numerically by a finite difference partial differential equation solver. The actual observed catch is usually assumed to follow a Poisson distribution with mean equal to the expected catch and maximum likelihood used to estimate the model parameters. Alternatively, the negative binomial distribution can be used to allow the variance of the observed catch to be greater than its mean.

Traditionally, the model uses only one common population density for all tagged individuals. All information about when and where the individuals were released is lost as soon as they have been added to the density. The likelihood depends only on the number caught. Later applications of this model (Adam and Sibert 2002; Sibert, personal communication) have improved this by dividing the tagged population into release cohorts and modeling a density via the ADR model for each cohort.

5.1. Modeling movement using advection-diffusion models

Pierre Kleiber

Some basic elements of diffusion-advection-reaction models are introduced, including the distinction between Eulerian and Lagrangian models, derivation of Fick's laws of diffusion, and the analytical solution in two dimensions from a point source. Considerations in implementing Eulerian models on a computer are discussed, including grid point and box transfer models and how to translate between them. An example is presented of an application of a box transfer model to tagged skipjack tuna by Kleiber and Hampton (1994), which shows the following:

"From an experiment with ordinary dart tags, we have found evidence of the effect of fish-aggregating devices (FADs) and of islands on the movements of skipjack tuna (*Katsuwonus pelamis*) around the Solomon Islands. By fitting a fish movement model to the tag data, we were able to estimate mortality and movement parameters (including diffusivity), parameters of a function that models FAD attraction, and a separate parameter of island attraction. Diffusivity was high enough to effectively distribute fish throughout the island archipelago (approximately 150 000 km^2) within a few months. Estimates of FAD parameters indicate that the presence of up to four or five FADs in an area approximately 50 x 50 km can reduce the propensity for skipjack to leave that area by approximately 50% but that deploying additional FADs in such an area does not significantly increase their effectiveness in holding skipjack. Estimates of the island attraction parameter imply that the propensity of skipjack for movement away from the archipelago is less than half the propensity for movement within it."

FOCUS QUESTIONS

How can parameters of advection-diffusion models be translated into parameters of block-transfer models used for stock assessment?

Pierre Kleiber presented a method to convert advection-diffusion processes estimated from tagging data into block transfer coefficient by measuring the flux across the boundaries of the blocks (see the abstract of the presentation for more details).

An alternative method is to view the data as the probability of observing an individual in a block or the probability of moving from one block to the next. The archival trajectory can be divided into small time steps, and the frequency within a block, or the transition between blocks, can be calculated. The observations will be correlated, and the sample size may be more related to the number of fish tagged than to the number of observations. This method, and others, may be biased by where the individual was tagged.

The archival tag data could be modeled using continuous fishing and movement. The models can be run at finer scales than the data to approximate the catch equation. The spatial scale could also be reduced. The alternating direction implicit (ADI) solution may also be appropriate.

6. ARCHIVAL TAGGING

Archival tags are relatively new. They are expensive, but they provide highly-detailed data for the entire period from release to recapture of the individual fish (or from release of the fish to "popping up," in the case of pop-up tags). Therefore, methods used to analyze traditional tagging experiments may not be appropriate, so new methods should be developed. Much of the current research has been focused on developing better estimates of tracks for these tags (*e.g.* Nielsen *et al*. 2006). Kalman filters have shown promise for this. They use advection-diffusion models similar to those used to model movement with data from traditional tagging experiments (Sibert *et al.* 1999).

The problem with the tracks from archival tags is that the positions of the fish are based on light measurements, and these can be inaccurate. The accuracy varies with latitude and season. To improve the estimates of the tracks, information on observation error (*e.g*. from archival tags placed on buoys) and covariates (such as temperature) have been used (Nielsen *et al*. 2006).

Studies have investigated compensating for the influences of the environment on behavior. This essentially involves determining correlations between environmental variables (*e.g*. temperature) and characteristics of the track (*e.g*. distance covered or turning).

Methods to incorporate the information from archival tags into stock assessment models have yet to be fully developed. For example, the advection-diffusion movement estimates from archival tag tracking information needs to be integrated into the stock assessment models that use block transfer movement. Sibert and Fournier (2001) suggest methods to integrated traditional tag data with archival tag data, and this needs to be extended to the stock assessment models.

6.1. Modeling archival tagging data with state-space models

John Sibert

A state space maximum likelihood framework to improve geolocation of archival tag tracks was described. Movement is modeled, using a random walk. The observation model takes into consideration the characteristics of light-based observations, such as the equinox effect, position, depth, time of year, and correlation between light measurements. A Kalman filter is used to estimate parameters and associated uncertainty in location estimates. The framework is extended to include sea-surface temperature, if available, to improve position estimates. All data are included in a single framework that is transparent, statistically-sound, and without *ad-hoc* solutions.

Results show that the track is influenced only by data for certain periods. This indicates that the storage capacity of archival tags could be optimized by recording only at the most information-rich periods.

The programs that implement the estimate framework are available for download at https://www.soest.hawaii.edu/tag-data/

6.2. A spatially explicit Southwest Pacific swordfish model: how can pop-up satellite archival tag data be used to improve movement estimates?

Nick Davies, Dale Kolody, and Rob Campbell

A population model was developed in 2006 for the regional stock assessment of Southwest Pacific swordfish, using the generalized modeling software CASAL. This was challenging because of (among other things) the uncertainty in stock structure and migration dynamics. The model was fitted to catch-per-unit-of-effort (CPUE) and catch-at-length observations collected from most fisheries in the region. There are indications of fish movement from these data, *e.g*., seasonality in CPUE and catch-at-length among areas, suggesting north-south migrations most likely related to spawning. Models were run to test structural assumptions for either a single stock, or one that is spatially disaggregated with options for homogeneous mixing, mixing on shared spawning grounds, or for discrete spawning stocks with foraging site fidelity (separate stocks that migrate to a common spawning ground, but return only to the foraging grounds from which they were originally recruited). Migration parameters were sensitive to both the structural and statistical assumptions. However, in the past two years, a limited number of direct movement observations have become available, including results from conventional and **pop-up satellite archival tags** (PSATs) from Australian and New Zealand releases. It is likely that data for around 20 to 30 PSAT tags may be used in revising the assessment model in 2008. These data will be used qualitatively to review the model's structural assumptions in terms of choices for spatial disaggregation and movement parameters. Further possible uses of these, and future tagging data will be considered in making inferences about movement dynamics having features such as: distinct spawning areas, foraging site fidelity, small or large net displacements, relatively discrete subpopulations, and age- or sex-specific movements.

FOCUS QUESTIONS

How can data from archival tagging be used in stock assessment models?

