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UPDATE OF RECENT DEVELOPMENTS IN MULTIFAN-CL AND RELATED SOFTWARE FOR STOCK ASSESSMENT

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Nick Davies[2], Dave Fournier[1], John Hampton[2], Pierre Kleiber[2], Simon Hoyle[3], Fabrice Bouyé[2], , and Shelton Harley[2]

[1] Otter Research Ltd
[2] Pacific Islands Fisheries Science Center, National Marine Fisheries Service, Honolulu, Hawaii, USA.
[3] Oceanic Fisheries Programme, Secretariat of the Pacific Community, Noumea, New Caledonia

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Introduction

MULTIFAN-CL (MFCL) is a statistical, age-structured, length-based model routinely used for stock assessments of tuna and other pelagic species. The model was originally developed by Dave Fournier of Otter Research Ltd for application to south Pacific albacore tuna (Fournier *et al.* 1998).

MFCL is typically fitted to total catch, catch rate, size-frequency and tagging data stratified by fishery, region and time period. Recent tropical tuna assessments (e.g. Davies *et al.* 2011; Hoyle *et al.* 2011, and Langley et al. 2011) encompass a time period of 1952 or 1972 to 2010 in quarterly time steps, and model multiple separate fisheries occurring in 3 to 6 spatial regions. The main parameters estimated by the model include initial numbers-at-age in each region (usually constrained by an equilibrium age-structure assumption), the number in age class 1 for each quarter in each region (the recruitment), growth parameters, natural mortality-at-age (if estimated), selectivity-at-age by fishery (constrained by smoothing penalties or splines), catch (unless using the catch-conditioned catch equation), effort deviations (random variations in the effort-fishing mortality relationship) for each fishery, initial catchability and catchability deviations (cumulative changes in catchability with time) for each fishery (if estimated). Parameters are estimated by fitting to a composite likelihood comprised of the fits to the data and penalized likelihood distributions for various parameters.

Each year the MFCL development team works to improve the model to accommodate changes in understanding of the fishery, to fix software errors, and to improve model features and usability. This document records changes made since August 2009 to the model and other components of the MFCL project, and updates the report for the previous period, 2009-10, (Davies *et al.* 2010).

Development overview

Team

The senior developer of MFCL is Dave Fournier, of Otter Software in Canada. Occasional programming is carried out by Pierre Kleiber (NMFS Hawaii), Simon D Hoyle, Nick Davies, and John Hampton (all SPC, New Caledonia). Other tasks include testing and debugging (ND, SDH, PK, JH, and Fabrice Bouye (SPC)); documentation (PK, SDH); and planning and coordination (SDH, JH, Shelton J Harley). Related project software are developed or managed by FB (MFCL Viewer, Condor, Gforge), PK (R scripts), and SDH (R4MFCL, Condor).

Calendar

September – December: Planning and ongoing code development
January: MFCL development meeting, 1-2 weeks

February – March: Testing and finalizing production version

April-July: Stock assessments

MFCL collaboration and versioning

The project management website based on the open source GForge software was established in 2008-09 has been maintained and provides the nucleus for source code management and versioning. The repository for MFCL source code development is held on the website and uses the open source software SVN (http://tortoisesvn.net/). Code developments are consecutively committed to the repository while tracing the different versions chronologically. The repository and overall development are coordinated via the GForge website http://gforge2.spc.int/, which is administered by Fabrice Bouye fabriceb@spc.int.

Problems with MFCL operation or compilation have been reported to the project management website so as to maintain a list of desired enhancements, and to allocate tasks among the project team. Some of the tasks identified during the previous reporting period (2008-09) have been addressed in the current period in the way of model developments. A main trunk exists for the MFCL source code, and a development branch has been created to hold these recent developments to the source currently being tested. A formal testing procedure has been designed before source code is committed from the development branch to the trunk, and a manual has been drafted for standardizing the source code compilation procedure, and posting of executables.

A version of the source code for ADMB (http://admb-project.org/) has been added to the project management website in a separate repository. Minor modifications were required to the ADMB source (currently held in a development branch) to facilitate the recent MFCL developments.

New website

Since problems were experienced with the existing MFCL website, on 23 June 2011, a new site was created using the Joomla software platform. This appears to be operating well with no failed downloads to date.

Postings to website

There have been two postings of MFCL updates to the website since August 2010.

Version 1.1.1.0 - 23 June 2011

Coinciding with the website upgrade in June 2011, MFCL executables were posted that incorporated the following list of changes (these are expanded upon later):

- integrated source code for Linux and Windows compilations.
- The number of estimable parameters was increased from 7000 to 8000.
- Flexible time period over which the Beverton-Holt stock-recruitment relationship (SRR) is calculated.
- Projection catch equations were modified be robust to exceptional mortality levels.
- The variance calculation of dependent variables has been fixed to deal with a problem for particular variables not being included.
- An updated user's guide that includes the developments from May 2010 to June 2011.

Version 1.1.2.0 - 9 August 2011

A list of the subsequent changes made to version 1.1.1.0 and that are reported here includes:

- Various recruitment assumptions for deterministic projections
- Streamlined input of tagging parameters and additional output for fit diagnostics
- Further work on catch equations for population projections
- A revised penalty calculation for tag release group-specific reporting rates
- A revised tagging likelihood function to be robust to population projections
- A revised Newton-Raphson calculation for tagged fish that accounts for a minimum age of tagged fish > 1.

Tool development

R4MFCL

The R scripts for working with MFCL, developed and released on the internet (http://code.google.com/p/r4mfcl/) have been updated to adapt to the recent MFCL file formats. These scripts are used to manipulate the input files, so that runs can be automated. Other scripts can be used to read in the output files, analyze the results, and generate plots and tables. See Hoyle *et al.* (2009) for a list of these R scripts. Further development was undertaken as part of the 2011 stock assessments that consolidated new features to the utilities package. One such improvement was R scripts that streamline the creation of a model run folder and submits the job to Condor with flexibility to the host platform operating system and architecture.

MULTIFAN-CL Viewer

A task has been noted to update the MFCL viewer with new diagnostic plots associated with the new feature for tag release group-specific recapture reporting rates (see below).

Condor parallel processing facility

The Condor (www.condor.wisc.edu) facility has been used routinely for managing multiple MFCL model runs on a grid currently numbering over 100 processors; being windows or linux platforms, and either 32- or 64-bit architecture. This grid enables intensive model runs for stock assessments, structural sensitivity analyses, and management strategy evaluation. The Condor version was recently updated.

MFCL user's guide

A revision has been completed that documents the developments in version 1.1.1.0 and this has been posted on the website. An update is in progress that documents the developments in version 1.1.2.0 and which are described below.

New MFCL features

Stochastic population projections

A significant development to MFCL in version 1.1.1.0 has been the facility to undertake model simulation runs that include projections into the future with stochastic recruitments. Additional features are currently being developed to include stochasticity in the population numbers-at-age in the first year of the projection period, and in the effort deviates over the projection period.

