

# Spatial Population Model User Manual

SPM v1.1-2013-03-02 (rev. 4887)

Alistair Dunn, Scott Rasmussen, and Sophie Mormede

March 2013





Citation: Dunn, A.; Rasmussen, S.; Mormede, S. (2013) Spatial Population Model User Manual, SPM v1.1-2013-03-02 (rev. 4887) . National Institute of Water & Atmospheric Research Ltd. *Unpublished report*. 174 p.





## Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Version . . . . .	1
1.2	Citing SPM . . . . .	1
1.3	Software license . . . . .	1
1.4	System requirements . . . . .	1
1.5	Necessary files . . . . .	2
1.6	Getting help . . . . .	2
1.7	Technical details . . . . .	2
<b>2</b>	<b>Model overview</b>	<b>3</b>
2.1	Introduction . . . . .	3
2.2	The population section . . . . .	4
2.3	The estimation section . . . . .	4
2.4	The observation section . . . . .	5
2.5	The report section . . . . .	5
<b>3</b>	<b>Running SPM</b>	<b>7</b>
3.1	Using SPM . . . . .	7
3.2	The input configuration file . . . . .	7
3.3	Redirecting standard output . . . . .	8
3.4	Command line arguments . . . . .	8
3.5	Constructing an SPM input configuration file . . . . .	9
3.5.1	Commands . . . . .	9
3.5.2	Subcommands . . . . .	9
3.5.3	The command-block format . . . . .	10
3.5.4	Commenting out lines . . . . .	11
3.5.5	Determining parameter names . . . . .	11
3.6	SPM exit status values . . . . .	11
<b>4</b>	<b>The population section</b>	<b>13</b>
4.1	Introduction . . . . .	13
4.2	Spatial structure . . . . .	13
4.3	Population structure . . . . .	14
4.4	Layers . . . . .	15
4.5	Time sequences . . . . .	17
4.5.1	Annual cycle . . . . .	17
4.5.2	Initialisation . . . . .	17
4.5.3	Model years . . . . .	18
4.6	Processes . . . . .	18
4.7	Population processes . . . . .	19
4.7.1	Recruitment . . . . .	19

4.7.2	Ageing . . . . .	22
4.7.3	Mortality . . . . .	23
4.7.4	Category transitions . . . . .	27
4.8	Movement processes . . . . .	28
4.8.1	Migration movement . . . . .	28
4.8.2	Adjacent cell movement . . . . .	29
4.8.3	Preference movement . . . . .	29
4.9	Derived quantities . . . . .	31
4.10	Derived layers . . . . .	32
4.11	Size-age relationship . . . . .	32
4.12	Size-weight relationship . . . . .	33
4.13	Selectivities . . . . .	34
4.13.1	Constant . . . . .	34
4.13.2	Knife-edge . . . . .	35
4.13.3	All-values . . . . .	35
4.13.4	All-values-bounded . . . . .	35
4.13.5	Increasing . . . . .	35
4.13.6	Logistic . . . . .	35
4.13.7	Inverse logistic . . . . .	35
4.13.8	Logistic producing . . . . .	36
4.13.9	Double-normal . . . . .	36
4.13.10	Double-exponential . . . . .	36
<b>5</b>	<b>The estimation section</b>	<b>37</b>
5.1	Role of the estimation section . . . . .	37
5.2	The objective function . . . . .	37
5.3	Specifying the parameters to be estimated . . . . .	37
5.4	Point estimation . . . . .	38
5.4.1	The numerical differences minimiser . . . . .	38
5.4.2	The differential evolution minimiser . . . . .	39
5.5	Posterior profiles . . . . .	39
5.6	Bayesian estimation . . . . .	40
5.7	Priors . . . . .	42
5.8	Penalties . . . . .	43
<b>6</b>	<b>The observation section</b>	<b>45</b>
6.1	Observations and likelihoods . . . . .	45
6.2	Proportions-at-age observations . . . . .	45
6.2.1	Likelihoods for proportions-at-age observations . . . . .	47
6.3	Proportions-by-category observations . . . . .	48
6.3.1	Likelihoods for proportions-by-category observations . . . . .	49
6.4	Abundance or biomass observations . . . . .	50

6.4.1	Likelihoods for abundance observations . . . . .	51
6.5	Process error . . . . .	52
6.6	Ageing error . . . . .	52
6.7	Simulating observations . . . . .	52
6.8	Pseudo-observations . . . . .	53
<b>7</b>	<b>The report section</b>	<b>55</b>
7.1	Print the model spatial map . . . . .	55
7.2	Print the partition . . . . .	55
7.3	Print the partition biomass . . . . .	56
7.4	Print the partition at the end of an initialisation . . . . .	56
7.5	Print a process summary . . . . .	56
7.6	Print a preference function summary . . . . .	56
7.7	Print derived quantities . . . . .	56
7.8	Print derived layers . . . . .	56
7.9	Print the estimated parameters . . . . .	56
7.10	Print the estimated parameters in a vector format . . . . .	56
7.11	Print the objective function . . . . .	57
7.12	Print the covariance matrix . . . . .	57
7.13	Print observations, fits, and residuals . . . . .	57
7.14	Print simulated observations . . . . .	57
7.15	Print the ageing error misclassification matrix . . . . .	57
7.16	Print layers and meta-layers . . . . .	57
7.17	Print a derived view via a categorical layer . . . . .	57
7.18	Print selectivities . . . . .	57
7.19	Print the random number seed . . . . .	58
7.20	Print the size-weight relationship . . . . .	58
7.21	Print the size-at-age relationship . . . . .	58
7.22	Print the weight-at-age relationship . . . . .	58
7.23	Print the results of an MCMC . . . . .	58
7.24	Print the MCMC samples as they are calculated . . . . .	58
7.25	Print the MCMC objective function values as they are calculated . . . . .	58
<b>8</b>	<b>Population command and subcommand syntax</b>	<b>59</b>
8.1	Model structure . . . . .	59
8.2	Initialisation . . . . .	60
8.3	Time-steps . . . . .	60
8.4	Processes . . . . .	61
8.4.1	Constant recruitment process . . . . .	61
8.4.2	Beverton-Holt recruitment process . . . . .	62
8.4.3	Local Beverton-Holt recruitment process . . . . .	63
8.4.4	Ageing process . . . . .	65

8.4.5	Constant mortality rate process . . . . .	65
8.4.6	Annual mortality rate process . . . . .	66
8.4.7	Event mortality process . . . . .	66
8.4.8	Biomass event mortality process . . . . .	67
8.4.9	Holling mortality rate . . . . .	68
8.4.10	Prey-switching predation process . . . . .	69
8.4.11	Category transition process . . . . .	70
8.4.12	Category transition rate process . . . . .	71
8.4.13	Migration movement . . . . .	71
8.4.14	Adjacent cell movement . . . . .	72
8.4.15	Preference movement . . . . .	73
8.5	Preference functions . . . . .	73
8.5.1	Constant . . . . .	74
8.5.2	Normal . . . . .	74
8.5.3	Double-normal . . . . .	74
8.5.4	Logistic . . . . .	75
8.5.5	Inverse-logistic . . . . .	75
8.5.6	Exponential . . . . .	76
8.5.7	Threshold . . . . .	76
8.5.8	Categorical . . . . .	76
8.5.9	Monotonic categorical . . . . .	77
8.6	Layers . . . . .	77
8.6.1	Numeric . . . . .	78
8.6.2	Categorical . . . . .	78
8.6.3	Distance . . . . .	78
8.6.4	Abundance . . . . .	78
8.6.5	Biomass . . . . .	79
8.6.6	Abundance-density . . . . .	79
8.6.7	Biomass-density . . . . .	79
8.6.8	Numeric meta-layer . . . . .	80
8.6.9	Categorical meta-layer . . . . .	80
8.6.10	Derived-layer . . . . .	81
8.7	Derived quantities . . . . .	81
8.7.1	Abundance . . . . .	82
8.7.2	Biomass . . . . .	82
8.8	Age-size relationship . . . . .	83
8.8.1	von Bertalanffy . . . . .	83
8.8.2	Schnute . . . . .	84
8.9	Size-weight . . . . .	85
8.9.1	None . . . . .	85
8.9.2	Basic . . . . .	85
8.10	Selectivities . . . . .	85



8.10.1	Constant . . . . .	86
8.10.2	Knife-edge . . . . .	86
8.10.3	All-values . . . . .	86
8.10.4	All-values-bounded . . . . .	86
8.10.5	Increasing . . . . .	87
8.10.6	Logistic . . . . .	87
8.10.7	InverseLogistic . . . . .	88
8.10.8	Logistic producing . . . . .	88
8.10.9	Double-normal . . . . .	89
8.10.10	Double-exponential . . . . .	89
<b>9</b>	<b>Estimation command and subcommand syntax</b>	<b>91</b>
9.1	Estimation methods . . . . .	91
9.2	Point estimation . . . . .	91
9.2.1	Numerical differences minimiser . . . . .	92
9.2.2	Differential evolution minimiser . . . . .	92
9.3	Monte Carlo Markov Chain (MCMC) . . . . .	93
9.3.1	Metropolis-Hastings . . . . .	93
9.4	Profiles . . . . .	95
9.5	Defining the parameters to be estimated and their priors . . . . .	95
9.6	Priors . . . . .	96
9.6.1	Uniform prior . . . . .	96
9.6.2	Uniform-log prior . . . . .	96
9.6.3	Normal prior . . . . .	97
9.6.4	Normal-by-stdev prior . . . . .	97
9.6.5	Lognormal prior . . . . .	97
9.6.6	Beta prior . . . . .	97
9.7	Defining catchability constants . . . . .	98
9.8	Defining penalties . . . . .	98
<b>10</b>	<b>Observation command and subcommand syntax</b>	<b>99</b>
10.1	Observation types . . . . .	99
10.1.1	Proportions at age . . . . .	99
10.1.2	Proportions by category . . . . .	101
10.1.3	Abundance . . . . .	103
10.1.4	Biomass . . . . .	105
10.2	Defining ageing error . . . . .	107
10.2.1	No ageing error . . . . .	107
10.2.2	Normal ageing error . . . . .	107
10.2.3	Off-by-one ageing error . . . . .	107
<b>11</b>	<b>Report command and subcommand syntax</b>	<b>109</b>
11.1	Available reports . . . . .	109