The discussion on archival tags with regard to estimating movement was combined with the discussion on advection-diffusion models. Archival tags were also discussed under the other topics, particularly behavior.

Information from archival tags could be used qualitatively to constrain movement. For example, it may provide information on fidelity to spawning sites. In his presentation on modeling swordfish, Davies suggested using archival tag data in this way to constrain movement.

Care needs to be taken when interpreting archival tag data. Because the recovery of the data is conditioned on being recaptured, the track may be biased. The early part of the track may be inversely correlated with effort (because the fish was not caught) and the later part of the track may be correlated with effort (because it was caught).

7. MARK-RECAPTURE DATA

There is a well developed set of statistical procedures for analyzing tagging data in a wildlife mark-recapture context (Lebreton *et al*. 1992). This includes the analysis of both studies that re-release individuals (or re-sight them) and those based on recoveries of dead animals. The methodology is generally based on parameterizing the probability of recapture and the probability of survival, and then basing inferences on a multinomial likelihood function. The field has well developed methods for hypothesis testing (*e.g*. the Akaike Information Criterion or AIC), goodness-of-fit tests, over dispersion, individual variability, and covariates.

It is interesting to note that many of the analyses are based on treating the re-released individuals as new individuals. Therefore, these methods can be applied to fisheries data for which the individuals are killed when recaptured. However, some of the goodness-of-fit tests may not be appropriate. Models that retain the memory as to whether an individual had previously been captured have been developed to determine if there is an effect of capture (trap shy or trap happy).

The Brownie models (Brownie *et al*. 1985) can be used for the estimation of both abundance and survival, and are therefore beneficial to the analysis of fisheries data.

7.1. Estimating survival of mako sharks

Anthony Wood

Survival for shortfin mako, *Isurus oxyrinchus*, in the northwest Atlantic was estimated from tag-recapture data. The data used in this study were collected by the U.S. National Marine Fisheries Service (NMFS) cooperative shark tagging program (CSTP) from 1962 to 2003. In total, 6309 shortfin mako sharks were tagged, of which 730 were recaptured. The high recapture rate of 11.6% for this species provided adequate recapture data to carry out survival analyses. Estimates of survival were generated with the computer software MARK, which provides a means for estimating parameters from tagged animals when they are later recaptured. The results of several models with various combinations of constant and time-specific survival and recovery rates were presented. A parametric bootstrap and the median approach were used to test the fit of the general model to the data. The estimated variance inflation factor indicated a very good model fit. The models with time-invariant survival rate had the most support from the data, and no group or time period effects were found. Recovery rate (*f*) appeared to increase from 0.043 in the early years to 0.056 in the later years. The nominal survival rate of 0.59 per year was adjusted with an estimated tag shedding rate of 0.26 per year to generate a final adjusted annual survival estimate of 0.79, with a 95% confidence interval of 0.71 to 0.87.

7.2. Integrating catch-at-age and multiyear tagging data: a combined Brownie and Petersen model for estimating mortality rates and abundance

J. Paige Eveson, Tom Polacheck, and Geoff M. Laslett

A framework for modeling data from a multiyear tagging experiment that integrates catch data into the traditional Brownie tag-recapture model was presented. For a cohort of fish tagged in consecutive years, this model allows for simultaneous estimation of age-specific natural mortality rates, age-specific fishing mortality rates, and abundance at the time of tagging. These are the primary quantities to be estimated in stock assessments. Having an approach for directly estimating them that does not require catch rates or data from fishery-independent surveys (which are often infeasible or provide insufficient data) provides a potentially powerful alternative for augmenting traditional stock assessment methods.

Simulations are used to demonstrate the value of incorporating catch data directly into the estimation framework. Results from the range of scenarios considered suggest that, in addition to providing a precise estimate of the population size (coefficients of variation ranging from ~10-25%), including catch data can also improve precision of the estimates of the mortality rates, especially fishing mortality (*e.g.* by more than 50% at age 1). The model is applied to southern bluefin tuna (*Thunnus maccoyii*) tag-recapture and catch data collected during the 1990s. For this application, the basic model is extended to allow for: multiple cohorts, uncertainty in reporting rate estimates, tag shedding estimates and their uncertainty, and delayed mixing. Time permitting, a discrete spatial version of the model will also be briefly presented, along with an application to data for southern bluefin tuna.

7.3. Comparison of fixed effect, random effect, and hierarchical Bayes estimators for mark recapture data, using AD Model Builder

Mark N. Maunder, Hans J. Skaug, David A. Fournier, and Simon D. Hoyle.

Mark-recapture studies are one of the most common methods used to obtain demographic parameters for wildlife populations. Time-specific estimates of parameters representing population processes include both temporal variability in the process (process error) and error in estimating the parameters (observation error). Therefore, to estimate the temporal variation in the population process, it is important to separate these two errors. Traditional random effect models can be used to separate the two errors. However, it is difficult to implement the required simultaneous maximization and integration for dynamic nonlinear non-Gaussian models. An alternative hierarchical Bayesian approach using Markov Chain-Monte Carlo (MCMC) integration is easier to apply, but requires priors for all model parameters.

AD Model Builder (ADMB) is a general software environment for fitting parameter-rich nonlinear models to data. It uses automatic differentiation to provide a more efficient and stable parameter estimation framework. ADMB has both random effects, using Laplace approximation and importance sampling, and MCMC to implement Bayesian analysis.

To demonstrate ADMB and investigate methods to analyze mark-recapture data, we implement fixed effect, random effect, and hierarchical Bayes estimators in ADMB and apply them to three mark-recapture data sets. Our results showed that unrestricted time effects, random effects, and hierarchical Bayes methods often give similar results, but not in all cases or for all parameters.

FOCUS QUESTIONS

What aspects of mark-recapture models should be incorporated into fisheries models?

Descriptions of mark-recapture analyses generally provide the assumptions of the analysis. This is often not the case for fishery assessment models, particularly those that integrate tagging data. More attention should be given to providing the assumptions implicit for fisheries assessment models.

Mark-recapture models have a well developed set of diagnostics that can be used to determine the adequacy of the model. These types of diagnostics are needed for fisheries models. (See the section on diagnostics below).

Due to the simple nature of many mark-recapture analyses, more detailed and computationally-intensive analyses can be conducted. For example, model averaging is commonly becoming applied in mark-recapture studies to address model uncertainty. These types of analyses should be considered when modeling fisheries data.