Rationale

The concept of the risk associated with a biological reference point, e.g. B_{MSY}, is increasingly being recognised by fisheries managers as having utility since it takes account of model uncertainty and natural variability when interpreting population model estimates. A risk-based limit reference point may therefore be defined, for example, as: a 10% probability of the stock size being less than that which supports B_{MSY}. Risk analysis may be used to evaluate the performance on alternative management strategies against the threshold 10% probability level. Typically, this analysis would incorporate the main sources of uncertainty, such as statistical uncertainty, model structural assumptions, and natural variability, such as recruitment variation. Incorporating this stochasticity in model projections creates variability in future population states from which estimates of risk relative to a particular reference point can be calculated.

Stochasticity in future recruitments is a dominant source of natural variability in fish populations and the functionality for this feature was included in version 1.1.1.0. This formulation of future population states is founded upon a fixed population state in the first year of the projections. Also, constant (zero) effort deviations are assumed. Variance estimates of these dependent variables, (numbers-at-age and effort deviations), are calculated as part of the Hessian calculations in MFCL, and may be used for generating stochastic quantities for simulations.

Methods

An excerpt of the MFCL user's guide describes the method for setting up input files for undertaking MFCL projections and incorporating stochasticity in: recruitments, numbers-at-age in the first year, and effort deviations for simulation projections, (Appendix A).

MFCL currently incorporates uncertainty in the initial population state, future recruitment and other model parameters into the projection by sampling the parameters from a multi-variate probability distribution (i.e. the variance-covariance matrix from the likelihood-based analysis). In MFCL statistical uncertainty for model parameters is calculated by employing the usual second order approximation to the mode of the posterior distribution (Fournier *et al.* 1998), and confidence intervals for derived variables are calculated by the inverse Hessian – Delta method. In this way, the distribution of estimated historical recruitments, numbers-at-age in the final year of the model + 1, and the fishery effort deviates.

During the January 2011 MFCL workshop, it was confirmed the stochastic projection functionality operates according to the formulations, and includes the three sources of stochasticity.

Paired Visual Studio 2010 projects in linux and windows were used for comparing model variables and making source code developments. Source code locations are described for the functions that generated stochasticity in each of the three variables.

1.   Recruitments

Random selection of future recruitments from a parametric distribution is undertaken in gradcforproj.cpp (ln 281) that writes a file simulated_numbers_at_age for the specified number of simulations. Parest_flags 232, 233 and 238 are set for the output of random recruitments.

2.   Numbers at age in 1st year of projections

Random selection of the population state numbers-at-age in the first year of the projection period is taken from a parametric distribution (choleski decomposition) which is undertaken in gradcforproj.cpp (ln 269). Parest_flag 237 is set for generating of random numbers at age.

3.   Fishery effort deviations

Random selection of fishery effort deviations for each year of the projection period is undertaken in veff_dev.cpp (ln 23) where deviates are sampled from a parametric distribution with a user-supplied standard deviation. Parest_flag 234 turns on the random effort devs, flag 235 specifies the standard deviation, and flag 236 provides an iseed for the random deviate (if desired).

Testing

The operation of the new feature for stochastic recruitments was tested using a "cut-down" bigeye tuna population model (years 1990-2008) for which the distributions of historical and future log-recruitments were compared and the results presented last year. This functionality operates well, with random recruitments generated for each specific region. It has been applied in an evaluation of alternative biological reference point for bigeye and yellowfin tuna in the Western and Central Pacific Ocean (Harley and Davies 2011).

The generation of stochasticity in all three variables is functioning, and an example of 20 simulation projection biomass trajectories including random recruitments and effort deviations is shown in Figure 1.

The generation of stochastic numbers-at-age in the first projection year was tested and, although functioning as formulated, produced exceptionally large variance for the example model being tested. This prompted closer examination of the variances for these variables, some of which were extremely high (Figure 2). A correction was made in the source code for log-normal bias in the distribution from which random deviates were generated but the large variance in stochastic variables persisted. The problem was attributed to the characteristic of the example model being over-parameterized, causing in large variance estimates from the Hessian calculation. The performance of this was tested using the current 2-point approximation with a 4-point Hessian approximation, and the current method was found to be satisfactory with the projection biomass trajectories essentially identical, minor differences in the projected numbers at age in each year and the covariance matrices being identical. We concluded there are differences in the 2-point and 4-point Hessians, but these translate to relatively small differences in the distributions for numbers-at-age.

To diagnose this problem further a singular value decomposition (SVD) was added to the source code, using the Lapack library to assist with understanding situations where the

Hessian is singular. Negative values in the SVD diagonal indicate variables that may be a problem when generating random deviates for the stochastic simulations. This development is potentially powerful for diagnosing over-parameterised models or in model selection. It is still being tested and if successful will be added to the trunk version of MFCL. Further testing of stochastic numbers-at-age is in progress using an alternative example test model.
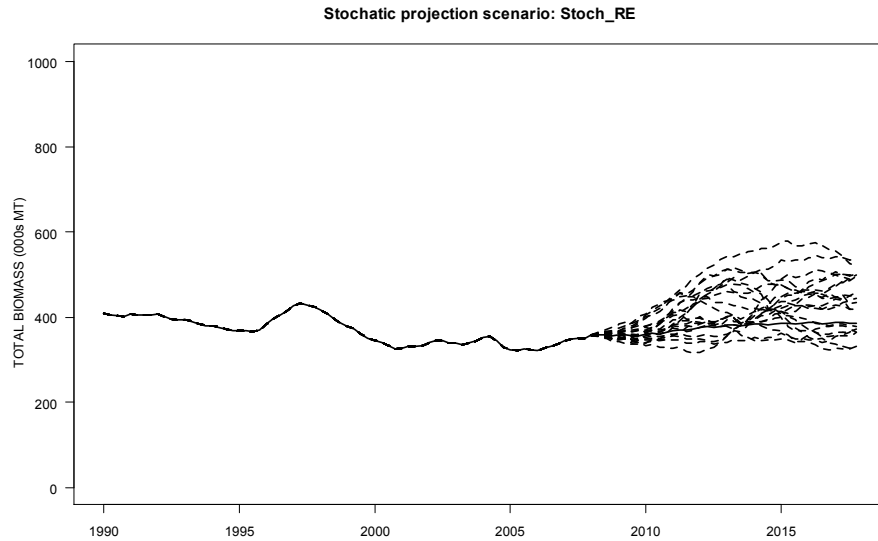
Stochatic projection scenario: Stoch_RE