11.2	Report commands and subcommands . . . . .	109
11.2.1	Print the co-ordinates of the spatial map . . . . .	110
11.2.2	Print the partition . . . . .	110
11.2.3	Print the partition biomass . . . . .	110
11.2.4	Print the partition at initialisation . . . . .	111
11.2.5	Print a summary of a process . . . . .	111
11.2.6	Print a summary of a preference function . . . . .	112
11.2.7	Print a derived quantity . . . . .	112
11.2.8	Print a derived layer . . . . .	112
11.2.9	Print a summary of the estimated parameters . . . . .	113
11.2.10	Print the estimated parameter values out as a vector . . . . .	113
11.2.11	Print the objective function values . . . . .	114
11.2.12	Print the covariance matrix . . . . .	114
11.2.13	Print a summary of the an observation, including fits, and residuals . . . . .	114
11.2.14	Print an observation using simulated values . . . . .	115
11.2.15	Print an ageing error misclassification matrix . . . . .	115
11.2.16	Print a layer . . . . .	116
11.2.17	Print a derived view via a categorical layer . . . . .	116
11.2.18	Print a selectivity . . . . .	117
11.2.19	Print the random number seed used . . . . .	117
11.2.20	Print mean size at age . . . . .	118
11.2.21	Print mean weight at size . . . . .	118
11.2.22	Print mean weight at age . . . . .	119
11.2.23	Print the results of an MCMC . . . . .	119
11.2.24	Print the MCMC samples as they are calculated . . . . .	119
11.2.25	Print the MCMC objective function values as they are calculated . . . . .	120
<b>12</b>	<b>Other commands and subcommands</b>	<b>121</b>
<b>13</b>	<b>Examples</b>	<b>123</b>
13.1	An example of a simple $1 \times 1$ non-spatial model . . . . .	123
13.2	An example of a simple $10 \times 6$ spatial model with movement . . . . .	127
<b>14</b>	<b>Post processing output using R</b>	<b>131</b>
14.1	Read and extract reports from a SPM output file. . . . .	131
<b>15</b>	<b>Troubleshooting</b>	<b>133</b>
15.1	Introduction . . . . .	133
15.2	Reporting errors . . . . .	133
15.3	Guidelines for reporting a bug in SPM . . . . .	133
<b>16</b>	<b>Acknowledgements</b>	<b>135</b>
<b>17</b>	<b>Quick reference</b>	<b>137</b>

17.1	Population command and subcommand syntax . . . . .	137
17.2	Estimation command and subcommand syntax . . . . .	145
17.3	Observation command and subcommand syntax . . . . .	147
17.4	Report command and subcommand syntax . . . . .	150
17.5	Other commands and subcommands . . . . .	153
<b>18</b>	<b>References</b>	<b>155</b>
<b>19</b>	<b>Spatial Population Model software license</b>	<b>157</b>
<b>20</b>	<b>Index</b>	<b>159</b>



---

## 1. Introduction

SPM (Spatial Population Model) is a generalised spatially explicit age-structured population dynamics and movement model. SPM can model population dynamics and movement parameters for an age-structured population using a range of observations, including tagging, relative abundance, and age frequency data. SPM implements an age-structured population within an arbitrary shaped spatial structure, which can have user defined categories (e.g., immature, mature, male, female, etc.), and age range.

This manual describes how to use SPM, including how to run SPM, how to set up an input configuration file. Further, we describe the population dynamics and estimation methods, and describe how to specify and interpret output.

### 1.1. Version

This document (last modified 2013-03-02) describes SPM v1.1-2013-03-02 (rev. 4887) . The SPM version number is suffixed with a date/time (yyyy-mm-dd) and revision number, giving the revision control system UTC date and revision number for the most recent modification of the source files. User manual updates will usually be issued for each minor version or date release of SPM, and can be obtained, on request, from the authors.

### 1.2. Citing SPM

A suitable reference for SPM and this document is:

Dunn, A.; Rasmussen, S.; Mormede, S. (2013) Spatial Population Model User Manual, SPM v1.1-2013-03-02 (rev. 4887) . National Institute of Water & Atmospheric Research Ltd. *Unpublished report*. 174 p.

### 1.3. Software license

This program and the accompanying materials are made available under the terms of the Common Public License v1.0 which accompanies this software (see Section 19).

Copyright ©2008-2013, National Institute of Water & Atmospheric Research Ltd. and the New Zealand Ministry for Primary Industries. All rights reserved.

### 1.4. System requirements

SPM is available for most IBM compatible machines running 64-bit Linux and Microsoft Windows operating systems.

Several of SPMs tasks are highly computer intensive and a fast processor is recommended. We recommend a minimum of 10 megabytes of free RAM (although, depending on the scope of the problem, you may need more). The program itself requires only a few megabytes of hard-disk space but output files can consume large amounts of disk space. Depending on number and type of user output requests, the output could range from a few hundred kilobytes to several hundred megabytes. However, we note that, depending on the model implemented, some of SPMs tasks can take a considerable amount of time.

### 1.5. Necessary files

For both 64-bit Linux and Microsoft Windows, only the executable file `spm` or `spm.exe` is required to run SPM. No other software is required. We do not compile a version for 32-bit operating systems.

SPM offers little in the way of post-processing of the output, and a package available that allows tabulation and graphing of model outputs is recommended. We suggest software such as Microsoft Excel, S-Plus, or **R** (R Development Core Team 2007). To assist in the post processing of SPM output, we provide the `spm` **R** package for importing the SPM output into R (see Section 14).

### 1.6. Getting help

SPM is distributed as unsupported software, however we would appreciate being notified of any problems or errors in SPM. See Section 15.2 for how to report errors to the authors. Further information about SPM can be obtained by contacting the authors.

### 1.7. Technical details

SPM was compiled on Linux using `gcc`, the C/C++ compiler developed by the GNU Project. The 64-bit Linux version was compiled using `gcc` version 4.1.2 20070115 (prerelease) (SUSE Linux). Note that SPM is not supported for Linux kernel versions prior to 2.6. The Microsoft Windows version was compiled using Mingw32 `gcc` (tdm-1) 4.6.1. The Microsoft Windows installer was built using the Nullsoft Scriptable Install System.

SPM uses two minimisers — the first is closely based on the main algorithm of Dennis Jr and Schnabel (1996), and which uses finite difference gradients, and the second is an implementation of the differential evolution solver (Storn and Price, 1995), and based on code by Lester E. Godwin of PushCorp, Inc. The random number generator used by SPM uses an implementation of the Mersenne twister random number generator (Matsumoto and Nishimura, 1998). This, the command line functionality, matrix operations, and a number of other functions use the BOOST C++ library (Version 1.48.0).

Note that the output from SPM may differ slightly on the different platforms due to different precision arithmetic or other platform dependent implementation issues. The source code for SPM is available either as a part of the installation, or on request from the authors.

---

## 2. Model overview

### 2.1. Introduction

The Spatial Population Model (SPM) is a generalised spatially explicit age-structured population dynamics and movement model. It allows the implementation of age-structured population models suitable for the simulation and estimation of parameters in models with a large number of areas. It implements a statistical catch-at-age population dynamics and movement model, using a discrete time-step state-space model that represents a cohort-based population age structure in a spatially explicit manner.

SPM is run from the console window on Microsoft Windows or from a terminal window on Linux. SPM gets its information from input data files, the main one of which is the *input configuration file*. Commands and subcommands in the input configuration file are used to define the model structure, provide observations, define parameters, and define the outputs (reports) for SPM. Command line switches tell SPM the run mode and where to direct its output. See Section 3 for the details.

The basic structure of an SPM model is a set of spatial cells, each of which contains a population. We define the model in terms of the *state*. The state consists of two parts, the *partition*, and any *derived quantities* or *derived meta-layers*. The state will typically change one or more times in every *time-step* of every year, depending on the *processes* defined for each model.

The partition is a representation of the population at an instance in time, and is a matrix of the numbers of individuals within each spatial cell, age, and category. A derived quantity is a cumulative summary of the partition at some point in time. A derived meta-layer is a cumulative summary of the partition in each of the cells at some point in time. Unlike the partition (which is updated as each new process is applied), each derived quantity records a single value for each year of the model run, and each derived meta-layer records a layer of values for each year of the model run. Hence, derived quantities build up a vector of values over the model run years, and derived meta-layers build up a list of layers over the model run years. For example, the total number of individuals in a category labelled mature at some point in the annual cycle may be a derived quantity and the total number of individuals in a category labelled mature in each cell of the model at some point in the annual cycle may be a derived meta-layer. The state is the combination of the partition and any derived quantities or derived meta-layer at some instance in time. Changes to the state occur by the application of processes. Additions to the vectors of derived quantities occur when a model is requested to add a value to each derived quantity vector.

Running of the model consists of two main parts — first the model state is initialised for a number of iterations (years), then the model runs over a range of predefined years.

The application of processes within each year is controlled by the *annual cycle*. This defines what processes happen in each model year, and in what sequence. Initialisation can be phased, and for each phase, the user need to define the processes that occur in each year, and the order in which they are applied.

For the run years, each year is split up into one or more time-steps (with at least one process occurring in each time-step). You can think of each time-step as representing a particular part of the calendar year, or you can just treat them as an abstract sequence of events.

The division of the year into an arbitrary number of time-steps allows the user to specify the exact order in which processes occur and when observations are evaluated. The user specifies the time-steps, their order, and the processes within each time-step. If more than one process occurs in the same time-step, then they occur in the order that they are specified. Observations are always evaluated at the end of the time-step in which they occur. Hence, time-steps can be used to break processes

into groups, and assist in defining the timing of the observations within the annual cycle.

An SPM model can be parametrised by both population processes (for example, ageing, recruitment, and mortality) and movement processes. Movement is parameterised by either adjacent cell movements, between cell migrations, or by global movements as a function of known attributes at each spatial location (termed preference functions — see later). SPM is designed to be flexible and to allow for the estimation of both population and movement parameters from local or aggregated spatially explicit observations.