Mark-recapture analyses often estimate the probability of recapture as a parameter in the model. This automatically incorporates tag reporting and tag shedding. These types of methods may be useful for fisheries data if estimates of tag reporting and tag shedding are not available. It also highlights the need to ensure that tag reporting and tag shedding are considered as part of the analysis. Fisheries models often use the catch as a measure of the number of fish checked for tags. There is often a great deal of uncertainty in the catch estimates, and this needs to be taken into consideration in the model. More focus is needed on incorporating variance in catch estimates when analyzing tagging data.

Simulation testing is frequently used in mark-recapture studies. More simulation testing is needed for the analyses used for fisheries data.

What additional information that is provided by multiple recaptures would improve fisheries models?

Multiple recaptures are difficult to obtain from commercial fisheries data. In most cases the fisherman wants to keep the fish for eventual sale. Also, the process of capture often kills the fish or, at least, causes so much physical or physiological damage to them that they are unlikely to survive.

Multiple captures could provide information on initial tag mortality (from the tag placement, rather than from the capture process) and initial tag loss. A simple way to use multiple recaptures to overcome initial losses is to ignore the initial capture event and treat the first recapture as the tagging event.

Multiple recaptures can be used to test for trap happiness and trap shyness. The data could also be used to estimate these effects. Data from snapper in New Zealand indicate trap shyness because fish caught by one gear are less likely to be caught by the same gear.

If fish are tagged only at age 1 (or any know age *e.g* 0) then their age will be known through their whole recapture history. This may be useful for species that are hard to age. This would also be useful even in the case of recaptures of dead fish.

Archival tags can be viewed as multiple recaptures, with each record being a a recapture. However, the series of recaptures will be highly correlated, and will be dependent on the fish finally being recaptured. Satellite tags would remove the bias caused by the need to be recaptured, but the recaptures will still be correlated.

8. GROWTH

Estimating growth from tagging data is a common objective of tagging experiments. Numerous methods have been used to estimate growth. Modern approaches use maximum likelihood estimation of the parameters of the growth model by fitting to growth increment data (*e.g.* Francis 1988). These approaches are often used to develop growth transition matrices (Punt *et al.* 1997) for use in length-based models, and therefore the individual variation in growth is important. The following factors need to be considered in this type of analysis: 1) measurement error, 2) individual variation in growth, 3) variation in growth as a function size and/or time, 4) effect of selectivity, 5) form of the growth model, and 6) special cases for molting individuals. In addition, the process of tagging an individual may itself affect the growth of the individual.

Measurement error can cause bias in the estimates of both mean growth and variation in growth. If the fish are measured at release on a “cradle” covered with some sort of smooth fabric with marks at 1-cm intervals, the cradle should be calibrated at frequent intervals, and the lengths at release should be adjusted to compensate for shrinkage or stretching of the fabric. Also, there may be bias in the measurements of the lengths at recapture if the recaptured fish are frozen when they are measured or if they have shrunk or stretched after recapture. Schaefer and Fuller (2006) measured freshly-caught bigeye before they were frozen aboard fishing vessels, put tags on them, and later retrieved them at fish-processing facilities after they had been thawed prior to processing and re-measured them. They found that the fish had shrunk between the two times that they were measured. Similar experiments should be performed with the other species of tunas, and, if the fish were found to have shrunk or stretched, the measurements of the lengths at recapture should be adjusted accordingly. Variation in measurement error is confounded with individual variation, and if it is not taken into consideration, the individual variation, which is of interest, will be over estimated. Measurement error can be estimated from short-term recoveries in either a separate analysis or integrated into the growth analysis. However, if the measurement error is in the length at release, this causes problems in the analysis because growth is conditioned on the length at release (Hampton 1991) and for computational convenience it is often assumed that the measurement error is in the length at recovery (*e.g.* Maunder 2002). Measurement error may be greater in the length at release than in the length at recapture because live fish (*e.g.* skipjack tuna) are harder to measure. However, measurement error may be greater in the length at recovery if the measurement is taken by fishermen or workers at fish-processing facilities rather than by trained scientists or technicians or due to shrinkage. Some investigators do not use measurements made by untrained persons.

The estimation of individual variation in growth (Hampton 1991) is important for determining growth transition matrices for length-based models. This is also termed process error, and is important for determining the likelihood function used for fitting the model to data. The estimation methods generally model the growth increment expected based on the size at release and the time at liberty, but not all the individuals will grow as predicted by the growth model. Commonly, it is assumed that the growth rates may randomly vary around the predicted growth following a normal distribution. However, more complicated variation patterns may occur. For example, some individuals may not grow at all, while those that do follow a lognormal distribution.

The amount of individual variation may depend on several factors, and models can be developed to take into account this variation. For example, it is likely that the variation will depend on the time at liberty and the length at release. Maunder (2002) presents a general variation model that takes both these factors into consideration.

The methods that are used to tag or recapture individuals may influence the estimates of growth. For example, if the recovery gear selects for larger fish, the faster-growing fish may be overly represented in the data. Methods have been developed that can adjust for the selectivity effect on the growth estimates.

The von Bertalanffy growth model is commonly used to represent the mean growth. However, the von Bertalanffy model may not be flexible enough for some species. For example bigeye tuna shows nearly linear growth for much of the size ranges (Schaefer and Fuller 2006) and the von Bertalanffy model cannot accurately model this growth rate while also modeling the asymptotic length seen in the data. Tunas have also shown a change in growth rates around the age of maturity that cannot be modeled by the von Bertalanffy model. Schnute (1981) and Francis (1995) provide a more flexible model.

Some species (*e.g.* lobster) have a discrete growth process, which may require special modeling approaches. For example, not all individuals may molt and those that do not molt do not grow. This may require complex models of growth and growth variation (*e.g.* the delta lognormal). An alternative approach to creating a growth transition matrix using a model of mean growth and a distribution for variation of growth, is to directly estimate the transition probabilities from each size class to the next, perhaps with some smoothing function over the matrix (a non-parametric approach).

Tagging data are not the only source of information on growth. Length-frequency data (see the original MULTIFAN model of Fournier *et al*. 1990) and aging data (*e.g* Schaefer and Fuller 2006) also provide information on the growth parameters. It may be appropriate to obtain growth information more than one data source. This could be done in a special analysis that combines the different sources of information or all the data be integrated directly into the stock assessment model. For example, Bentley *et al*. (2001) used both tagging data and length-frequency data in a length-based model for rock lobster.