Figure 1. Biomass trajectories for 20 simulation projections of the cut-down bigeye model with stochasticity in future recruitments and effort deviations.
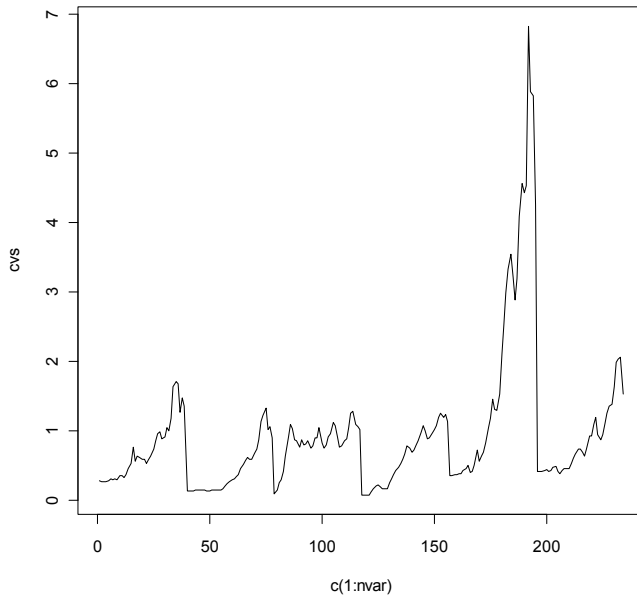

Figure 2. Coefficients of variation on numbers-at-age for regions 1 to 6 (with 40 age classes in each, making 240 variables).

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Functionality for multiple species/stocks/sexes

A development has been in progress since July 2010 to increase the dimensionality of MFCL to accommodate multiple species, stocks and sexes. This development is still in progress.

Rationale

This is a substantial development to the model since it changes the fundamental structure of the model by expanding the dimensions at the regional level. It has substantial benefits for modeling Pacific tuna and billfish populations which often have sex-specific growth rates or regional differences in growth (Nicol et al. 2011). Parameters specific to sex, species, or stocks may be accommodate and, if required, shared among selected dimensions. This may reduce the number of parameters required in fitting models for species that share fisheries having the same characteristics.

Methods

Test model data sets have been created for bigeye and yellowfin for either 5 or 6 regions, using a reduced model time period (1990-2009). The input "frq" file format has been changed to integrate multiple sex/spp/stock catch, effort and size composition data within one file. Source code has been adapted for the increased dimensions and – preliminary fits have been completed.

A large part of the January 2011 workshop was dedicated to this development, creating separate growth and length-weight functions. These biological processes are fundamental to many model calculations and an account of the von Bertalanffy growth coefficients in the source code was done. The "ini" file inputs have been modified to include inputs of growth and length-weight parameters for *n* species. Using the multi-species input data, these coefficients were traced and modified in respect of the particular region/species, for the mean length and selectivity-at-length calculations.

Testing

Testing of the components is ongoing as part of the development, with a comprehensive examination of all model quantities occurring upon completion.

Flexibility in time period for Beverton-Holt stock-recruitment relationship calculation

The time period over which the Beverton-Holt stock-recruitment relationship (SRR) is calculated has been made flexible and user-defined. Earlier versions assume the entire model calculation period in deriving the SRR used for equilibrium yield estimation. This is now the default option and flags may be set to define a part of the model period to be used for the SRR. This feature enables users to explore the effects of selecting a period considered to be more reliable or representative.

Rationale

Typically recruitment is regarded as a random variable estimated relative to an average level. Annual deviates from the average are normally estimated from fitting the model to data

containing information on relative cohort strengths, such as catch-at-age or catch-at-age. It is often assumed these are deviates about the SRR, and they may be expected to be randomly and normally distributed. However, sometimes the estimated deviates exhibit a trend which may be regarded as implausible, or are poor estimates over part of the time period. In such cases, one may consider restricting the recruitments to be used for deriving equilibrium yield estimates to be taken from a subset of the time period, especially if this subset has reliable information or is more representative. On this basis, such a feature was added to MFCL.

Methods

Yield estimates based upon the SRR are now calculated according to two options. Assuming average recruitment is determined from the SRR calculated over the full model analysis period is now the default option (age flag 199 = 0). The alternative (age flag 199 > 0) calculates the SRR using recruitments and biomass over a specified historical period, defined by age flags 199 and 200. The operation of these flags tags place in the Beverton-Holt calculations (`newbh.cpp`) and the user's selection for the flags has been explained in the updated manual.

Testing

Following testing of this feature it was applied in the 2011 bigeye stock assessments. A simple comparison of the equilibrium yield plots for two options is shown in Figure 3. One option used a subset of the historical period: 1989 to 2009. This clearly shows the impact of selecting the recent period characterized by high recruitments which consequently increases the average level for the SRR, and hence, the equilibrium yield estimates (Table 1). In this example, the ratio of average recruitments in the second half of the model period to the first half was 1.72. The effect of using the recent high recruitments for deriving the SRR is to scale up the equilibrium yield estimates proportionally, such that the virgin unfished biomass is 68% higher.

Table 1. Equilibrium yield estimates derived from model options using the SRR derived over the complete model time period (SRR_full) and over part of the time period (SRR_t1_t2).

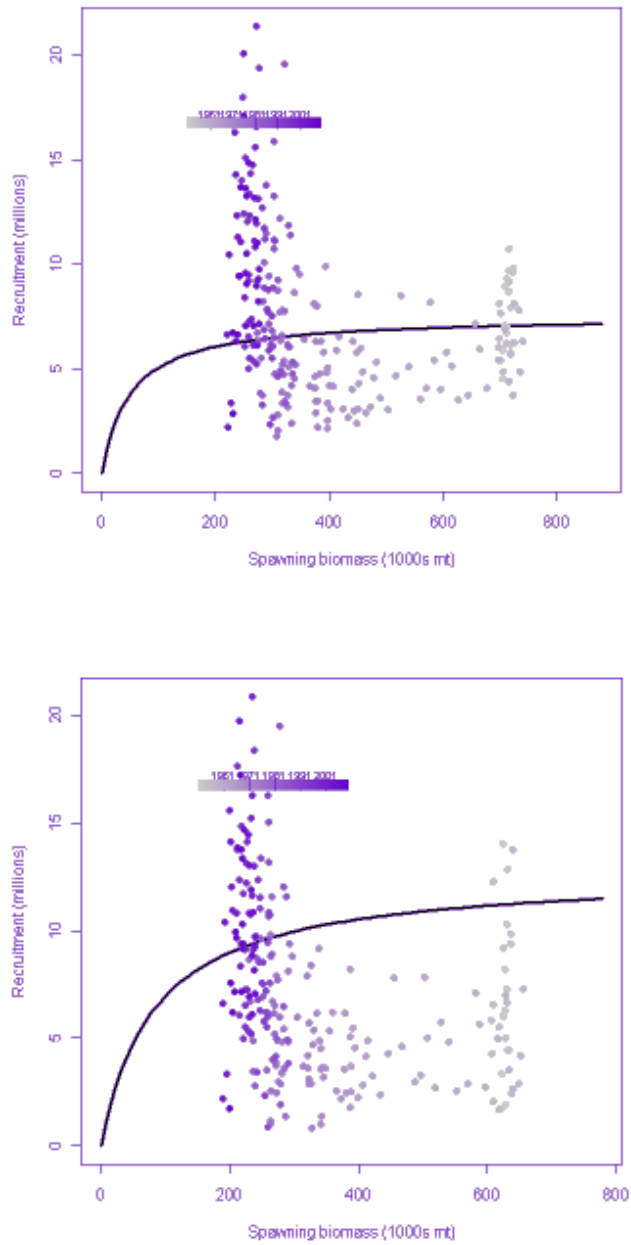| Equilibrium yield estimate	SRR_full	SRR_t1_t2
MSY	76,760	131,400
F_{MSY}	0.04	0.04
B0	1,432,000	2,405,000
B_{MSY}	498,500	840,900
B_{MSY}/B_0	0.35	0.35
SB_0	739,900	1,243,000
SB_{MSY}	214,800	361,000
SB_{MSY}/SB_0	0.29	0.29

Figure 3. Beverton-Holt stock-recruitment relationships derived using all recruitments over the model time period (top) or from the most recent period characterized by higher average recruitment (bottom).