The population structure of SPM follows the usual population modelling conventions and is similar to those implemented in other population models, for example CASAL (Bull et al., 2012). The model records the numbers of individuals by age and category (e.g., male, female), as well as the locations of these cohorts within a spatial grid. In general, cohorts are added via a recruitment event, are aged annually, and are removed from the population via various forms of mortality. The population is assumed to be closed (i.e., no immigration or emigration from the modelled area)

A model is implemented in SPM using an input configuration file, which is a complete description of the model structure (i.e., spatial and population processes), observations, estimation methods, and reports (outputs) requested. SPM runs from a console window on Microsoft Windows or from a text terminal on Linux. A model can be either *run*, estimable parameters can be *estimated* or *profiled*, MCMC distributions calculated, and these estimates can be used by SPM as parameters of an operating model to *simulate* observations.

A model in SPM is specified by an input configuration file, and comprises of four main components. These are the population section (model structure, population and spatial dynamics, etc.), the estimation section (methods of estimation and the parameters to be estimated), the observation section (observational data and associated likelihoods), and the report section (printouts and reports from the model). The input configuration file completely describes a model implemented in SPM. See Sections 8, 9, 10, and 11 for details and specification of SPMs command and subcommand syntax within the input configuration file.

## 2.2. The population section

The population section (Section 4) defines the model of the movement and population dynamics. It describes the model structure (both the spatial and population structure), initialisation and run years (model period), population and movement processes (for example, recruitment, migration, and mortality), layers (the known attributes of each spatial cell), selectivities, and key population parameters.

## 2.3. The estimation section

The estimation section (Section 5) specifies the parameters to be estimated, estimation methods, penalties and priors. Estimation is based on an objective function (e.g., negative log posterior). Depending on the run mode, the estimation section is used to specify the methods for finding a point estimate (i.e., the set of parameter values that minimizes the objective function), doing profiles, or MCMC methods and options, etc.

Further, the estimation section specifies the parameters to be estimated within each model run and the estimation methods. The estimation section specifies the choice of estimation method, which model parameters are to be estimated, priors, starting values, and minimiser control values.

Penalties and priors act as constraints on the estimation. They can either encourage or discourage (depending on the specific implementation) parameter estimates that are ‘near’ some value, and



hence influence the estimation process. For example, a penalty can be included in the objective function to discourage parameter estimates that lead to models where the recorded catch was unable to be fully taken.

## **2.4. The observation section**

Types of observations, their values, and the associated error structures are defined in the observation section (Section 6). Observations are data which allow us to make inferences about unknown parameters. The observation section specifies the observations, their errors, likelihoods, and when the observations occur. Examples include relative or absolute abundance indices, proportions-at-age frequencies, etc. Estimation uses the observations to find values for each of the estimated parameters so that each observation is ‘close’ (in some mathematical sense) to a corresponding expected value.

## **2.5. The report section**

The report section (Section 7) specifies the model outputs. It defines the quantities and model summaries to be output to external files or to the standard output. While SPM will provide informational messages to the screen, the SPM will only produce model estimates, population states, and other data as requested by the report section. Note that if no reports are specified, then no output will be produced.



---

### 3. Running SPM

SPM is run from the console window (i.e., the DOS command line) on Microsoft Windows or from a terminal window on Linux. SPM gets its information from input data files, the key one of which is the input configuration file.

The input configuration file is compulsory and defines the model structure, processes, observations, parameters (both the fixed parameters and the parameters to be estimated), and the reports (outputs) requested. The following sections describe how to construct the SPM configuration file. By convention, the name of the input configuration file ends with the suffix `.spm`, however, any file name is acceptable.

Other input files can, in some circumstances, be supplied to define the starting point for an estimation or as a point estimate from which to simulate observations.

Simple command line arguments are used to determine the actions or *tasks* of SPM, i.e., to run a model with a set of parameter values, estimate parameter values (either point estimates or MCMC), project quantities into the future, simulate observations, etc.. Hence, the *command line arguments* define the *task*. For example, `-r` is the *run*, `-e` is the *estimation*, and `-m` is the *MCMC* task. The *command line arguments* are described in Section 3.4.

#### 3.1. Using SPM

To use SPM, open a console (i.e., the command prompt) window (Microsoft Windows) or a terminal window (Linux). Navigate to a directory of your choice, where your input configuration files are located. Then type `spm` with any arguments (see Section 3.4 for the the list of possible arguments). SPM will print output to the screen and return you to the command prompt when it completes its task. Note that the SPM executable (binary) must be either in the directory where you run it or somewhere in your `PATH`. Note that an automated installer is available for SPM on Microsoft Windows. If you use the installer, then it will give you the option of modifying your `PATH` for you (as well a a number of other options to make using the program a little easier). Otherwise, see your operating system documentation for help on identifying or modifying your `PATH`.

#### 3.2. The input configuration file

The input configuration file is made up of four broad sections; the description of the population structure and parameters (the population section), the estimation methods and variables (the estimation section), the observations and their associated likelihoods (the observation section), and the outputs and reports that SPM will return (the report section). The input configuration file is made up of a number of commands (many with subcommands) which specify various options for each of these components.

The command and subcommand definitions in the input configuration file can be extensive (especially when you have a model with a large spatial structures that has many layers and/or observations), and can result in a input configuration file that is long and difficult to navigate. To aid readability and flexibility, we can use the input configuration file command `@include file`. The command causes an external file, *file*, to be read and processed, exactly as if its contents had been inserted in the main input configuration file at that point. The file name must be a complete file name with extension, but can use either a relative or absolute path as part of its name. Note that included files can also contain `@include` commands — but be careful that you do not set up a recursive state. See Section 12 for more detail.

### 3.3. Redirecting standard output

SPM uses the standard output stream `standard output` to display run-time information. The standard error stream is used by SPM to output the program exit status and run-time errors. We suggest redirecting both the standard output and standard error into files. With the bash shell (on Linux systems), you can do this using the command structure,

```
(spm [arguments] > out) >& err &
```

It may also be useful to redirect the standard input, especially if you're using SPM inside a batch job software, i.e.

```
(spm [arguments] > out < /dev/null) >& err &
```

On Microsoft Windows systems, you can redirect to standard output using,

```
spm [arguments] > out
```

And, on some Microsoft Windows systems (e.g., Windows7), you can redirect to both standard output and standard error, using the syntax,

```
spm [arguments] > out 2> err
```

Note that SPM outputs a few lines of header information to the output. The header consists of the program name and version, the arguments passed to SPM from the command line, the date and time that the program was called (derived from the system time), the user name, and the machine name (including the operating system and the process identification number). These can be used to track outputs as well as identifying the version of SPM used to run the model.

### 3.4. Command line arguments

The call to SPM is of the following form.:

```
spm [-c config_file] [task] [options]
```

**-c *config\_file*** Define the input configuration file for SPM. If omitted, then SPM looks for a file named `config.spm`.

and where *task* is one of;

**-h** Display help (this page).

**-l** Display the reference for the software license (CPLv1.0).

**-v** Display the SPM version number.

**-r** Run the model once using the parameter values in the input configuration file, or optionally, with the values from the file denoted with the command line argument `-i file`.

**-e** Do a point *estimate* using the values in the input configuration file as the starting point for the parameters to be estimated, or optionally, with the start values from the file denoted with the command line argument `-i file`.

- p** Do a likelihood *profile* using the parameter values in the input configuration file as the starting point, or optionally, with the start values from the file denoted with the command line argument `-i file`.
- m** Do an *MCMC* estimate using the values in the input configuration file as the starting point for the parameters to be estimated, or optionally, with the start values from the file denoted with the command line argument `-i file`.
- s number** Simulate the *number* of observation sets using values in the input configuration file as the parameter values, or optionally, with the values for the parameters denoted as estimated from the file with the command line argument `-i file`.

In addition, the following are optional arguments [*options*],

- i file** Input one or more sets of estimated parameter values from *file*. See Section 11.2.10 for details about the format of *file*.
- q** Run *quietly*, i.e., suppress verbose printing of SPM.
- g seed** Seed the random number *generator* with *seed*, a positive (long) integer value. Note, if `-g` is not specified, then SPM will generate a random number seed based on the computer clock time.

### 3.5. Constructing an SPM input configuration file

The model definition, parameters, observations, and reports are specified in an input configuration file. The population section is described in Section 4 and the population commands in Section 8. Similarly, the estimation section is described in Section 5 and its commands in Section 9, and in Section 7 and Section 11 for the report and report commands.

#### 3.5.1. Commands

SPM has a range of commands that define the model structure, processes, observations, and how tasks are carried out. There are three types of commands,

1. Commands that have an argument and do not have subcommands (for example, `@include file`)
2. Commands that have a label and subcommands (for example `@process` must have a label, and has subcommands)
3. Commands that do not have either a label or argument, but have subcommands (for example `@model`)

Commands that have a label must have a unique label, i.e., the label cannot be used on more than one command of that type. The labels must start with a letter or underscore, can contain letters, underscores, or numbers. Labels must not contain white-space, a full-point ('.'), or other characters that are not letters, numbers, or an underscore.

#### 3.5.2. Subcommands

Subcommands in SPM are for defining options and parameter values for commands. They always take an argument which is one of a specific *type*. The types acceptable for each subcommand are defined in Section 8.10.10, and are summarised below.

Like commands (`@command`), subcommands and their arguments are not order specific — except that all subcommands of a given command must appear before the next `@command` block. SPM may report an error if they are not supplied in this way, however, in some circumstances a different order may result in a valid, but unintended set of actions, leading to possible errors in your expected results.

The arguments for a subcommand are either,

**switch** true/false

**integer** an integer number

**integer vector** a vector of integer numbers

**integer range** a range of integer numbers separated by a hyphen (-), for example 1994-1996 2000 is expanded to an integer vector of values 1994 1995 1996 2000).

**constant** a real number (i.e., double)

**constant vector** a vector of real numbers (i.e., vector of doubles)

**estimable** a real number that can be estimated (i.e., estimable double)

**estimable vector** a vector of real numbers that can be estimated (i.e., vector of estimable doubles)

**string** a categorical (string) value

**string vector** a vector of categorical values

Switches are parameters which are either true or false. Enter *true* as `true` or `t`, and *false* as `false` or `f`.

Integers must be entered as integers (i.e., if `year` is an integer then use 2008, not 2008.0)

Arguments of type integer vector, integer range, constant vector, estimable vector, or categorical vector contain one or more entries on a row, separated by white space (tabs or spaces).