8.1. Integrating age-length, tagging growth increment, and shrinkage data to estimate growth

Mark N. Maunder, Kurt M. Schaefer, and Daniel W. Fuller

The age-at-length data for 254 fish, based on otolith increment counts, along with the growth increment data for 451 fish from tagging-and-release experiments, and shrinkage data for 73 fish, were combined into a single analysis to estimate growth of bigeye tuna in the eastern Pacific Ocean. Francis' (1995) formulation of the generalized von Bertalanffy model was used. Shrinkage due to rigor mortis was modeled as a linear function of length. Maunder's (2002) general variance equation, which is a function of time at liberty and length at release, was used to model variation in growth. The likelihoods from all three data types were combined and the parameters from all models estimated simultaneously while sharing values for the common parameters. Shrinkage was taken into consideration in the growth model observations.

The models fit the data reasonably well, but the growth equation predicted unrealistically great lengths for ages exceeding the range of the data. A lack of fit could be seen in the growth increment data for large fish. This may have been due to the greater number of observations at intermediate lengths influencing the parameter estimates. Giving greater weight to the data for the larger fish resulted in more realistic estimates of the lengths of older fish.

Several aspects of the analysis require further investigation. The age-length and growth increment models are equivalent if they are deterministic, but differ if stochastic. The bias caused by the stochastic models should be investigated (see Everson *et al*. 2004). The effects of size-specific selectivity, length-based sampling, and potential measurement error should be investigated. Age conditioned on size analysis (*e.g.* inside a stock assessment model) is needed to estimate variation in length at age, since the data were not randomly sampled. Methods should be developed to compensate for the overrepresented length and/or ages in the data.

FOCUS QUESTIONS

How can growth increment data obtained from tagging experiments be integrated directly into stock assessment models?

There have been few stock assessment models in which growth increment data from tagging studies have been integrated into the model. Most, if not all, are length-based models, and the growth increment data are used to estimate the parameters of the growth transition matrix. In addition to growth increment data obtained from tagging experiments, growth information obtained from length-frequency data and from age-length data can be used. Therefore, all three of these data types, if available, should be used to inform the growth curve. It is now standard practice to integrate length-frequency data and age-length (often as age conditioned on length due to the sampling design) into the assessment model. Growth estimates from tagging growth increment data can be integrated into the assessment as priors, which allows more detailed investigation of the growth increment data within a separate analysis. However, it is difficult to develop a multivariate prior to simultaneously represent all the parameters of the growth model, particularly if there is the common banana-shaped distribution. The growth model may need to be reparameterized so that the prior is more multivariate normal. In addition, factors such as selectivity can bias the estimates. Integrating the tagging growth increment data into the assessment model permits adjustment for selectivity because the estimates of selectivity are available from the assessment model.

Integration into the assessment model may also help adjust for the difference between age-length and growth increment models that occurs when the growth models are treated as stochastic. Laslett *et al.* (2002) estimated the age at release of each individual for the growth increment model, using a random effect. In this approach, the assessment model can be used to derive the age at release, given the length at release.

The growth estimates are conditioned on the individual surviving and being recaptured. Integrating length-increment data into the assessment model has the advantage of eliminating the bias of selectivity because the estimates of selectivity are directly available within the assessment model. However, because most assessment models that include length information assume a normal distribution of length at age, size-based selectivity does not influence the distribution of the length at age. In this case, fast-growing fish that have higher selectivity are not modeled appropriately, which may bias the results. Implementation of growth morphs, if feasible, may adjust for this bias.

How should over represented lengths be dealt with in growth increment analysis?

Joseph and Calkins (1969) and Bayliff (1988a) created categories for lengths of skipjack at release, and calculated the average growth rates for the fish in each category, rather than growth rates for individual fish.

Non-parametric methods could be used so that the estimates of growth at particular lengths are influenced more by the observations of length at release that are in the neighborhood of that length, rather than all lengths.

Other issues

The process of tagging fish can put stress on them, which may impact the growth of the individuals that are tagged. This should be considered in any analysis of tagging growth increment data.

Many fish species show substantial annual variation in growth rates. To determine annual variation in growth rates from tagging data, multiple years of tagging and recapture data are needed. There may also be variability among region, so tagging data should be collected from each region to investigate this variability.

Recent analysis of tuna tagging data indicates that the growth curve is linear for much of the life of the tuna, but drops off rapidly at greater ages. Currently-used growth curves (*e.g.* von Bertalanffy) have difficulty describing this type of growth pattern. More general growth curves (*e.g.* Laslett *et al.* 2002) may be useful to describe this growth pattern. An alternative explanation is the existence of a dome shaped selectivity curve, which prevents the larger fish being observed in the data. Bayliff *et al.* (1991), on the other hand, found that the growth of Pacific bluefin tuna was best represented by a Gompertz growth equation for fish between 191 and 564 mm in length and a linear function for fish between 564 and 1530 mm in length.

9. BEHAVIOR

Tagging studies of all varieties have been used to evaluate the behavior of fish. However, these studies are focused more on investigating ecological process rather than on input into stock assessment and management. One use of behavioral aspects of tagging data for stock assessment is the standardization of CPUE data, using the habitat preference determined from archival tagging data (Hinton and Nakano 1996). The habitat preference of a species is matched with the habitat that the longline fishing effort is occupying, and the CPUE is adjusted appropriately. Unfortunately, this method has subsequently been shown to perform poorly for several species (Maunder *et al.* 2006). The poor performance may be due to several factors, such as 1) mismatch in the spatio-temporal stratification of the habitat preference and the environmental data used in the analysis, 2) differences between habitat preference during feeding and other periods, and 3) lack of knwledge concerning the depth at which the gear is fishing. The poor performance of the method has led to the development of a statistical approach to estimate the habitat preference (Maunder *et al*. 2006).

Behavioral information may help to provide input into stock assessments in a variety of ways, and more research should be applied in this area. For example, behavioral information about tuna at FADs may help to develop an index of abundance from purse-seine CPUE data around FADs.

Bayliff (1988b) and Hilborn (1991) used tagging data to study the stability of schools of skipjack tuna released in two different regions of the Pacific Ocean, and they both found that the schools break up and reform rather quickly (although the latter cautioned that there may be "cohesive subunits" within the schools). Hilborn (1991) discussed the implications of these findings with regard to management.

9.1. Horizontal movements of tunas and stock structure

Kurt M. Schaefer and Daniel W. Fuller

An important consideration in the regional management of tunas is understanding the distribution of the stocks of fish being exploited and the movement patterns of individuals within those stocks. Tagging-and-recapture experiments utilizing conventional plastic dart and intramuscular tags and geolocating archival and pop-up archival tags have been used successfully to provide estimates of horizontal movements, mixing, and stock structure of tunas.