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Recruitment options for deterministic projections

Rationale

Typically population projection scenarios explore a range of assumptions regarding future population states, including alternative recruitment regimes. It is useful therefore to make flexible the basis for generating future recruitments. This feature was added to MFCL and was used in undertaking projections for evaluating options for conservation and management measures.

Methods

The source code was modified to make use of age_flag settings that specify the annual recruitments used for deterministic projections which select from the following three options:

1. Use SRR to define projected recruitment, distributed among regions according to the average for the full model estimation period. Future recruitments are calculated from the SRR according to future spawning biomass levels. **SRR_full_period**. Flag settings: af(190) = 0, af(191) = 0, af(195) = 0

2. Use average absolute annual recruitments from each region over a specified historical period, to be assumed constant for regional recruitments in the projection period. **av_recr_T1:T2.** T1 = last_real_year-aflag(190)+1, to T2=last_real_year-aflag(191). Flag settings: af(190) = start period, af(191) = end period, af(195) = 0

3. Use SRR to define the total (sum across regions) projected recruitment, distributed among regions according to the average for a defined period, T1 = last_real_year-aflag(190)+1, to T2=last_real_year-aflag(191); **SRR_T1:T2**. Flag settings: af(190) = start period, af(191) = end period, af(195) = 1

Age_flags(190, 191 and 195) are user-defined for specifying among these options. For the option **av_recr_T1:T2**

Testing

Using the bigeye model, each projection recruitment option was tested and compared.

The test data set contained 272 time periods to the end of the projection period. In the code last_real_year is the final year of the model analysis period - not including the projections time periods, therefore, in this example 1952.125 to 2009.875 = 232 time periods. For the test, a partial period for deriving projection average recruitment was specified for a recruitment period from 1981 to 2009, and so age_flag(190) = 116, and age_flag(191) = 0.

The command line switches for the six options (3 projection options, 2 yield calculation options in each) investigated were:

1. Option 1 **SRR_full_period** - switch 3 1 1 1 -999 55 0 1 145 0
2. Option 2 **av_recr_T1:T2** - switch 6 1 1 1 -999 55 0 1 145 0 2 190 116 2 191 0 2 195 0
3. Option 3 **SRR_T1:T2** - switch 6 1 1 1 -999 55 0 1 145 0 2 190 116 2 191 0 2 195 1

The effect of the alternative recruitment assumptions (Figure 4) is clearly apparent on the projection total biomass trajectories (Figure 5).
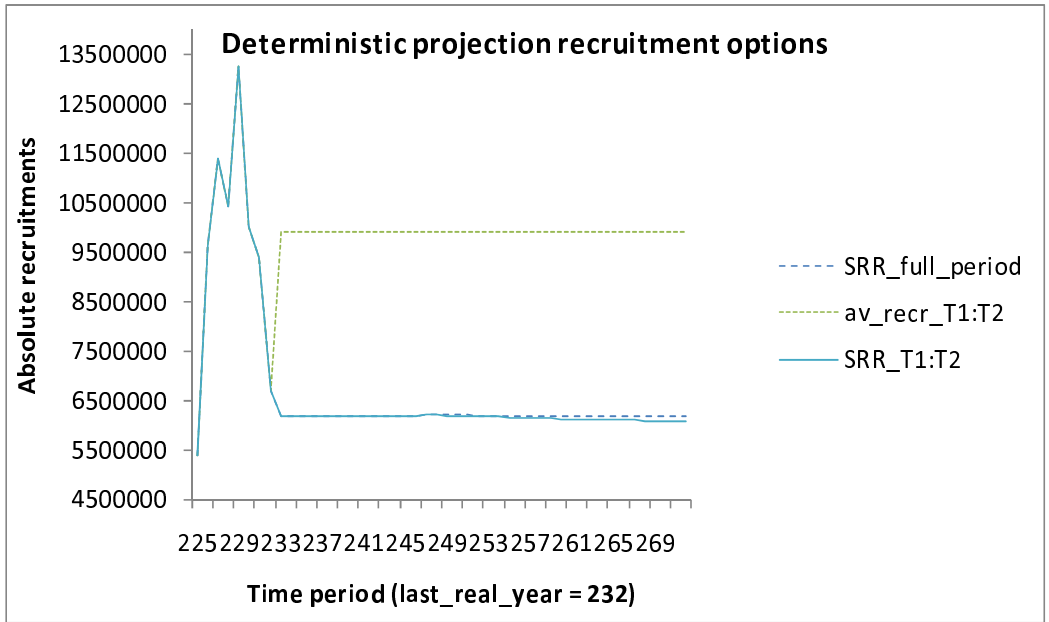
Figure 4. Comparison of projection recruitments assumed under the three options possible with the new feature in MFCL using an example bigeye model.
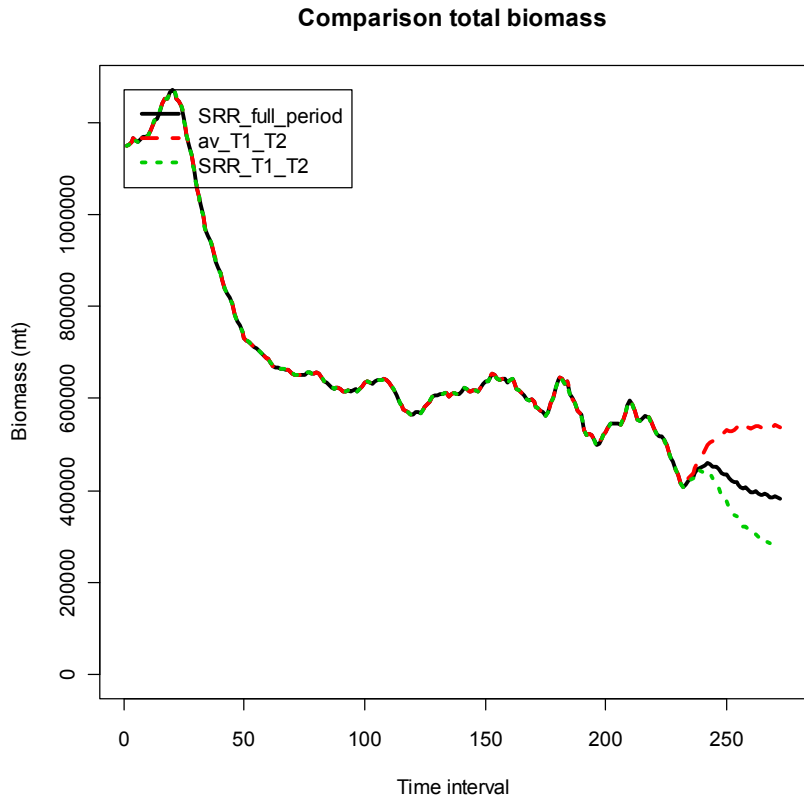

Figure 5. Comparison of projection total biomass assumed under the three options possible with the new feature in MFCL using an example bigeye model.