*Estimable* parameters are those parameters that SPM can estimate, if requested. If a particular parameter is not being estimated in a particular model run, then it acts as a constant. Within SPM only estimable parameters can be estimated. And, you have to tell SPM those that are to be estimated in any particular model. Estimable parameters that are being estimated within a particular model run are called the *estimated parameters*.

### 3.5.3. The command-block format

Each command-block either consists of a single command (starting with the symbol `)` and, for most commands, a label or an argument. Each command is then followed by its subcommands and their arguments, e.g.,

`@command`, or

`@command argument`, or

`@command label`

and then

subcommand argument

subcommand argument

etc.,

Blank lines are ignored, as is extra white space (i.e., tabs and spaces) between arguments. But don't put extra white space before a @ character (which must also be the first character on the line), and make sure the file ends with a carriage return.

There is no need to mark the end of a command block. This is automatically recognized by either the end of the file, section, or the start of the next command block (which is marked by the @ on the first character of a line). Note, however, that the @include is the only exception to this rule. See Section 12) for details of the use of @include.

Note that in the input configuration file, commands, sub-commands, and arguments are not case sensitive. However, labels and variable values are case sensitive. Also note that if you are on a Linux system then external calls to files are case sensitive (i.e., when using @include *file*, the argument *file* will be case sensitive).

Characters used in labels must be alphanumeric and can include underscores (\_). Other characters will result in an error.

### 3.5.4. Commenting out lines

Text that follows a # on a line are considered to be comments and are ignored. If you want to remove a group of commands or subcommands using #, then comment out all lines in the block, not just the first line.

Alternatively, you can comment out an entire block or section by placing curly brackets around the text that you want to comment out. Put in a { as the first character on the line to start the comment block, then end it with }. All lines (including line breaks) between { and } inclusive are ignored. (These should ideally be the first character on a line. But if not, then the entire line will be treated as part of the comment block.)

### 3.5.5. Determining parameter names

When SPM processes a input configuration file, it translates each command and each subcommand into a parameter with a unique name. For commands, this parameter name is simply the command name. For subcommands, the parameter name format is either,

```
command[label].subcommand if the command has a label, or
command.subcommand if the command has no label, or
command[label].subcommand(i) if the command has a label and the subcommand arguments
are a vector, and we are accessing the ith element of that vector.
```

The unique parameter name is used to reference the parameter when estimating, applying a penalty, or applying a profile. For example, the parameter name of subcommand `r0` of the command `@process` with the label `MyRecruitment` is,

```
process[MyRecruitment].r0
```

## 3.6. SPM exit status values

When SPM completes its task successfully or errors out gracefully, it returns a single exit status value (0) to the operating system. The operating system will return (-1) if SPM terminates unexpectedly.

To determine if *SPM* has completed its task successfully, check the standard output for error and information messages.



---

## 4. The population section

### 4.1. Introduction

The population section specifies the model structure, movement and population dynamics, and other associated parameters. It describes the model structure (both the spatial and population structure), defines the population (for example, recruitment, migration, and mortality) and movement processes, defines the layers (the known attributes of each spatial cell), selectivities, and model parameters.

The population section consists of several components, including;

- The spatial and population structure
- Model initialisation (i.e., the state of the model at the start of the first year)
- The years over which the model runs (i.e., the start and end years of the model)
- The annual cycle (time-steps and processes that are applied in each time-step)
- The specifications and parameters of the processes;
  - Population processes (i.e., processes that add, remove individuals to or from the partition, or shift numbers between ages and categories in the partition)
  - Spatial processes (i.e., processes that move or shift cohorts between spatial locations but do not alter their ages or categories)
- Layers (used by processes, observations and reports) and their definitions
- Selectivities
- Parameter values and their definitions
- Derived layers, meta-layers and quantities required as parameters for some processes (i.e., spawning stock biomass to resolve the spawner-recruit relationship in a recruitment process)

### 4.2. Spatial structure

The spatial structure of SPM is represented by an  $n_{rows} \times n_{cols}$  grid, with rows  $i = 1 \dots n_{rows}$  and columns  $j = 1 \dots n_{cols}$ . Each cell of this matrix records the population structure at that point in space, where the population structure is represented by an  $n_{categories} \times n_{ages}$  rectangular matrix (with categories  $k = 1 \dots n_{categories}$  and ages  $l = 1 \dots n_{ages} = age_{min} \dots age_{max}$ ). Hence we can describe any spatial and population element of the model as  $element(i, j, k, l)$ . We define, within the spatial grid ( $n_{rows} \times n_{cols}$ ), locations where the population can and cannot potentially be present using a *layer*.

SPM implements a single spatial structure, a grid of *square* cells (Figure 4.1). The spatial grid can be of an arbitrary size, but must be rectangular.

The dimensions of the spatial grid are user defined but must be at least a  $1 \times 1$  grid (i.e., a single spatial cell), and the largest spatial structure currently allowed by SPM is a grid of  $1000 \times 1000$  cells – although we note that models of this size are untested and will probably have very long run times.

Associated with the  $n_{rows} \times n_{cols}$  spatial structure is the one compulsory layer (see Section 4.4), the *base layer*. This defines the locations where the population can and cannot potentially be present (e.g., in a marine model, the locations associated with the sea and not land). These are defined as the cells where the base layer has a value greater than zero. There must be at least one cell in the spatial grid where the population can be present. In addition, the base layer also defines the relative *area* of each spatial cell that is used for density calculations within SPM.

	Col 1	Col 2	Col 3	Col 4
Row 1	(1,1)	(1,2)	(1,3)	(1,4)
Row 2	(2,1)	(2,2)	(2,3)	(2,4)
Row 3	(3,1)	(3,2)	(3,3)	(3,4)

**Figure 4.1: An illustration of the spatial structure**

Models are implemented as a grid of square cells making up a rectangular matrix. Distance between cells is determined as the euclidean distance between cell centres, modified by an arbitrary scalar.

Hence, the definition of the spatial structure includes;

- The type of spatial grid and its dimensions,  $n_{rows}$  and  $n_{cols}$
- The label of a numeric layer to be used as the base layer (defining the locations where the population can be present as well as the area of each cell)
- The length (distance) of a side of the grid cell to be used as the scaler for distance calculations

### 4.3. Population structure

The population structure in SPM is represented by a matrix containing an arbitrary number of user defined categories (rows), and an arbitrary age range (columns). Hence, each spatial cell has a population state described as  $n_{categories} \times n_{ages}$  rectangular matrix with categories  $k = 1 \dots n_{categories}$  and ages  $l = age_{min} \dots age_{max}$ .

The names and number of categories are user defined, but there must be at least one category defined for a model. The ages are defined as a sequence from  $age_{min}$  to  $age_{max}$ , with the last age optionally a plus group. In order to calculate bio mass, the age-size relationship for each category must also be defined.

Hence, the definition of the population structure includes;

- The number and labels of the categories,  $k_{categories}$
- The age\_size relationship for each category
- The minimum and maximum ages that define the ages of the model,  $l_{ages}$
- If the last age is a plus group

## 4.4. Layers

*Layers* are used by SPM to evaluate locations where the population may be present (via the *base layer*), to provide sets of known attributes or values of each spatial location (for some processes and for preference based movements), and to group or categorise cells for use by processes and observations. Layers consist of an  $n_{rows} \times n_{cols}$  matrix and can be either *numeric* or *categorical*. See Section 4 for further details.

Layers are a key underlying concept in SPM. They comprise of a grid of known values, with a value for every spatial cell in the model. Layers are used by processes, observations, and outputs commands to supply spatially explicit covariates and any categorical groupings required.

Every model must define at least one layer, the base layer  $L_B$ . A layer is defined as a  $n_{rows} \times n_{cols}$  matrix of values (albeit with one exception — the distance layer — which we describe below), where the value in each cell represents a known quantity. For example layers may represent classifications, physical attributes, or some other known or assumed quantity. Typically they are provided by the user as a matrix of values, although some layer (e.g., abundance and distance layers) can be calculated by SPM during a model run.

Within SPM, layers are used in the following contexts:

1. The base layer: The base layer  $L_B$  is a special layer (there must be exactly one base layer defined within the model) that defines the locations where the population can and cannot potentially be present (e.g., locations associated with the sea and not land in a marine model). Here, we define that a cell may potentially have part of the population present if every element  $L_B(i, j) \geq 0$ . Further, positive values of the base layer  $L_B$  represent the *area* represented by that spatial cell. Note, the values in the base layer must be numeric.
2. Covariate layers: A model may have many covariate layers, and these are used as covariates of some population or movement process (e.g., the sea floor depth may be a covariate of some movement process). The values in layers used as covariates can be either numeric or categorical.
3. Classification layers: A model may have many classification layers, and these are used as a classification or grouping variable for aggregating data over individual spatial cells  $(i, j)$ , e.g., statistical areas or management areas. Such layers are typically used to aggregate the population within cells into groups so-as to allow comparison with observations. The values in layers used as classification layers must be categorical.

SPM defines the following types of layer;

1. Numeric layers: A model may have many numeric layers, and these can be used as covariates of a population or movement process (e.g., depth may be a covariate of some movement process), and/or locations of event mortality. Numeric layers can contain only continuous (numeric) variables. Values for a numeric layer must be supplied for each cell by the user.
2. Categorical layers: A model may have many categorical layers, and these can be used as a classification or grouping variable for aggregating data over individual cells, e.g., management areas; or as covariates of a population or movement process. Such layers are typically used to aggregate the population within cells into groups for comparing with observations, or to apply specific movement characteristics. The values in layers used as categorical layers can contain any characters (except white space), and are interpreted as categorical values. Values for a categorical layer must be supplied for each cell by the user.
3. Distance layers: A distance layer is one that defines the distance between any two cells. By default, SPM calculates the values of the distance layer as the Euclidean distance. Here, the

distance between cell  $a$  and cell  $b$  can be defined as,

$$d(a, b) = \lambda \sqrt{(x_a - x_b)^2 + (y_a - y_b)^2} \quad (4.1)$$

where  $x$  and  $y$  represent the  $x$ - and  $y$ -coordinates of  $a$  and  $b$  respectively, and  $\lambda$  is an arbitrary scaler representing the length of one side of the square. Unlike other types of layers, distance layers are not a  $n_{rows} \times n_{cols}$  grid of values, but rather a matrix of dimension  $(n_{rows} \times n_{cols}) \times (n_{rows} \times n_{cols})$  where the distance between each cell and every other cell is evaluated. Note that under this definition, the distance between any cell and itself is 0.