An overview of recent (2000-2007) IATTC tuna tagging data, processing, and analyses, is presented. A Microsoft (MS) Access data base was created for handling all tag release and recapture information from both conventional and electronic tags. The program has numerous custom functions built in for calculating linear displacements, directions, and times at liberty. It is also related to the IATTC observer data base for gathering ancillary information about the purse-seine sets in which the tagged fish were recaptured. Queries are written to extract release and recapture information from the data base for use in other software packages. Two of the primary packages are MS Excel for statistical analyses and the Environmental Systems Research Institute for mapping and spatial analyses.

Proprietary software packages from Lotek Wireless and Wildlife Computers are used for interfacing with their archival tags, decoding data, and viewing. Several methods have been employed to improve position estimates, including movement models and matching sea-surface temperature data derived from tags with remote sensing data. Spatial analyses of the processed position data are done within ArcView, using various extensions. Processed time series data from the archival tags are imported into MS Access. Algorithms have been developed in Visual Basic code for performing analyses of behavior.

The overall distributions of the recaptures of skipjack, yellowfin, and bigeye tunas tagged and released with conventional plastic dart tags in similar locations in the equatorial eastern Pacific Ocean (EEPO), illustrate similar latitudinal and longitudinal ranges of dispersion. After 30 days at liberty, 93 percent of the recaptured skipjack and 93 percent of the recaptured yellowfin were within 1,000 nm of their release positions, and 95 percent of the recaptured bigeye were within 1,003 nm of their release positions.

Evaluations of horizontal movement patterns and habitat utilization of bigeye in the EEPO and yellowfin off northern Mexico, based on archival tag data, are presented. The 95-percent utilization distribution (UD) of the position estimates for bigeye at liberty for more than 150 days is about 1,700,000 km^2 and the probable core area, 50-percent UD is only about 8 percent of that, illustrating restricted movements and confined distributions. The 95-percent utilization distribution (UD) of the position estimates for yellowfin at liberty for more than 150 days, is only about 700,000 km^2 and the probable core area, 50-percent UD is only about 13 percent of that, again illustrating restricted movements and confined distributions.

9.2. Vertical movements of tunas and their vulnerability to capture

Kurt M. Schaefer and Daniel W. Fuller

Tuna tagging studies in the eastern Pacific Ocean (EPO), utilizing archival tags, have provided useful information on the vertical movements, behavior, habitat utilization, and vulnerability to capture by fishing gear. Understanding the physiological limitations and environmental tolerances of tunas, so as to define their habitat within spatial and temporal strata, including seasonal variability in oceanographic conditions, is important for estimation of species-specific vulnerability to various fishing gears for incorporation into stock assessments.

Evaluation of the depth and temperature records from recovered archival tags has resulted in discrimination of distinct vertical movement patterns for bigeye, yellowfin, and skipjack tunas in the EEPO, including association with floating objects, foraging at daytime depths of the deep-scattering layer (DSL), and surface orientation. The species-specific catchability by purse-seine fisheries is considered relative to the proportions of time spent associated with floating objects and to surface orientation. We describe geographic and seasonal differences in the surface-associated behavior of yellowfin in the EPO.

The simultaneous reductions in ambient temperatures and dissolved oxygen concentrations experienced by all three species of tunas when diving to depths of the DSL during the day for foraging, and their observed behavioral responses recorded in the archival tag records, provides insights to the physiological requirements and limitations for each species. Bigeye are observed to have much greater vertical mobility than yellowfin and skipjack, due to an apparent greater tolerance to changes in ambient temperature and dissolved oxygen occurring at depth.

Vertical habitat utilization distributions are presented for each species as the proportions of time at depth and temperature, by day and night, relative to thermocline depth. In addition, the proportions of time between dawn and dusk spent by large bigeye (>110 cm) within time and depth intervals, relative to dissolved oxygen concentrations, ambient temperature and light levels, and presumed prey distribution are considered regarding their importance in evaluations of bigeye vulnerability to capture by longline gear.

9.3. Application of electronic tag data in standardizing catch rates for stock assessments

Mark N. Maunder, Keith A. Bigelow, Michael G. Hinton, Adam D. Langley, and Minoru Kanaiwa

We describe the statistical application of the habitat-based standardization (statHBS) of catch-per-unit-effort (CPUE) data to derive indices of relative abundance. The framework is flexible, including multiple component models to accommodate factors such as habitat, sampling, and animal behavior. It allows the use of prior information or the completely independent estimation of model components (*e.g.* habitat preference). The integration with a general linear model framework allows convenient comparison with traditional methods used to standardize CPUE data. The statistical framework allows model selection and estimation of uncertainty.

Analyses have showed that environmental preference information from archival tags is often not consistent with that estimated from statistical analysis of the CPUE data. This may be due to 1) differences in spatial-temporal scales between the environmental data and archival tag data, 2) failure to adjust archival tag information for non-feeding periods, or 3) biases in the sampling models. Our analyses have also shown, for several species, that environmental conditions are more important for analyzing CPUE data than is depth.

We describe several improvements that could be made to the statHBS methodology including 1) total habitat adjustments, 2) estimating parameters of the sampling model, 3) setting and retrieval, 4) parameterizing habitat preference, and 5) and multi-species applications.

FOCUS QUESTIONS

What information about behavior obtained from tagging data can be used to standardize CPUE data?

A large amount of behavioral information is obtained from archival and acoustic tags. This information can be used to help interpret catch data from commercial fisheries. Integrating this information into the analysis of catch and effort data may improve current estimates of abundance based on CPUE data and provide new methods to develop these or alternative indices of abundance.

Information on habitat preference from archival tag has been used to standardize longline CPUE data (see Hinton and Nakano 1996). However, several problems have been identified with using the data in this context, and further developments of the methods have reduced the reliance of the standardization on the tagging data (see Maunder *et al.* 2006). Improvement of the fishing gear models and the use of multi-species data may result in methods that rely more on the tagging data, but further work needs to be carried out before this can be known.

Behavioral information for fish associated with fish-aggregating devices (FADs) may help in developing methods to derive indices of abundance from purse-seine catch and effort data for fish associated with FADs. Characteristics such as residence time could be used to model the catch rates or accumulation rates of fish associated with FADs as a function of local fish density. However, this is a complex system and will require information on other aspects such as the density and dynamics of FADs in the local area. Some preliminary analyses have been carried out on the Tropical Atmosphere Ocean (TAO) buoys in the EPO. Additional discussions about this can be found in the report of the IATTC workshop on developing indices of abundance from purse-seine catch and effort data[1]o. The deployment of acoustic recorders on FADs in the vicinity of Papua New Guinea may provide a good opportunity to investigate the development of indices of abundance from fisheries using large-scale arrays of moored FADs in archipelagic waters. Further research is required on drifting FADs on the high seas. These topics will be discussed at the 2007 Pelagic Fisheries Research Program Principal Investigators meeting (see http://www.soest.hawaii.edu/PFRP/).