Streamlined input of tagging parameters and additional output

Rationale

The feature for estimating recapture rates of tagged fish relative to both release group and fishery group was added to MFCL in 2010. However, the procedure for controlling the inputs of the associated parameters was awkward. Since these inputs were required routinely for all the 2011 assessments, it was best to improve the input procedure and also the reporting of the model fits with these data.

Methods

Recapture reporting rates with the added subscripted dimension of tag release group entails input of the following additional parameters:

> # tag fish rep
>
> # tag fish rep group flags
>
> # tag_fish_rep active flags
>
> # tag_fish_rep target
>
> # tag_fish_rep penalty

The tag_fish_rep target and tag_fish_rep penalty parameters specify the mean and variance of the priors associated with the tag release group-specific reporting rates being estimated.

The procedure for input of these parameters has been integrated into the `-makepar` run and the parameters are now input via the `ini` file. After the statement `# number of age classes` section at the top of the `ini` file, the above five sections of tag reporting rate parameters are input.

In addition to this modification, the assumed starting value for the SRR steepness value has been added to the `ini` file. After the statement `# Length-weight parameters` section near the bottom of the `ini` file, the following has been added:

> `# sv(29)`
>
> `0.75`

where the value 0.75 is simply an example value that is supplied following the section title.

An additional output file (`temporary_tag_report`) has been generated containing tag recaptures (observed and predicted) subscripted by: release group, recapture region, fishery, year, month, and age. This output permits detailed diagnosis of model fit in respect of the strata. For example, one may wish to consider the observed and expected rates of tag attrition.

In formatting this output file, the year needs to be matched to the year of the tag-release group and the columns define the age-classes of the recaptured fish. For example, the skipjack model assumes 16 age classes and in the first year and month (time period e.g. year 7 month 2) of the release group there are 16 columns in the predicted and observed recaptures. This reduces to 15 in the following time period (e.g. year 7 month 5), and so on. In this manner one can assign ages to the recaptured fish in each time period of recapture.

R script has been written that reads in the additional output file and has been added to the R4MFCL library package. Examples of a diagnostic possible using these data is presented in Figure 6. This can be illustrate in respect of individual release group, recapture fishery, recapture region, or age class.
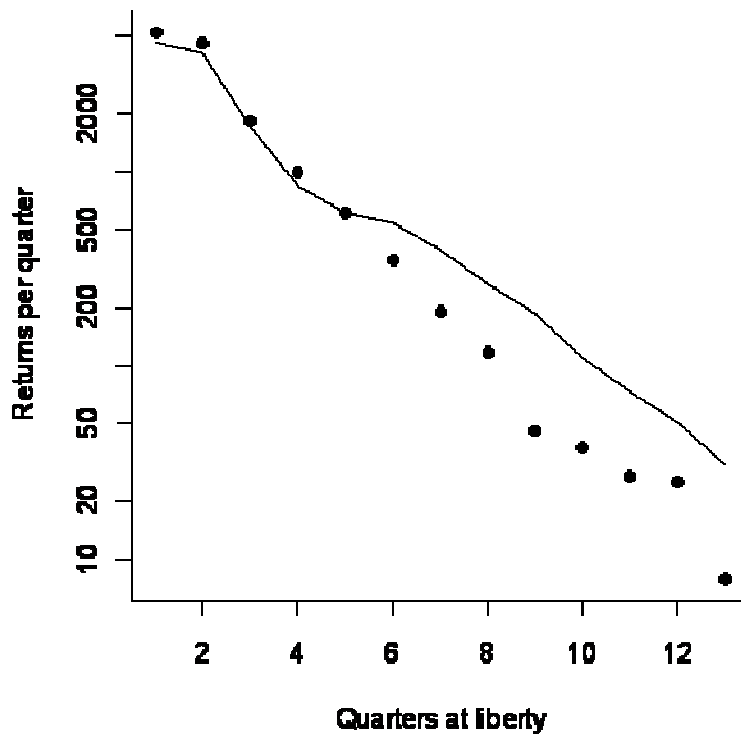
Figure 6. Number of observed (points) and predicted (line) tag returns by periods at liberty (quarters).

Testing

Since these alterations had no affect on model formulations in MFCL, no detailed testing was required besides checking the integrity of the input versus the output.

Tagging recapture reporting rates

Rationale

The feature for estimating recapture rates of tagged fish relative to both release group and fishery group was added to MFCL in 2010. Further testing was required in advance of the 2011 assessments to ensure the parameterization employed in the assessments was compatible with the functionality in MFCL.

Testing

Tests entailed comparisons of variations of two models, each using one of the two reporting rates (RRs) structures:

> Model1: fishery-specific RRs
>
> Model2: fishery x release group-specific RRs

For Model 2 the RRs were set up to be identical to that of Model 1, i.e., every row of the RR matrix was identical and had the same fishery grouping, in other words, every release-group specific reporting rate had the same fishery grouping as Model 1, and therefore the same parameters. This was achieved by setting each row of the Model 2 tagging parameters, specific to release groups, identical to those input to Model 1. It would be expected that these two models would converge to the same solution.

As expected single evaluations using the same start parameters produces almost identical results and with only slightly different objective function values

> Model1: 1037600.560695728400

> Model2: 1037600.559910761300

The tag RR penalty values and tag likelihood obtained from this single model evaluation were compared and found to be identical and therefore the slight difference in total objective function values was attributable to another likelihood term besides the RRs.

Other enhancements and bug fixes

A listing of the current and proposed tasks in the project is presented in Table 2. The main developments against tasks ##, ## and ## completed to date have been discussed above, and other lesser enhancements and fixes are briefly mentioned below.

Increased maximum number of estimable parameters

MFCL is being applied to increasingly larger and more complex modeling problems requiring higher numbers of parameters. For example the 2011 albacore stock assessment model entailed the estimation of 7084 parameters. For the version 1.1.2.0 the maximum number of estimable parameters was increased to 8000.