4. Abundance layers: The abundance layer is the sum of the number of individuals within cell  $a$  in categories  $k$  and with selectivity  $S_l$  at age  $l$ .

$$N(a) = \sum_k \sum_l S_l \text{element}(i, j, k, l) \quad (4.2)$$

SPM calculates the values of the layer when running the model at the point in time where the value is required.

5. Biomass layers: The biomass layer is the sum of the biomass of individuals within cell  $a$  in categories  $k$ , with selectivity  $S_l$  at age  $l$ , and mean weight  $w_{kl}$

$$N(a) = \sum_k \sum_l w_{k,l} S_l \text{element}(i, j, k, l) \quad (4.3)$$

SPM calculates the values of the layer when running the model at the point in time where the value is required.

6. Abundance-density layers: The abundance density layer is the density of the number of individuals within cell  $a$  with area  $A_a$  in categories  $k$ , with selectivity  $S_l$  at age  $l$ ,

$$N(a) = \frac{1}{A_a} \sum_k \sum_l S_l \text{element}(i, j, k, l) \quad (4.4)$$

SPM calculates the values of the layer when running the model at the point in time where the value is required.

7. Biomass-density layers: The biomass-density layer is the density of the biomass of individuals within cell  $a$  with area  $A_a$  in categories  $k$ , with selectivity  $S_l$  at age  $l$ , and mean weight  $w_{kl}$ ,

$$N(a) = \frac{1}{A_a} \sum_k \sum_l w_{k,l} S_l \text{element}(i, j, k, l) \quad (4.5)$$

SPM calculates the values of the layer when running the model at the point in time where the value is required.

8. Derived layers: SPM can calculate the value in each cell of a derived layer at some user-defined time-step each year, either as an abundance or as a biomass. Derived layers are actually a vector of layers, one for each year of the model (including the initialisation phases). Derived layers are the sum of abundance or biomass in a set of categories after applying a selectivity at the end of some time step for every model year.
9. Meta-layers: SPM defines a special type of layer known as a *meta-layer*. Meta-layers allows individual layers to be indexed by year and applied as an annually varying layer within the model. For example, assume that we had a model where we wished to use Sea Surface Temperature (SST) as a layer, perhaps to drive some movement process. The SST values for each year of the model would be defined as individual layers, each with a unique label. A

meta-layer could be defined that indexed the individual annual SST layers by year, and used as a covariate layer in the movement process. Meta-layers have a *default* layer that is used for time periods that are not specifically defined. Meta layers can be used wherever ordinary layers are used, with *SPM* extracting the appropriate layer value corresponding to the year or initialisation phase.

- (a) Numeric meta-layers: Numeric meta=layers are a meta layer of numeric layers — the individual ordinary layers that make up the meta-layer must all be of numeric type.
- (b) Categorical meta-layers: Categorical meta=layers are a meta layer of categorical layers — the individual ordinary layers that make up the meta-layer must all be of categorical type.

## 4.5. Time sequences

The time sequence of the model is defined in two parts;

- Initialisation
- Run years

### 4.5.1. Annual cycle

The annual cycle is implemented as a set of processes that occur, in a user-defined order, within each year. time-steps are used to break the annual cycle into separate components, and allow observations to be associated with different sets of processes. Any number of processes can occur within each time-step, in any order and can occur multiple times within each time-step. Note that time-steps are not implemented during the initialisation phases (effectively, there is only one time-step), and that the annual cycle in the initialisation phases can be different from that which is applied during the model years.

### 4.5.2. Initialisation

Model initialisation can occur in several phases, each which iterates through a number of years carrying out the population and/or spatial processes defined for that phase. At the end of the initialisation step, *SPM* runs through the model years carrying out processes in the order defined in the annual cycle, and can evaluate expected values of observations in order to calculate likelihoods, or simulate observations from the current state.

*SPM* initialises the initial equilibrium state as an iterative process, because a general solution that initialises complex structured movement models can be difficult to implement using analytic techniques. However, initialising via iteration for a long-lived species with complex movements can take many iterations, and be slow to run. In *SPM*, we allow for user-defined multi-phased initialisation using iteration to allow the user to optimize models for speed. Each phase of the initialisation can involve any number of population and/or movement processes.

In each initialisation phase, the processes defined for that phase are carried out and used as the starting point for the following phase or, if it is the last phase, then the years that the model is run over. The first phase is always initialised with each element (i.e., each age and category within each spatial cell) set at zero. Note that this means that recruitment processes where the numbers of recruits is based on a stock recruitment or density dependant relationship will likely fail if used in the first phase of an initialisation.

The multi-phase iteration also allows the user to determine if the initialisation has converged in a particular model run. Here, add an additional initialisation phase for, say, 1 year as the last initialisation phase (with the same processes applied). Then, using the initialisation reports (`@report[label].type=initialisation_phase`), print a copy of the partition just before and just after that phase. If the initialisation has converged to an equilibrium state, then the partition at both these time intervals will be the same.

Hence, for initialisation you need to define;

- The initialisation phases
- The number of years in each phase and the processes to apply in each

### 4.5.3. Model years

Following initialisation, the model then runs over a number of user-defined years. For this part of the model, the annual cycle can be broken into separate time-steps, and observations can be associated with the state of the model at the end of any time-step, i.e., likelihoods for particular observations are evaluated, if required, at the end of each time-step.

Processes are carried out in the order specified within each time-step, and can be the same or different to processes in other initialisation phases of the model. The run years define the years over which the model is to run and the annual cycle within each year. The model runs from the start of year `initial` and runs to the end of year `current`.

- The time-steps and the processes applied in each
- The initial year (i.e., the model start year)
- The current year (i.e., the model end year)

## 4.6. Processes

Processes produce changes in the model partition, by adding, removing or moving individuals between spatial cells (movement processes), and ages or categories (population processes). These include processes such as recruitment, mortality, ageing, and various forms of movement.

SPM has two types of processes, *population* and *movement* processes. Population processes are those processes which modify, move or otherwise change the numbers of individuals *within* a spatial cell, i.e., they do not affect the spatial location of a cohort. Movement processes, on the other hand, move, shift or otherwise modify cohorts *between* spatial cells, but do not affect the age or category of the numbers in each cohort.

The population processes include recruitment, ageing, mortality events (e.g., natural and exploitation) and category transition processes (i.e., processes that move individuals between categories, while preserving their age structure). See Section 4 for a complete list of available processes.

Each of these processes is carried out in the user-defined prescribed order when initialising the model, and then for a user-defined order in each year in the annual cycle.

SPM implements three different types of movement processes;

1. A migration movement rate of cohorts between any two locations, and is roughly analogous to movements between areas as implemented in other population models, such as CASAL (Bull et al., 2012).

2. An adjacent cell movements, parametrised by some function of an underlying layer — equivalent to, for example, movement processes implemented in Fish Heaven (Ball and Constable, 2000, Ball and Williamson, 2003).
3. Movement parametrised as a probability density function. Here, the key underlying idea is that the spatial distribution of cohorts at any point in time and at any location can be represented as a density function based on attributes of that location, local abundance, and/or distance from their previous location (Bentley et al., 2004a,b).

An SPM model can be parametrised by both population processes (for example, ageing, recruitment, and mortality), and movement processes. Population processes are those processes which modify, move or otherwise change the numbers of individuals within a spatial cell, i.e., they do not affect the spatial location of a cohort. Movement processes, on the other hand, move, shift or otherwise modify cohorts between spatial cells, but do not affect the age or category of the numbers in each cohort.

## 4.7. Population processes

Population processes are those processes that change the population state of individuals, but retain their location. The population processes are described below.

### 4.7.1. Recruitment

Recruitment processes are defined as process that introduces new individuals into the model. SPM implements three types of recruitment process, constant recruitment, Beverton-Holt recruitment (Beverton and Holt, 1957), and local Beverton-Holt recruitment.

In the recruitment processes, the number of individuals are added to a single age class within the partition, with the amount defined by the type of recruitment process and its function. If more than one category is defined, then the proportion of recruiting individuals to be added to each category is specified by the `proportions` parameter. For example, if recruiting to categories labelled male and female, then you might set the proportions as 0.5 and 0.5 respectively to denote that half of the recruits recruit to the male category and the remaining half to the female category.

For the constant and Beverton-Holt recruitment processes, the number of individuals in cell  $\text{cell}(i, j)$  following recruitment in year  $y$  is,

$$\text{element}(i, j, k, l) \leftarrow \text{element}(i, j, k, l) + p_k(R_y/n) \frac{L_{ij}}{\sum_i j L_{ij}} \quad (4.6)$$

where age is the age defined as the recruitment age,  $p_k$  is the proportion recruitment to category  $k$  defined to have recruitment,  $n$  is the number of spatial locations where recruitment occurs, and the recruitment to each cell is scaled to be proportional to the value of the layer in that cell. See below for how  $R_y$  is determined in each of these cases.

In the local Beverton-Holt recruitment process, individuals are recruited to an individual cell, based on the local abundance or biomass (i.e., the local SSB). For each cell where  $\text{cell}(i, j)$  is a member of some layer  $L_R$ , the number of individuals in that cell following recruitment in each year  $y$  is

$$\text{element}(i, j, k, l) \leftarrow \text{element}(i, j, k, l) + p_k R_y L_{ij} \quad (4.7)$$

where age is the age defined as the recruitment age,  $p_k$  is the proportion recruitment to category  $k$  defined to have recruitment, and the recruitment to each cell is the product of the Beverton-Holt stock recruitment relationship ( $R_y$ ).

**Constant Recruitment**

In the constant recruitment process the total number of recruits added each year is  $R_y$ , and is simply  $R_0$ , i.e.,

$$R_y = R_0 \quad (4.8)$$

It is equivalent to a Beverton-Holt recruitment process where steepness is set equal to one ( $h = 1$ ).