10. DIAGNOSTICS

Most tagging analyses rely on estimating the model parameters, using statistical procedures to fit the model to observations from the tagging study. To ensure that the parameter estimates are reliable, methods are needed to check the model fit. These types of procedures are well developed for mark-recapture analysis applied in wildlife research. However, fisheries applications generally ignore these procedures, and they have not yet been developed for the integrated approach. Estimates of confidence intervals and plots of residuals provide some indication of the model performance. Simulation testing can provide a more rigorous evaluation of the methodology. However, more research is needed in the evaluation of model fit in fisheries tagging analysis.

FOCUS QUESTIONS

What diagnostics should be applied when analyzing tagging data?

There has bee a substantial focus on diagnostics in the use of mark-recapture analyses, but there has been little work on diagnostics for fisheries stock assessment models that use tagging data. In particular, diagnostics for integrated analysis is difficult and lacking.

Initial diagnostics should start with an exploratory analysis of the data. This involves looking at the data with respect to different quantities, such as time, area, length at release, and fishing effort.

A standard diagnostic tool for tagging data should be the tag attrition plot. On a log scale with time, the tag recoveries should be a straight line, provided fishing effort and vulnerability to capture are constant. Points off the straight line at the start indicate non-mixing, mortality due to tagging and handling, or tag shedding. A curved line indicates size or age-specific mortality or variation in reporting rates.

Residual plots (either as residuals or as observed versus expected) are a standard tool to identify problems with the model fit. These can be used to identify runs in residuals (non-random residuals) or residual distributions not consistent with the distributional assumptions of the likelihood functions. Tagging

[1] http://www.iattc.org/PDFFiles2/Report_PS_CPUE_meeting_Nov04ENG.pdf

analyses often involve many data points, and examining residuals for individual points is not informative. A decision is required about how to aggregate residuals and what quantities to plot the residuals against (*e.g*. tagging group, age, time, *etc.*).

Previous experience suggests that the tagger can have an impact on the recovery rates, due to mortality due to tagging and handling or to shedding of the tags, and results for different taggers should be examined to see if there is a tagger effect. The model may require parameters to describe the tagger effect.

The likelihood of each data component should be examined under several sensitivity tests to determine which data component is providing information about each parameter. This should then be compared to which parameters each data set is expected to provide information about.

Sensitivity analysis should be carried out on the weighting of each data set to determine if there are conflicts among the data sets.

It may be useful to analyze each data set separately, using traditional approaches that have well-defined diagnostics. The data sets should be used in an integrated analysis if the diagnostics tests indicate reasonable fit with the traditional approaches. If the reason for lack of fit is known, it may be possible to adjust for the lack of fit in the integrated analysis. If there is no lack of fit in the separate analyses, but there is in the integrated model, this may help diagnose problems (*e.g*. conflict in the different data sets).

Another diagnostic tool commonly used in integrated models is the comparison of the mean-squared error of the fit to the data with the assumed standard deviation (or sample size) of the likelihood used to fit the data. An inconsistency indicates an incorrect assumption. The mean-squared error is a function of both observation error and process error, and the discrepancy may indicate an incorrect process model or the need to model variability in model processes.

If the diagnostic tests indicate a problem with the model, this can often be remedied by adding additional parameters to the model. However, adding additional parameters reduces the amount of information in the data. Attention should be made to ensure that the additional parameter are appropriate, rather than just a convenient way to improve the fit.

Many diagnostics are qualitative, rather than quantitative. One simple diagnostic is to compare the results with expert opinion or logic. For example, some applications of integrated analysis using tagging data produce movement estimates that are contradictory to the tagging data, which is probably the result of variations in length-frequency data controlling the fit. However, it is often difficult to visualize movement data, particularly if there are seasonal or age-specific components to movement. Some methods that have been used to visualize movement are diagrams of flux across boundaries, plots of population composition by source of recruits over time, and movies.

Simulation analysis can be used to investigate the performance of the model. In the simple case, the simulation model would be exactly the same as the estimation model and the data generated similar to that used in the application. The simulations can be conducted under different parameter values to determine any biases due to true parameter values. Simulation scenarios could be made more complicated to investigate certain problems seen in the actual analysis.

11. DESIGNING TAGGING EXPERIMENTS

Tagging experiments must be designed appropriately if they are meet their goals. Much of the existing tagging data were obtained from poorly-designed experiments or from experiments that were not designed to provide input into stock assessments or for management advice. It is therefore important that comprehensive planning is made before any tagging study is conducted. Unfortunately, there are only a few papers (Wetherall and Yong 1981; Hampton 1989; Bailey 1990; Bertignac 1996a and 1996b; Xiao 1996; Bills and Sibert 1996 and 1997; Polacheck *et al*., 2002) on this subject. This may be because papers on design of tagging studies are considered less interesting or important than papers presenting the results of the studies. Furthermore, tagging tunas is expensive, so much of the tuna tagging has been carried out by scientists or technicians who have tagged fish opportunistically wherever and whenever the vessel that they were aboard happened to catch fish. Even when a vessel is chartered for the purpose of tagging tunas, tunas are not necessarily available at the locations and times called for in the design of an experiment.

The first part of designing a tagging study is to determine the objective of the study. Which of the main outputs of the study, growth, exploitation rate, natural mortality, biomass, behavior, and/or movement, are most desirable:? How will the data be used to estimate these processes and how will they be incorporated into stock assessments and ultimately the management process? What type of spatial-temporal coverage is required?

Once the objectives have been determined, the details of the tagging program need to be determined. For example, how many fish must be tagged to obtain the desired precision? This will depend on several factors, such as the reporting rates and exploitation rates. How should the limited resources be used; should more tagged fish be released or should more of the catch be sampled for tagged fish? These factors will also depend on the type of tags that are used. For example, more effort will be required to recover coded wire tags, but because the investigators do not have to rely on the fishermen or processors to return them, the reporting rates (detection rates) will be high.

One main factor is the practicality of the design. For example, it is ideal to tag the fish in proportion to their densities in the various areas encompassed by the study. However, this is often not possible because it is difficult to tag fish in certain areas with certain gears (*e.g.* in the central Pacific with longlines or purse seines). If it is not possible to tag in proportion to the density of fish, the analysis of the data may require that recaptures made shortly after the fish were released be ignored, as the tagged fish recaptured during that period may not be adequately mixed with the untagged fish. However, the disproportionate number of tags caught during this period needs to be taken into consideration and an additional tag-only exploitation rate may need to be estimated. It is also important to get recoveries from all areas and gears, but some fleets may not report tags, or their reporting rates may low or temporally variable.