Source code management

While making changes to the source code for various developments in 2010, the code in Linux and Windows diverged due to the requirements of the gcc and VS2010 compilers. These differences were subsequently resolved and the source code for compiling in Linux and Windows were merged, thus restoring the trunk version on the repository.

Fixes

A number of fixes were made to formulations in MFCL in 2011.

Deterministic projections under zero fishing mortality

An error occurred in deterministic projections using average recruitments defined over a specified period when fishing mortality is set to zero (fish_flag(55)). In this case, projection recruitments became zero.

New code was inserted into `lesmatrix.cpp` (ln 20) that identifies the fishing or no_fishing scenarios when deriving `average_recruitment_for_projections` and uses `N_q0` for deriving `average_recruitment_for_projections` when af179q0==1.

This was subsequently tested by comparison with projection with non-zero fishing mortalities that ensured integrity.

Large catch deviates in projections with constant catch strategy

A catch calculation error occurred in projections having large constant catches that exhibited large positive catch deviates, i.e. the model predicted catches substantially under-estimated those specified for the projection period. It was diagnosed that this was due to the projection catch equations dealing with extra-ordinary circumstances of low population numbers and high fishing mortality (due to high specified constant catches) by assigning an asymptotic fishing mortality. The equations were made more robust by modifying rmax in relation to age_flag(116) to be set at a higher level permitting higher projection fishing mortalities. This flag will be set at a lower value for estimation model runs but can be relaxed for exploring extreme projection scenarios.

Tag likelihood term made robust to projections, and robust to a minimum age class > 1

During a single model evaluation for a projection, the objective function term for the tagging data altered. It was tested with both a catch-based and an effort based projection and the same problem occurred. This was corrected by setting the tagging likelihood calculation to exclude time periods within the projection time period when undertaking model projections.

Another correction to the tag likelihood term was required for dealing with tagged fish populations having a minimum age that exceeds 1.

Penalty calculation for tagging RRs by release group and fishery

A correction was made to likelihood penalty calculations to modify the summation of penalties over RRs specific to both release groups and fishery groups. This calculation was made over only unique recapture rate estimates so that only one penalty is accumulated per independent recapture rate parameter.

Newton-Raphson calculation of catch and fishing mortality for tagged fish

As noted above for the tag likelihood term, instances of release groups of tagged fish having a minimum age exceeding 1 was found to cause errors in the Newton-Raphson calculation of fishing mortalities for the tagged population. The formulation was corrected in the source code.

Application of new features

A number of the new features described above have been used as part of the 2011 tuna assessments. The general nature of the application is described and the significance of its utility for the management of tuna outlined.

Flexibility in time period for Beverton-Holt stock-recruitment relationship calculation

Equilibrium yield estimates calculated using a SRR derived from all or part of the estimated recruitments has been applied formally in the 2011 bigeye stock assessment (Davies et al. 2011). The interpretation of the model results for this assessment is dominated by an increasing trend in recruitments, such that the ratio of average recruitments for the second and first halves of the time period is 1.72. Uncertainty exists as to what is causing this pattern, and consequently what period of the recruitment time series is most representative of the underlying productivity of the current population. The reference case model reported equilibrium yield estimates for *MSY*-based biological reference points using the SRR derived over the full model time period, i.e. including all the recruitment estimates. A one-off sensitivity model that used only the recent time period (1989 to 2009) for the SRR was also reported with substantially higher stock productivity and reference point estimates (Table 1 and Figure 3). This result has significance for the decisions of fisheries managers regarding stock status since the one-off sensitivity results indicate a more pessimistic stock status, but a more optimistic prognosis.

Additional output for tagging diagnostics

The 2011 tuna stock assessments included the results of the large-scale PTTP tagging study for skipjack, yellowfin and bigeye undertaken since 2006. Sample sizes of tag releases and recaptures fitted in the models were substantially increased and potentially exerted large influence on the results. Therefore, it was necessary to carefully examine diagnostics of the fit to these tagging data for departures from the statistical assumptions made. The MFCL development in 2011 to report additional detail on observed and predicted recaptures was essential for this examination. An example of the type of diagnostics of the model fit to these data is presented in Figure 6, and the full set of diagnostics are presented in the assessments (Hoyle et al. 2011, Langley et al. 2011, Davies et al. 2011).

Recruitment options for deterministic projections

In 2008 the Western and Central Pacific Fisheries Commission formulated a comprehensive conservation and management measure (CMM) for bigeye and yellowfin entailing catch and effort reductions, as well as gear restrictions. The potential effects of this CMM for these species were evaluated using deterministic projections of the MFCL models developed for the 2011 stock assessments. For the bigeye projections, these evaluations considered alternative assumptions for future recruitments given the uncertainty over which periods of the historical recruitments were most representative of future productivity. Examples of these the effects of these alternative assumptions are presented in Figures 4 and 5, and the evaluations are reported by SPC-OFP (2011).

Stochastic projections

Harley and Davies (2011) present an evaluation of stock status of bigeye, skipjack and yellowfin tunas against potential limit reference points, which included using stochastic projections to investigate future stock status. This approach employed the recent MFCL development for stochastic recruitments in simulation projections. The results of this evaluation are presented for bigeye in Figure 7.

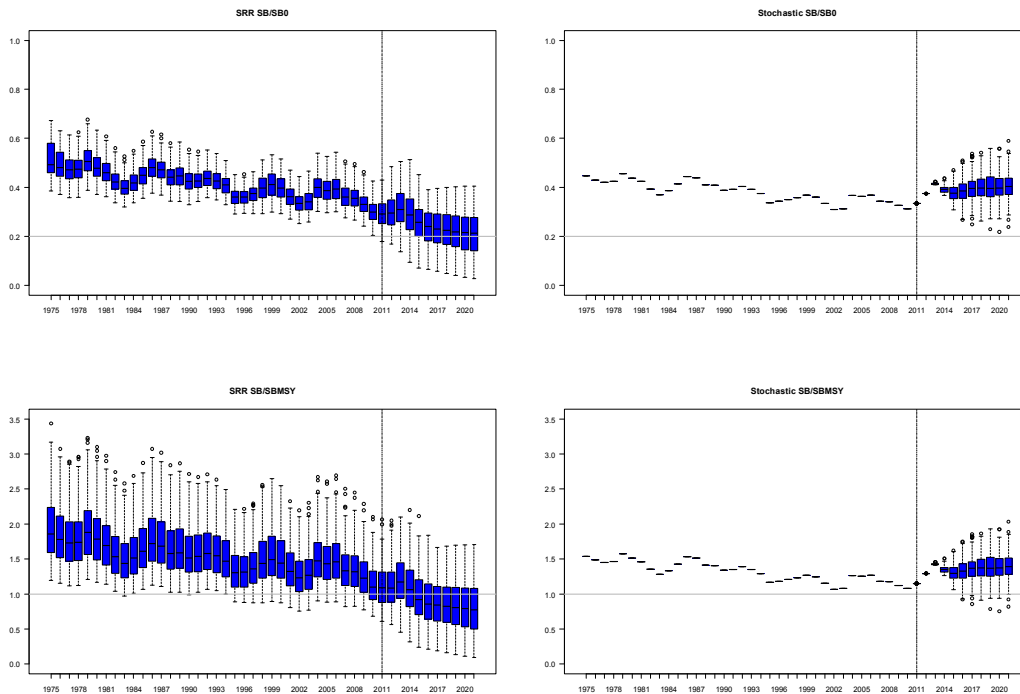**Figure 7.** Comparison of stock status in relation to spawning biomass reference points for bigeye tuna from the deterministic projections (left) and stochastic projections from the reference case model (right). (Taken from Harley and Davies 2011).