For example, to specify a constant recruitment process, where individuals are added to the category ‘immature’ at  $age = 1$ , and the number to add is  $R_0 = 5 \times 10^5$  in areas proportional to the value of the layer recruitment, then the syntax is,

```
@process Recruitment
type constant_recruitment
categories immature
proportions 1.0
R0 500000
age 1
layer recruitment
```

**Beverton-Holt recruitment**

In the Beverton-Holt recruitment process the total number of recruits added each year is  $R_y$ , and is the product of the average recruitment  $R_0$ , the annual year class strength multiplier,  $YCS$ , and the stock-recruit relationship i.e.,

$$R_y = R_0 \times YCS_{y-offset} \times SR(SSB_{y-offset}) \quad (4.9)$$

where *offset* is the number of years offset to link the year class with the year of spawning  $y$ , and  $SR$  is the Beverton-Holt stock-recruit relationship parametrised by the steepness  $h$ ,

$$SR(SSB_y) = \frac{SSB_y}{B_0} / \left( 1 - \frac{5h-1}{4h} \left( 1 - \frac{SSB_y}{B_0} \right) \right) \quad (4.10)$$

Note that the Beverton-Holt recruitment process requires a value for  $B_0$  and  $SSB_y$  to resolve the stock-recruitment relationship. Here, a derived quantity (see Section 4.9) must be defined that provides the annual  $SSB_y$  for the recruitment process.  $B_0$  is then defined as the value of the  $SSB$  at the end of one of the initialisation phases. During initialisation the  $YSC$  multipliers are assumed to be equal to one, and recruitment that happens in the initialisation phases that occur before and during the phase when  $B_0$  is determined is assumed to have steepness  $h = 1$  (i.e. in those initialisation phases, recruitment is simply equal to  $R_0$ ). Recruitment in the initialisation phases after the phase where  $B_0$  was determined follow the Beverton-Holt stock-recruit relationship defined above. Recruits are then distributed across cells in proportion to the values in a numeric layer.

For example, assume a Beverton-Holt recruitment process, where individuals are added to the category ‘immature’ at  $age = 1$ , the number to add is  $R_0 = 5 \times 10^5$  in areas proportional to the value of the layer `MyRecruitment`. Then `SSB_Biomass` is a derived layer that specifies the total spawning stock biomass, with  $B_0$  the value of the derived quantity at the end of the initialisation phase labelled `phase1`. The  $YCS$  are standardised to have mean one in the period 1994 to 2004, and recruits enter into the model two years following spawning. Then the command specification is,



```

@process Recruitment
type BH_recruitment
categories immature
proportions 1.0
R0 500000
steepness 0.75
age 1
layer MyRecruitment
B0 phasel
SSB SSB_Biomasss
standardise_YCS_years 1994-2004
YCS_years 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006
YCS_values 1 1 1 1 1 1 1 1 1 1 1 1 1
SSB_offset 2

```

Note that if not specified, *SSB\_offset* is set at the value of *age*. This corresponds to cases where recruitment happens after spawning. *SSB\_offset* can be user-defined to a different value if needed — for example, if recruitment happens in a time-step before spawning, the offset will need to be specified as *age* + 1.

### Local Beverton-Holt recruitment

The local Beverton-Holt recruitment process assumes that, for recruitment, each cell acts like a local population and is independent of its neighbours. The value of the  $SSB_y^i$  in each cell  $i$  for each year  $y$  is used to determine the amount of recruitment that enters that cell. If desired, locally recruits can subsequently be subjected to movement (see Section 4.8).

If the recruitment to cell  $i$  is  $R_y^i$ , then  $R_y^i$  is the product of the average recruitment  $R_0^i$  for that cell, the annual year class strength multiplier (assumed to be the same for all cells in each year), and the stock-recruit relationship, i.e.,

$$R_y^i = R_0^i \times YCS_{y-offset} \times SR(SSB_{y-offset}^i) \quad (4.11)$$

where *offset* is the number of years offset to link the year class with the year of spawning, and *SR* is the Beverton-Holt stock-recruit relationship parametrised by the steepness  $h$  and initial biomass  $B_0^i$

$$SR(SSB^i) = \frac{SSB^i}{B_0^i} / \left( 1 - \frac{5h-1}{4h} \left( 1 - \frac{SSB^i}{B_0^i} \right) \right) \quad (4.12)$$

Note that the local Beverton-Holt recruitment process requires a value for  $B_0^i$  and  $SSB_y^i$  to resolve the stock-recruitment relationship. Here, a derived layer (see Section 4.10) must be provided that defines  $B_0$  and the annual  $SSB_y$  for the recruitment process. As for the Beverton-Holt recruitment process above,  $B_0$  is then defined as the value of the  $SSB$  at the end of one of the initialisation phases. During initialisation the YCS multipliers are assumed to be equal to one, and recruitment that happens in the initialisation phases that occur before and during the phase when  $B_0$  is determined is assumed to have steepness  $h = 1$  (i.e. in those initialisation phases, recruitment is simply equal to  $R_0$ ). Recruitment in the initialisation phases after the phase where  $B_0$  was determined follow the Beverton-Holt stock-recruit relationship defined above.  $R_0^i$  is defined for each cell as the portion of the total recruitment  $R_0$  distributed relative to the recruitment layer *layer*.

For example, assume a local Beverton-Holt recruitment process, where individuals are added to the category ‘immature’ at *age* = 1, the number to recruit in each cell is  $R_0 = 5 \times 10^5$  multiplied by the

proportional value of the layer `MyRecruitment`. Then `SSB_Biomass` is a derived layer that specifies the spawning stock biomass in each cell, with  $B_0$  the value of the derived quantity at the end of the initialisation phase labelled `phase1`. The YCS are standardised to have mean one in the period 1994 to 2004, and recruits enter into the model two years following spawning. Then the command specification is,

```
@process Recruitment
type local_BH_recruitment
categories immature
proportions 1.0
R0 500000
steepness 0.75
age 1
layer MyRecruitment
B0 phase1
SSB SSB_Biomasss
standardise_YCS_years 1994-2004
YCS_years 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006
YCS_values 1 1 1 1 1 1 1 1 1 1 1 1 1
SSB_offset 2
```

Note that if not specified, *SSB\_offset* is set at the value of *age*. This corresponds to cases where recruitment happens after spawning. *SSB\_offset* can be user-defined to a different value if needed — for example, if recruitment happens in a time-step before spawning, the offset will need to be specified as  $age + 1$ .

#### 4.7.2. Ageing

The ageing process simply moves all individuals in the named categories to the next age class. The ageing process is defined as,

$$\text{element}(i, j, k, l) \leftarrow \text{element}(i, j, k, l - 1) \quad (4.13)$$

except that in the case of the plus group (if defined),

$$\text{element}(i, j, k, age_{max}) \leftarrow \text{element}(i, j, k, age_{max}) + \text{element}(i, j, k, age_{max-1}). \quad (4.14)$$

For example, to apply ageing to the categories `immature` and `mature`, then the syntax is,

```
@process Ageing
type ageing
categories immature mature
```

Note that ageing is *not* applied by SPM by default. As with other processes, SPM will not apply a process unless its defined and specified as a process within the annual cycle. Hence, it is possible to specify a model where a category is not aged. SPM will not check or otherwise warn if there is a category defined where ageing is not applied.

### 4.7.3. Mortality

Six types of mortality processes are permissible in SPM, constant rate, annually varying rate, event, biomass-event, a density-dependent relationship based on the Holling (Holling, 1959) Type II or Type III function, and a density-dependent relationship based on prey-switching process. These processes remove individuals from the partition, either as a rate (for constant or annually varying mortality processes), as a total number (abundance), or as a biomass of individuals. SPM does not implement the Baranov catch equation or any other process where both natural and event mortality are applied simultaneously. To approximate concurrent natural and event mortality, the population processes must be defined to remove some natural mortality (e.g., as a constant or annually varying), then some event mortality (e.g., fishing) in sequence. It is up to the user to specify how this happens.

The constant rate, annually varying rate, event, biomass-event mortalities can depend on a layer. In these cases, the value of instantaneous mortality applied to the population state within each cell is the product of the layer value, a selectivity, and the mortality rate. If the layer is static, mortality is effectively constant each year but can be different in each cell; if the layer is a derived layer and therefore calculated each year, mortality can change every year in every cell.

#### Constant mortality rate

To specify an constant annual mortality rate ( $M = 0.2$ ) for categories ‘male’ and ‘female’, then,

```
@process NaturalMortality
type constant_mortality_rate
categories male female
selectivities One One
M 0.2 0.2
```

Note that the mortality rate process requires a selectivity. To apply the same mortality rate over all age classes, use a selectivity defined as  $S_i = 1.0$  for all ages  $i$ , e.g.,

```
@selectivity One
type constant
c 1
```

A constant rate could also be defined as a multiplier of a layer. For example, let the mortality rate applied to the population at cell  $a$  in category  $k$  and age  $l$  be denoted  $M(a, k, l)$ , and given a value from a layer  $L_a$  at  $a$ , a constant mortality rate  $M$ , and a selectivity-at-age  $S_l$  at age  $l$  for some user-defined categories  $k$  then,

$$M(a, k, l) = ML_a S_l \quad (4.15)$$

And the resulting number of individuals remaining in cell  $a$  in category  $k$  at age  $l$  from applying the constant mortality process is,

$$n'(a, k, l) = n(a, k, l) \exp(-M(a, k, l)) \quad (4.16)$$

#### Annual mortality rate

Mortality for the annual rate is similar to the constant rate, except that rate applied each year is a separate parameter, and is applied equally to all of the specified categories. For example, if annual

rates were applied to males and females between 1996 and 2000, five values of  $M$  and the years that these apply to would need to be provided, e.g.,

```
@process AnnualMortality
type annual_mortality_rate
categories male female
selectivities One One
years 1996 1997 1998 1999 2000
M 0.20 0.15 0.22 0.25 0.21
```

### Event and biomass-event mortality

The event mortality process and biomass mortality processes act in a similar manner, except that they remove a specified abundance (number of individuals) or biomass respectively, rather than applying mortality as a rate. However, the maximum abundance or biomass to remove is constrained by a maximum exploitation rate.