11.1. Results from recent southern bluefin tuna tagging experiments: puzzling changes between the 1990s and 2000s, with implications for experimental design

Tom Polacheck and J. Paige Eveson

Large numbers of juvenile southern bluefin tuna have been tagged in the waters off Western Australia (WA) and South Australia (SA) beginning in 1959. Fish tagged and caught in the commercial fishery off WA are predominately 1-year-old fish, with a small and variable proportion of 2-year-olds. Fish tagged and caught in the commercial fishery off SA are dominated by 2- and 3-year-olds. For releases prior to 2000, large numbers of tagged fish released off WA were recaptured off SA, and the return rates for fish of similar ages and/or sizes tagged in the two areas were similar after their first year of release. This demonstrated a large degree of interaction/mixing of fish between these two areas and a general movement from WA to SA as the fish aged. Results from large-scale tagging experiments since 2002 have resulted in low return rates of 1-year-olds tagged off WA, but relatively high return rates from the same cohorts of fish tagged off SA. Moreover, return rates for 2-year-olds tagged in both areas are similar and high, as are the return rates for 3-year-olds tagged off SA. Taking into account estimates of reporting rates, estimates of annual fishing mortality rates for fish tagged off SA are extremely high (in some cases greater than 1.0), and contrast markedly with the low rates estimated for the same cohorts and ages of fish tagged off WA. Moreover, tag returns from longliners on the high seas show a similar bias toward fish tagged off SA. In addition, longline tag returns and archival tagging data indicate that juvenile fish during their winter movements are now predominately moving into the Indian Ocean, whereas in the past both the Indian Ocean and the Tasman Sea were utilized.

Three possible reasons for the lack of returns from smaller tagged fish compared to earlier tagging experiments are: (1) recent high tagging mortality of small fish, (2) incomplete mixing and changed movement patterns, and (3) extremely high and increased natural mortality rates on smaller/younger fish. The first of these seems unlikely, given that tagging techniques were similar and a large amount of the tagging was done by the same individuals during the 1990s and 2000s. If the lack of returns from smaller/younger fish since 2000 from WA is due to changes in spatial dynamics, it would appear that these fish are not only not going to SA, but are also not going to the traditional fishing areas where the longline fisheries are operating. Overall, the results indicate major, difficult to explain, changes in the spatial and/or population dynamics of juvenile southern bluefin tuna. These changes have potentially major implications for the stock assessments and the management of the fishery. More generally, the results demonstrate the importance of tagging broadly both in time and space, the need to address mixing issues in the analyses of tagging data, and the dangers of assuming that spatial dynamics are static in the design and analyses of tagging experiments.

11.2. Designing tagging experiments for tuna in the western and central Pacific Ocean

Simon Nicol, John Hampton, Bruno Leroy, David Itano, and Antony Lewis

The objectives of the Pacific Tuna Tagging Programme (PTTP) in the western and central Pacific Ocean (WCPO) are: (1) to obtain data that will contribute to, and reduce uncertainty in, WCPO tuna stock assessments; (2) to obtain information on the rates of movement and mixing of tunas in the equatorial WCPO and between this region and adjacent regions of the Pacific basin, and the impact of fish-aggregating devices (FADs) on movement at all spatial scales; (3) to obtain information on species-specific vertical habitat utilization by tunas in the tropical WCPO, and the impacts of FADs on vertical behavior; and (4) to obtain information on local exploitation rates and productivity of tunas in various parts of the WCPO. The design of the tagging experiment is based upon past experience from tagging tropical tunas and from a first phase of this project that has been implemented in the Exclusive Economic Zone of Papua New Guinea.

To achieve these objectives, the project uses conventional, archival, and acoustic tagging of skipjack, yellowfin, and bigeye tuna throughout the equatorial WCPO (10°N-10°S; 120°E-130°W). A chartered commercial pole-and-line vessel suitably modified for tagging is used in the western part of this region (west of 180°). One or more chartered smaller vessels (possibly Pacific Island-based longliners) will be used to undertake shorter cruises of 1-2 months in the central Pacific, targeting bigeye tuna by hand lining on drifting FADs, oceanographic moorings, and seamounts. The feasibility of the use of an eastern Pacific-based pole-and-line fishing vessel in the central Pacific is also being investigated.

Two critical issues need to be addressed in the design of tuna tagging programs: (1) implementation of methods that ensure that enough fish are tagged; and (2) implementation of measures to maximize the return of the tags from the recaptured tagged fish. The former can be achieved through the use of experienced cruise leaders and incentive/reward schemes for boat operators. The latter can be achieved through wide publicity, attractive rewards, lotteries, and in-country tag-recovery officers. Tag-seeding experiments should be conducted, and the results used to adjust the numbers of returns to compensate for non-reporting. Addressing both issues in the design of tagging studies will help ensure that the recapture data are sufficient for use in stock assessment and other ecological models.

11.3. A simulator-estimator modeling approach to derive cost-effective biomass estimation programmes for New Zealand snapper (*Pagrus auratus*) stocks

Jeremy McKenzie, Dave Gilbert, and Nick Davies

Tagging for the purposes of biomass estimation has been integral to the assessment of New Zealand snapper (*Pagrus auratus*) stocks since the early 1980s. Due to the high expense involved, the frequency of tagging programmes on each of the main stocks has been, by and large, decadal. There have been five major snapper tagging programmes since the first in 1981, each successively more logistically and analytically complicated than its predecessor. A sixth snapper tagging programme is proposed for late 2008. The design process for this programme has five components: (1) to specify a tagged population ‘functional reality’; (2) to construct a population operation model or simulator; (3) to choose an estimator model; (4) to specify a set of candidate designs; (5) to conduct a cost-benefit evaluation. This design project uses a simulation/estimation approach to investigate design scenarios incorporating known sources of bias: (1) spatial heterogeneity in distribution of tagged fish; (2) mark-rate changes due to growth; (3) movement of tagged fish among spatial strata. Other ancillary factors, such as initial mortality, are also included in the simulations. However, these are provided as inputs, rather than directly estimated.

In the simulator model, between-stratum movement is governed by a probability matrix such that at any given time a fish can be in any stratum, but there are some strata in which it is more likely to be found. Movement probabilities are defined relative to a particular stratum, termed the “home stratum.” The total number of relative movement probabilities is therefore the number of strata squared. Since movement probabilities do not change through time, there is no net change in the stratum populations through time due to movement. We believe that this is implicitly true of New Zealand snapper stocks, and this is essentially why we have incorporated the “home fidelity” movement model (as we call it) in the simulator. We are currently exploring the performance of two estimators: the Petersen estimator, for which movement is estimated as a proportional shift in absolute numbers between times t and + 1; a home fidelity estimator for which the movement is as described above. Both estimators have been implemented in AD Model Builder. In addition to movement parameters, both estimators also derive a set of population parameters and a set of growth parameters.