Future work

The future work plan for MFCL is outlined in Table 2. A summary list of the high priority tasks in progress or immediately forthcoming follows.

Enhancements:

- Dimension for multiple species/stocks/sex
- Allow region-specific environmental correlates of recruitment
- Scheme to estimate seasonal variability in selectivity coefficients
- time-series variation in selectivity correlated with a metric for gear configuration or other variable hypothesized to affect selectivity
- scheme to allow time-series variation in movement coefficients correlated with an environmental index
- Estimate biological parameters at length

Testing and Fixes:

- Development of testing framework, complete testing:
- Catch-conditioned model
- Length-based selectivities; constant over time
- Tag release group-specific reporting rates and likelihood functions
- Stochastic projections
- Statically linked runtime dll files for *.exe releases
- Check for log-normal bias in MSY calculation
- Tasks to rationalise runtime screen output
- Output of total likelihood components

MFCL utilities:

- running stochastic projections
- MFCL viewer to include tag release group-specific reporting rate diagnostics

Discussion

A number of changes have been made to MFCL during 2010-2011. Although fixes to the source code addressed problems with model formulations over this period, they did not substantially change the management implications of model results, such as stock status relative to reference points employed by the Commission, in any significant way.

The most significant development made during 2011 in terms of both developmental effort expended, and importance for tuna stock assessments, has been in modifying the underlying structure of MFCL by expanding the regional dimension to accommodate multiple species, stocks or sexes. This has entailed substantial coding modifications for dealing with additional inputs, expanded parameter structure, and modifying object structures at a basic level. Being part-way complete with this development, no meaningful illustration of the progress is possible, besides hypothetical multi-species biomass plots for populations still lacking biological parameters specific to each, and yet to be coded. Therefore, none have been provided in this report. Nonetheless, good progress has been made with multi-species population dynamics currently functional. This significance of this development for tuna stock is increasing, with recent important findings of heterogeneity in growth among regions and sexes (Nicol et al. 2011). This development currently has the highest priority for 2011-12.

Increasingly MFCL is being used to evaluate potential management strategies and so the projection functionality is a significant feature. Good progress was made with adding functionality to the structural projection assumptions (i.e. future recruitments), but in particular the statistical assumptions. The work completed in 2011 to generate stochastic variables for projections has been valuable, but further progress is needed to consolidate this with the variables: numbers-at-age in the first projection year and fishery effort deviates. The

statistical basis for the distributions from which random deviates are taken was tested. This has ensured the integrity of the current functionality, but it also identified a need to complement MFCL with the SVD diagnostic tool during 2011-12.

The developments to the input/output of tagging data and model estimates were timely in having immediate utility for the 2011 stock assessment models which estimated RRs specific to release groups and fishery groups and required detailed model fit diagnostics. Further work is needed to consolidate these developments in 2011-12, both in MFCL and with the support utilities such as R4MFCL and MULTIFAN-CL viewer.

As in previous years, considerable further work is required to comprehensively test all changes to the model, and to update all the changes to the manual. Although, substantial progress has been made, this remains a very important task for 2011-2012 to develop the model testing routine to facilitate more rapid testing of new executables. It is proposed to use the cut-down models prepared in 2010-11 for this purpose.

A necessary task is to update the support utilities for MFCL because increasingly model evaluations are made within the structure of a particular project. Examples include, structural uncertainty grid analysis, risk analysis, or evaluation of alternative management options (TUMAS). These tools have been developed somewhat independently of the MFCL project repository, and a repository structure for this code would assist in avoiding conflicts among their various applications, and to keep track of the developments needed to keep pace with new versions of MFCL.

Table 2: 2010-2011 work plan for MFCL, including work completed and suggested future enhancements.

GF ID	Item	Description / Comment	Priority (high=5)	Who	Comments
PROBLEMS					
12 & 27	Hessian problems	Mostly fixed, just problems with dependent variables due to (probably) variables changed type to doubles from dvars. Pierre working on this.	5	Pierre	**Complete**
Add	Projection problem	Possible problem with effort devs and catchability dev with zero effort devs in the projections. Large change in F. May require change to projection approach. Cause needs more analysis - initially try q devs at shorter time step.	5	Dave	**2**
NEW FEATURES					
40	Multi-species/stock/sex dimensionality	Adapt the structure to accommodate multiple species, stocks and sexes by expanding the dimensions at the regional level.	5	Dave	In progress - inputs and operation complete; parameterisation being developed.
19	Region-specific environmental recruitment correlates	Allowing for recruitment deviates in each region to be correlated with some environmental variable. See the following file for a discussion of recruitment modelling options: I:\assessments\Pop dy modelling\MFCL\Recruitment.doc	3		
20	Selectivity varying with a covariate	Implement a scheme to allow time-series variation in selectivity, both as a random effect and correlated with an environmental or other index (e.g. mean latitude fished)	2		
21	Individually-specified penalty	Allow individually-specified penalty weights (priors) for movement coefficients to constrain parameters and make them estimable.	3		Some structure there now but we probably want

	weights for movement coefficients	Probably best done in conjunction with 23 and 24 when the new tagging data is incorporated.			something more flexible.
22	Seasonally varying selectivity coefficients	Implement a scheme to estimate seasonal variability in selectivity coefficients	3		
24	Time-series variation in movement coefficients	Implement a scheme to allow time-series variation in movement coefficients correlated with an environmental index. Probably best done in conjunction with 21 and 23 when the new tagging data is incorporated.	2		
25	Stochastic projections	Compute uncertainty in projected population biomass by propagating uncertainty in recruitment and effort deviations. Parameter estimates and likelihood function for the time period supported by data must be unaffected (e.g. Maunder, Harley, and Hampton paper in ICESJMS).	5	Dave, Nick	Complete - variability in recruitment (resampled). Further testing of effort devs, and numbers-at-age in 1st projection year in progress.
26	Estimate biological parameters at length	Maturity, fecundity, spawning fraction are typically length-specific properties (at least the data on them is) and so they are converted to age based on the initial growth curve. As soon as a growth curve is estimated there is an inconsistency.	3		
36	Yield-related analysis capabilities	Estimate indicative yields by fishery for both MSY and Equilibrium yield. Also estimate region-specific scalars. the current MSY calculations estimate a single F-scalar across all fisheries. Anything more than scalars would cause estimation difficulties. Required for management options project	5	Dave	Region-specific yield calculations are already an option in MFCL. (See section in code called "Daves_folly"). Anything else to do? **7**
37	Hyperstability	Implement fishery-specific hyperstability, as a relationship between vulnerable biomass and catchability	3		