The event mortality types must be defined using a layer. Here, the abundance or biomass to remove from a the population for each cell  $a$  is the value of the layer at  $a$  (denoted  $F_a$ ) — except where there are too few individuals for the event mortality to be taken (as defined by the maximum exploitation rate). In this scenario, SPM removes as many individuals or as much biomass as it can while not exceeding the maximum exploitation rate. Event mortality processes require a penalty function to discourage parameter values that do not allow a the defined number of individuals to be removed. Here, the model penalises those parameter estimates that result in an insufficient number of individuals in defined categories (after applying selectivities). See Section 5.8 for more information on specifying penalties.

For example, the event mortality applied to user-defined categories  $k$ , with the numbers removed at age  $l$  determined by a selectivity-at-age  $S_l$  is applied as follows:

First, calculate the vulnerable abundance for each category  $k$  in  $1 \dots K$  for ages  $l = 1 \dots L$  that are subject to event mortality,

$$V(k, l) = S(l)N(k, l) \quad (4.17)$$

And hence define the total vulnerable abundance  $V_{total}$  as,

$$V_{total} = \sum_K \sum_L V(k, l) \quad (4.18)$$

Hence the exploitation rate to apply is

$$U = \begin{cases} C/V_{total}, & \text{if } C/V_{total} \leq U_{max} \\ U_{max}, & \text{otherwise} \end{cases} \quad (4.19)$$

And the number removed  $R$  from each age  $l$  in category  $k$  is,

$$R(k, l) = UV(k, l) \quad (4.20)$$

For example, to specify fishing mortality based on spatially explicit catches (and given for each year as a layer, ‘Catch2000’, ‘Catch2001’, etc.,) over categories ‘immature’ and ‘mature’ with selectivity ‘FishingSel’ and assuming a maximum possible exploitation rate of 0.7, then the syntax is,

```
@process Fishing
type event_mortality
categories immature mature
years 2000 2001 2002 2003
layers Catch2000 Catch2001 Catch2002 Catch2003
U_max 0.70
selectivities FishingSel FishingSel
penalty event_mortality_penalty
```

### Holling mortality rate

The density-dependent Holling mortality process applies the Holling Type II and Type III functions (Holling, 1959), but is generalised using the Michaelis-Menten equation (Michaelis and Menten, 1913). The function removes a number or biomass from a set of categories according to their total (selected) abundance (or biomass) and some 'predator' abundance (or biomass), but constrained by a maximum exploitation rate.

For example, the mortality applied to user-defined categories  $k$ , with the numbers removed at age  $l$  determined by a selectivity-at-age  $S(l)$  is applied as follows:

First, calculate the total predator abundance (or biomass) over all predator categories  $k$  in  $1 \dots K$  and ages  $l = 1 \dots L$  that are applying the mortality,

$$P(k, l) = S_{predator}(l) N_{predator}(k, l) \quad (4.21)$$

And define the total predator abundance (or biomass)  $P_{total}$  as,

$$P_{total} = \sum_K \sum_L P(k, l) \quad (4.22)$$

Then, calculate the total vulnerable abundance (or biomass) over all prey categories  $k$  in  $1 \dots K$  and ages  $l = 1 \dots L$  that are subject to the mortality,

$$V(k, l) = S_{prey}(l) N_{prey}(k, l) \quad (4.23)$$

And hence define the total vulnerable abundance (or biomass)  $V_{total}$  as,

$$V_{total} = \sum_K \sum_L V(k, l) \quad (4.24)$$

and then, the the number to remove is determined as,

$$R_{total} = P_{total} \frac{a V_{total}^{x-1}}{b + V_{total}^{x-1}} \quad (4.25)$$

where  $x = 2$  for Holling type II function and  $x = 3$  for Holling type III function, or any value of  $x \geq 1$  for the generalised Michaelis-Menten function.

Hence the exploitation rate to apply is

$$U = \begin{cases} R_{total}/V_{total}, & \text{if } R_{total}/V_{total} \leq U_{max} \\ U_{max}, & \text{otherwise} \end{cases} \quad (4.26)$$

And the number removed  $R$  from each age  $l$  in category  $k$  is,

$$R(k, l) = UV(k, l) \quad (4.27)$$

The density-dependent Holling mortality process will be applied as a biomass or an abundance depending on the value of the `is_abundance` switch.

### Prey-switching mortality

The density-dependent prey-switching process applies predation mortality from any single predator group to all of its prey groups simultaneously. It removes an abundance (or biomass) from each prey group according to the total (selected) abundance (or biomass) of this prey group, the total (selected) abundance (or biomass) of all other prey groups, some 'predator' abundance (or biomass), and the preference (electivity) of the predator to each prey group, but constrained by a maximum exploitation rate. Note that each prey group can be composed of a number of individual categories, as can the predator group.

For example, the mortality applied to the user-defined prey group  $g$  of category  $k$ , with the numbers removed at age  $l$  determined by a selectivity-at-age  $S(l)$  is applied as follows:

First, calculate the total predator abundance (or biomass) over all predator categories  $k$  in  $1 \dots K$  and ages  $l = 1 \dots L$  that are applying the mortality,

$$P(k, l) = S_{predator}(l) N_{predator}(k, l) \quad (4.28)$$

And define the total predator abundance (or biomass)  $P_{total}$  as,

$$P_{total} = \sum_K \sum_L P(k, l) \quad (4.29)$$

Then, given the total vulnerable abundance (or biomass) of prey group  $g$  over all categories  $k$  in  $1 \dots K$  and ages  $l = 1 \dots L$  that are subject to the mortality,

$$V(g, k, l) = S_{prey}(l) N_{prey}(k, l) \quad (4.30)$$

And define the total vulnerable abundance (or biomass) of each prey group  $V(g)_{total}$  as,

$$V(g)_{total} = \sum_K \sum_L V(g, k, l) \quad (4.31)$$

The vulnerable abundance (or biomass) of every prey group  $g$  in  $1 \dots G$  is calculated simultaneously. Then the abundance (or biomass) to remove from each prey group  $g$  is a function of its electivity  $E(g)$ , the abundance (or biomass) of all other prey groups  $i$  in  $1 \dots G$ , the electivity of the predator for each prey group  $E(i)$ , and the total consumption rate of the predator  $CR$  and its abundance (or biomass)  $P_{total}$ ,

$$R(g)_{total} = P_{total} CR \frac{V(g)_{total} E(g)}{\sum_G V(i)_{total} E(i)} \quad (4.32)$$

Hence the exploitation rate to apply to each prey group  $g$  is

$$U(g) = \begin{cases} R(g)_{total} / V(g)_{total}, & \text{if } R(g)_{total} / V(g)_{total} \leq U_{max} \\ U_{max}, & \text{otherwise} \end{cases} \quad (4.33)$$

And the number removed  $R(g)$  in each prey group  $g$  from each age  $l$  in category  $k$  is,

$$R(g, k, l) = U(g) V(g, k, l) \quad (4.34)$$

Note that prey switching occurs only between prey groups specified by the process, and the total predator consumption rate represents the consumption of the predator on those prey groups alone. Also note that the electivities must sum to one.

The density-dependent prey-switching process will be applied as a biomass or an abundance depending on the value of the `is_abundance` switch.

#### 4.7.4. Category transitions

Category transition processes move individuals between categories. SPM implements two types, the total number and a rate.

The category transition process moves a number  $n$  between some source and sink category (or categories). This process may be used, for example, to implement a 'tagging' process for mark-recapture data. We define the transition process with selectivity  $S$  for source category  $a$  and sink category  $b$  as,

$$\begin{aligned} \text{element}(i, j, a, l) &\leftarrow \text{element}(i, j, a, l) - \frac{nS_l}{\sum_l S_l} \times \text{element}(i, j, a, l) \\ \text{element}(i, j, b, l) &\leftarrow \text{element}(i, j, b, l) + \frac{nS_l}{\sum_l S_l} \times \text{element}(i, j, a, l) \end{aligned} \quad (4.35)$$

Category transition processes require a penalty function to discourage parameter values that do not allow a the defined number of individuals to be moved. Here, the model penalises those parameter estimates that result in an insufficient number of individuals in the source category (after applying the selectivity) available to be moved. See Section 5.8 for more information on specifying penalties.

If multiple categories of sources or sinks are defined, then they must be defined in 'pairs'. The proportions of selected individuals in the source categories is used to define the proportions of individuals 'moved' to the sink categories, as defined by the order that they are specified. For example, to 'tag' a population of immature and mature individuals, then you might define a category transition process `tagging` with selectivities `tagging-Sel`, as,

```
@process tagging
type category_transition
from immature mature
selectivities tagging-Sel tagging-Sel
to immature-tag mature-tag
years 2001 2002 2003
layers TagRelease2001 TagRelease2002 TagRelease2003
penalty tag_release_penalty
```

Note that this syntax can be used to combine individuals, simply by repeating a category label when specifying the sink categories.

The transition rate type moves a proportion  $p$  between a source and sink category. The transition rate process with selectivity  $S$  for source category  $a$  and sink category  $b$  is,

$$\begin{aligned} \text{element}(i, j, a, l) &\leftarrow \text{element}(i, j, a, l) - pS_l \times \text{element}(i, j, a, l) \\ \text{element}(i, j, b, l) &\leftarrow \text{element}(i, j, b, l) + pS_l \times \text{element}(i, j, a, l) \end{aligned} \quad (4.36)$$

If multiple categories of sources or sinks are defined, then they must be defined in 'pairs'. SPM treats each pair of categories as an independent transition — but note that these are applied in order that they are specified. For example, to 'mature' males and females in a model with four categories `male-immature`, `female-immature`, `male-mature`, and `female-mature`, then you might define a category transition process `maturation` with selectivities `male-maturity` and `female-maturity`, as,

```
@process maturation
type category_transition_rate
from male-immature female-immature
to male-mature female-mature
proportions 1.0 1.0
selectivities male-maturity female-maturity
```

Note that this syntax can be used to combine individuals, simply by repeating a category label when specifying the sink categories. Similarly, individuals within a category can be split into more than one category by repeating a category label when specifying the source categories.