FOCUS QUESTIONS

The blue shark tagging data in the Atlantic presented by Alexandre Aires-Da-Silva illustrate the need for well-designed tagging experiments. Despite the availability of decades of data for this population, analysis of the data is problematic and the results provide little management advice. Information on reporting rates and wider spatial distribution of recaptures and recoveries would have greatly increased the usefulness of the data.

What analyses are essential for designing experiments?

Simulation analysis is a flexible method to evaluate the design of a tagging experiment. However, simulation analysis can quickly get out of hand due to the huge number of combinations that can be evaluated. Therefore, simulation studies should be used to develop general principles or constructed to evaluate the main components of a particular experiment. For example, simulation studies could be used to determine the benefits of a multi-year tagging program versus a single-year tagging program. The simulation studies could be used to determine the best allocation of funds among the different components of the tagging program (e.g. releases versus recaptures). Results from previous tagging experiments could be used to develop the simulator. The simulation analysis could be extended into a full management strategy evaluation (see the previous IATTC workshop on management strategies (http://www.iattc.org/PDFFiles2/Management-strategies-WS-Oct-06-ReportENG.pdf), which evaluates the tagging program in the context of the data collected, estimator used to analyze the data, and management action based on the results. Simulation analysis should also consider which auxiliary information should be collected (e.g. reporting rates, tag loss, etc.) and what are the management quantities of interest. Simulation analysis should examine both bias and uncertainty in the quantities of interest. The simulation analysis should be carried out over alternative states of nature to determine the sensitivity of the experimental design.

Are there guidelines for designing tagging experiments?

Polacheck *et al.* (2002) provide guidelines for designing tagging studies. Also see the papers mentioned at the start of this section.

Just as much effort should be put into recaptures (*e.g.* estimating reporting rates) as goes into releases.

Some factors that should be considered when designing a tagging experiment include:

- Release and recovery sample sizes;
- Spatial coverage;
- Tag types: conventional, electronic, passive integrated transponder;
- Capture methods, pole and line, handline, recreational gear, longline, purse seine;
- Recovery methods, including advertising, lotteries, use of recovery agents;
- Tag-seeding experiments;
- Tagging mortality experiments;
- Double tagging.

What are some of the practicalities that need to be considered when designing a tagging experiment?

Experimental design can easily be studied using theory or simulation analysis. Unfortunately, there are many problems that arise in implementing the tagging experiment. These types of problems need to be incorporated into the analysis of the tagging experimental design. Some of these are described below.

Due to the nature of the method used to release tagged fish, it may not be possible to release the tagged fish in proportion to the spatial and temporal fish densities. This may mean that a large proportion of the fish is tagged in the same area. Will these fish mix completely with the population, how long will it take, and are the fates of the fish independent? Do more fish need to be released to compensate for the fish caught during the mixing period?

Limited vessel or staff availability may limit tagging to certain areas and a sequential tagging program. Perhaps tagging over a period of years will be required to cover all areas. Would it be better to release fish in all areas at the same time using multiple vessels?

If fish are tagged at fish-aggregating devices (FADs), should they be enticed away from the FADs so that they are not all caught shortly after their release by vessels fishing at the FADs?

Due to unforeseen practical problems, it may be necessary to refine the tagging program as it is being carried out. This may be due to problems with port access, availability of bait, and which species and size of fish are available in the spatio-temporal stratum in which tagging is being conducted.

How should recreational fishery based tagging programs be designed?

Many studies have shown a large effect of the tagger, which is particularly a problem with recreational-based tagging programs that rely on numerous taggers, many of whom have had little training. There may be a large amount of variability in tagging-related mortality and tag loss. Modeling tagging-related mortality by tagger as a random effect may be an option to deal with the variability. Using the first recapture as the initial marking event may deal with variability in tag loss and tag-related mortality.

Reporting rates may also vary substantially among areas and years. Brownie-type models deal with the variability in reporting rates over time.

Recreational tagging programs should include substantial training to the recreational fishermen to ensure adequate survival of the fish. This requires training on bringing the fish to the boat without exhausting it, attaching the tags to the fish, and releasing the fish. It might be best to restrict the tagging program to major recreational participants who have had substantial training, rather than distributing tags to anyone who asks for them.

Double tagging should be a standard practice for recreational-based tagging programs.

Due to the number of issues involved with recreational programs, the results may be used only qualitatively to generate hypotheses or possibly reject some hypotheses.

Other issues

It is important that the objectives of the tagging program be clearly defined. This enables the tagging experiment to be evaluated in the context of the objectives.

Previous tagging studies should be analyzed to provide advice for future tagging studies. This includes examining the practical problems in implementing the tagging study.

It is important to get estimates of mortalities due to handling and tagging, rates of shedding of tags, and reporting rates, as otherwise much of the usefulness of the data may be lost.

Agents are often stationed at important locations at which fish are landed. These agents measure fish, make abstracts of the logbooks of fishing vessels, collect data on transshipments of fish, receive tags and information about their recapture, and pay rewards for the tagged fish.. The use of agents at these locations increases the reporting rates for the tags and the accuracy of the data on recapture. The agents sometimes collect gonads, otoliths or other hard parts, *etc*., from the tagged fish.

Observers on fishing vessels can recover tags at sea, which ensures that the recovery data are accurate. (However, large quantities of fish are brought aboard purse-seine vessels at the same time, so the observers may not be able to examine all the fish for the presence of tags when they are brought aboard the vessel.

One consideration of the tagging program, with respect to both recaptures and recoveries, is whether it should be conducted in a single year or carried out over multiple years. Due to the infrastructure needed to be developed to implement the tagging program, the costs of additional years may be less than those of the first year. Analysis should be carried out to determine the value of the additional information obtained from a multi-year study.

Consideration should be given to double-tagging fish with both acoustic and archival tags so that the appropriateness of acoustic receiving stations can be evaluated if a fish is recovered.

- Some known sources of bias in tagging analyses that should be considered include:
- Tag rate heterogeneity by length (tagging gear selectivity);
- Proportion of the population that cannot be tagged;
- Trap shyness or happiness;
- Spatial heterogeneity of mark rate (non-mixing);
- Movement;
- Initial mortality;
- Growth of fish between release and recapture (recruitment to catchable size);
- Reporting rate;
- Tag loss.

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Appendix A.

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