38	Projections for mgmt options project	1. Modify MULTIFAN-CL to run under the control of the management options application. [Probably no changes needed, but output cleanup might help] 2. Automate production of input files for projections under alternative management options. Adding projection period into par file could be done in R. 3. Link to an encrypted catch-effort database in order to define effects of time-area closures at one month (or less) and 1 degree square resolution (as in IATTC-77-04). (N.B. the model itself will still run at a regional level). Area boundaries will be selected from a predefined set, in order to help maintain data confidentiality. 4. Link to encrypted catch-effort database and estimate indicative yields by location.	5	Fabrice + Dave + Simon + Shelton + Nick	Mostly completed as input to the TUMAS project. Tasks 3 and 4 are still in progress
	Other tag workshop tasks	Placeholder			**6**
OUTPUT					
13+	Report effort penalties .	A new output file should be created that provides all values for penalties and likelihood components. For diagnostic purposes it would be good to have it for each phase. Simon to put together a potential file structure.	5		Already under way **4**
	Cut down dep vars	Design a new dependent variable report (i.e. *.dep -> *.var) that is relevant for what we now need for our assessments. The existing one, if it works, contains a lot of time consuming stuff that is no used.	4	Pierre	
	Likelihood components	Output of total likelihood components for diagnostics	3	Nick	
OTHER					
4	Testing 1	Set up an automated procedure for testing MFCL executables before use. 1. Design a set of doitall files that test the full range of important MFCL options. This would initially be the current doitall's for the YFT SKJ BET and ALB assessments. 2. Store the output files the above runs with a stable version of MFCL in a test directory. 3. Write an R script to produce figures that compare outputs between the 'good' runs and the new runs. 4. Write an R script to automate the whole procedure including (as an option) submitting all the runs to condor.	4		Nick to set up
41	Testing 2	Set up "cut-down" models (say 1987 init-year) for quick runs and testing, one for each	4	Nick	cutbet - completed; cutyft

		species. Follow John's approach for modifying the *.par file according to a specified 00.par file. Enables rapid runs for checking code operation.			- completed; others in progress
42	Testing 3	Complete testing of recent features: catch-conditioned model; length-based selectivities; stochastic projections; release group-specific tag reporting rates; tagging likelihood functions; constant selectivity-at-length; structured recruitment estimates (seasonal recruitments +annual deviates); fit to tags during mixing period.	4	Nick	In progress
43	Compilation 1	Create standard VS2010 platform with SP1 for windows compilations.	4	Nick	Tested an initial compilation; to be established on compilation platforms.
44	Compilation 2	Include Lapack library for single value decomposition in Windows compilation	4	Dave, Nick	
45	Compilation 3	Review outputs and temporary file use (Gforge tasks 47 - 50)	4	Nick	

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Appendix A: MFCL User's Guide – excerpt for undertaking stochastic projections

4.4.1 Stochastic projections

The above description is for single model evalutions in a deterministic projection, with parameter values held constant during the projection period. MULTIFAN-CL can be run in simulations with three sources of stochasticity: annual recruitments, population numbers at age in the first projection year, and fishery effort deviations. This feature has utility for risk analyses and evaluating relative performance of assumed future fishery management strategies. It entails five steps:

1. Hessian calculation for the fitted model parameters over the model estimation period (e.g. 1952 – 2008).
2. Construction of "*.frq" and "proj.par" files for input to deterministic projections.
3. Hessian calculation for the log-normal distribution of historical recruitments
4. Hessian calculation to generate time series of future simulated recruitments
5. Actual simulation run.

The first step has been described previously (see 4.5.1) and the deterministic projection in the second step has been described above. It is recommended to test the newly constructed projection input par file operation with a single model evaluation to ensure that it works, e.g.:

> ./mfclo32 bet.frq proj.par ttt -switch 6 1 1 1 2 190 0 2 191 0 2 148 4 2 155 0 -999 55 0

The third and fourth steps entail Hessian calculations to generate the stochastic parameter inputs for the parameters. For the third step age flag(20) must be set to the number of simulations, and parest flag(145) is set to 7 and 8 for steps 3 and 4 respectively. An example follows for 200 simulations:

> ./mfclo32 bet.frq ttt ttt -switch 2 1 145 7 2 20 200 ./

> ./mfclo32 bet.frq ttt ttt -switch 5 -999 55 0 1 145 8 1 234 1 1 235 20 1 237 1

Note that in the input par file "ttt", age flag(20) must also set to the number of simulations, (in this example 200). Also note that if the flag setting for stochasticity in the numbers-at-age in the first projection year (parest flag 237) is set, then this stochasticity will occur in simulation projections in the fifth step, even if the flag settings are disabled. To remove this source of stochasticity from subsequent projections, it will be necessary to repeat the fourth step Hessian calculation with the flags disabled.

In the fourth and fifth steps it is necessary to supply the appropriate flags to specify the sources of stochasticity.

1. Recruitments
   Future recruitments are randomly resampled (multinomial) from historical estimates for each simulation year. To create the vector of projection years parest flags(232 and 233) are both set to 0, and parest flag(238) must be set to 0 to allow placement of

simulation recruitments. Age flag(20) must be > 0 to initiate the simulations and set to the number of simulations.

2. Numbers at age in 1st year of projections
    Random selection of the population state numbers-at-age in the first year of the projection period is taken from a parametric distribution (Choleski decomposition) and is activated by setting parest flag(237) to 1. If parest flag(231) is set to 0 a pre-defined seed for the random number generator is used, else the flag value supplied will be used.

3. Fishery effort deviations
    Random selection of fishery effort deviations for each year of the projection period is undertaken in veff_dev.cpp (ln 23) where deviates are sampled from a parametric distribution with a user-supplied standard deviation. Parest_flag 234 turns on the random effort devs, flag 235 specifies the standard deviation, and flag 236 provides an iseed for the random deviate (if desired).

For the simulations parest flag(1) is set = 1 since the simulations relate to a single model set of parameters. An example follows for the fifth step that runs 200 simulations and activates all three sources of stochasticity:

> ./mfclo64 bet.frq proj.par ttt -switch 7 1 1 1 -999 55 0 2 20 200 1 145 0 1 234 1 1 235 20 1 237 1

It is recommended that fish flag (55) be set = 0 so as not to disable the fisheries, i.e. it maintains the estimated catchabilities for the projections. The simulation run output is contained in the files:

"projected_numbers_at_age";

"projected_randomized_catch_at_age";

"projected_randomized_catches"; and,

"other_projected_stuff".