#### 4.8. Movement processes

Movement processes are those processes that move individuals between cells but retain their population state, and are defined such that,

$$\text{element}(i, j, k, l) \leftarrow \text{element}(i, j, k, l) + p \times \text{element}(i', j', k, l) \quad (4.37)$$

i.e., each element in cell  $(i, j)$  is updated as the sum of itself and some proportion  $p$  of a neighbouring element in cell  $(i', j')$ . To conserve abundance we also update  $\text{element}(i', j', k, l)$  as,

$$\text{element}(i', j', k, l) \leftarrow \text{element}(i', j', k, l) - p \times \text{element}(i', j', k, l) \quad (4.38)$$

SPM assumes that each movement process occurs simultaneously over all cells (synchronous updating), i.e., all cell updates from each individual movement process are first evaluated for all cells, and then applied to all cells affected.

SPM implements three types of movement;

1. A migration movement rate of cohorts between any two locations, and is roughly analogous to movements between areas as implemented in other population models, such as CASAL (Bull et al., 2012).
2. An adjacent cell movements, parametrised by some function of an underlying layer — equivalent to, for example, movement processes implemented in Fish Heaven (Ball and Constable, 2000, Ball and Williamson, 2003).
3. Movement parametrised as a probability density function. Here, the key underlying idea is that the spatial distribution of cohorts at any point in time and at any location can be represented as a density function based on attributes of that location, local abundance, and/or distance from their previous location (Bentley et al., 2004a,b).

##### 4.8.1. Migration movement

The migration process moves individuals from one sets of locations (the source, or emigration layer) to another set of locations (the sink, or immigration layer). A migration can involve one or more categories. The emigration at age is defined as some constant proportion multiplied by a selectivity and the source layer applied as a proportion. The immigration at age is defined as the number emigrating at age distributed proportionally into the sink layer. Migrations are similar to the migration process used in some limited space models such as CASAL (Bull et al., 2012).



For example, let the emigration applied to the population at cell  $a$  in category  $k$  and age  $l$  be denoted  $E(a, k, l)$ , and given a value from an source layer  $Le_a$  at  $a$ , a constant migration proportion  $P$ , and a selectivity-at-age  $S_l$  at age  $l$  for some user-defined categories  $k$  then,

$$E(a, k, l) = \frac{PLe_a S_l}{\sum_a Le_a} \quad (4.39)$$

And let the immigration applied to the population at cell  $a$  in category  $k$  and age  $l$  be denoted  $I(a, k, l)$ , and given a value from an sink layer  $Li_a$  at  $a$ , for some user-defined categories  $k$  then,

$$I(a, k, l) = \frac{E(a, k, l) Li_a}{\sum_a Li_a} \quad (4.40)$$

#### 4.8.2. Adjacent cell movement

The adjacent cell movement moves a proportion of individuals in each cell to its four neighbouring cells, and hence mimics a simple diffusion process. It can be applied to a limited range of spatial locations and/or as a gradient by using a layer. An adjacent cell movement can involve one or more categories and movement at age is defined as some constant proportion multiplied by a selectivity and the diffusion layer as a proportion over the four adjoining cells. If no layer is supplied, the process moves the population equally to the adjacent cells (i.e., a constant 0.25 proportion is assumed for each of the adjacent cells).

For example, let the movement from cell  $a$  to neighbouring cell  $b$  in category  $k$  and age  $l$  be denoted  $V(a, b, k, l)$ , and given a value from layer  $L_b$  at  $b$ , values from layer  $L_n$  at the four neighbouring cells to  $a$  (including cell  $b$ ), a constant migration proportion  $P$ , and a selectivity-at-age  $S_l$  at age  $l$  for some user-defined categories  $k$  then,

$$V(a, b, k, l) = \frac{PL_b S_l}{\sum_4 L_n} \quad (4.41)$$

The movement value of all cells into all their neighbouring cells are calculated simultaneously from the population layer at the time of movement, and the balance of all movements is returned.

#### 4.8.3. Preference movement

Preference movements allows movement from any  $cell(a) \rightarrow cell(b)$ , for  $\forall a, b \in L_B$  and is implemented as a function of the product of up to  $n$  independent *preference functions*. We define the probability of moving from any cell  $a$  to any cell  $b$ , for all  $a, b \in L_B$ , as a function of the relative preference for that cell. Here, we use the term *preference function* (Bentley et al., 2004a,b) to describe the movement probability distributions.

We assume that the population and spatial extent are defined, and that there is a preference function that is a function of some (typically estimable) parameters and a spatially explicit set of known attributes. The preference function movement process allows the number of parameters describing movement to be reduced, and results in a movement process that is some function of some underlying property of each location. For example, if we assume that movement between areas was a function of the Euclidean distance between areas, we could model movement between any two areas as a linear decay or exponential decay function (Bentley et al., 2004a). Alternately, if distribution and density were correlated with bathymetric depth for a marine organism, we might model the movement and distribution as a function of depth.

### The total preference function

Movement in SPM can be defined as a probability distribution based on an underlying preference function. Here, we define the preference for a cell  $x$  as the preference function  $f_x(\theta_x, P(x))$ , where  $\theta_x$  are the parameters for  $f_x$ . So, given a set of  $n$  attributes for cell  $x$ , we can define a preference function for each, and hence we define the aggregated or total preference function for any cell  $x$  as the weighted product of individual preference functions,

$$P_x = f_1(\theta_1, P_1(x))^{\alpha_1} \times f_2(\theta_2, P_2(x))^{\alpha_2} \times f_3(\theta_3, P_3(x))^{\alpha_3} \times \cdots \times f_n(\theta_n, P_n(x))^{\alpha_n} \quad (4.42)$$

where  $\alpha_i$  is an arbitrary weighting factor for attribute  $i$ . In order to avoid over-parametrisation, it is recommended that at least one  $\alpha_i$  be fixed to the value of one.

Then we define the probability of moving from cell  $a$  to any cell  $b$  (where  $b$  is defined as the set of all possible cells, including  $a$ ),

$$p(a \rightarrow b) = \frac{P_a}{\sum_{i \in \forall b} P_i} \quad (4.43)$$

Note that there are three forms of preference function,

1. Those that are a function of some underlying attribute of a cell, as defined by some arbitrary layer  $L$
2. Those that are a function of the abundance (perhaps with a selectivity and for a subset of all categories) of each cell
3. Those that are a function of the distance between the sink and the source cells.

Preference functions of the first type are determined only by the parameters of the preference function and some underlying, fixed, attribute. Preference functions of the others are dynamic, i.e. they depend on the relative locations of the cells or on the density of a cell at a particular point in time.

### Preference functions

Preference functions in SPM include constant, Normal, double-Normal, logistic, inverse-logistic, Exponential, threshold, categorical, and monotonic categorical. These are defined as,

1. The constant preference function has dependent variable  $x$  and has no parameters, and is defined as,

$$f(x) = x, \text{ where } 0 \leq x \leq 1 \quad (4.44)$$

2. The Normal preference function has dependent variable  $x$  and parameters  $\theta = (\mu, \sigma)$ , and is defined as,

$$f(x|\mu, \sigma) = 2^{-[(x-\mu)/\sigma]^2} \quad (4.45)$$

3. The double-Normal preference function has dependent variable  $x$  and parameters  $\theta = (\mu, \sigma_L, \sigma_R)$ , and is defined as,

$$f(x|\mu, \sigma_L, \sigma_R) = \begin{cases} 2^{-[(x-\mu)/\sigma_L]^2}, & \text{if } x \leq \mu \\ 2^{-[(x-\mu)/\sigma_R]^2}, & \text{if } x \geq \mu \end{cases} \quad (4.46)$$

4. The Logistic preference function has dependent variable  $x$  and parameters  $\theta = (a_{50}, a_{to95})$ , and is defined as,

$$f(x|a_{50}, a_{to95}) = 1/[1 + 19^{(a_{50}-x)/a_{to95}}] \quad (4.47)$$

5. The inverse-Logistic preference function has dependent variable  $x$  and parameters  $\theta = (a_{50}, a_{to95})$ , and is defined as,

$$f(x|a_{50}, a_{to95}) = 1 - 1/[1 + 19^{(a_{50}-x)/a_{to95}}] \quad (4.48)$$

6. The Exponential preference function has dependent variable  $x$  and parameter  $\theta = (\lambda)$ , and is defined as,

$$f(x|\lambda) = \exp(-\lambda x), \text{ where } x \geq 0 \text{ and } 0 \text{ otherwise} \quad (4.49)$$

7. The threshold preference function has dependent variable  $x$  and parameters  $\theta = (N, \lambda)$ , and is defined as,

$$f(x|N, \lambda) = \begin{cases} 1, & \text{if } 0 \leq x \leq N \\ 1/\left(\frac{x}{N}\right)^\lambda, & \text{if } x \geq N \\ 0, & \text{otherwise} \end{cases} \quad (4.50)$$

8. The categorical preference function has dependent variables  $x_i$  and parameters  $\theta = (\lambda_i)$ , and is defined so that for each value  $x_i$ , there is a corresponding parameter  $\lambda_i$ .

Note that for the categorical preference function, the preference function is potentially over-parameterised if  $\alpha \neq 1$ . Typically the values of  $x$  are supplied via a categorical layer, with  $x_i$  representing the unique values of the layer.

9. The monotonic categorical preference function has dependent variables  $x_i$  and parameters  $\theta = (\hat{\lambda}_i)$ . As for the categorical preference function, it is defined so that for each  $x_i$ , there is a corresponding parameter  $\hat{\lambda}_i = \lambda_i$  for the first unique value of  $x_i$  and  $\hat{\lambda}_i = \lambda_i + \lambda_{i-1}$  otherwise, and that  $\forall i, \lambda_i \geq 0$ .

Note that for the monotonic categorical preference function, the preference function is potentially over-parameterised if  $\alpha \neq 1$ . Typically the values of  $x$  are supplied via a categorical layer, with  $x_i$  representing the unique values of the layer.

#### 4.9. Derived quantities

Some processes require, as arguments, a population value derived from the population state. These are termed *derived quantities*. Derived quantities are values, calculated by SPM as the end of a specified time-step in every year, and hence they have a single value for each year of the model. Derived quantities can be calculated as either an abundance or as a biomass. Abundance derived quantities are simply the count or sum of cells within some categories (after applying a selectivity) within cells defined by a layer. Biomass derived quantities are similar, except they are a measure of biomass. Derived quantities are also calculated during the initialisation phases, and hence the time-step during each phase must also be specified. If the initialisation time-steps are not specified, SPM will calculate the derived quantity during the initialisation phases in every year, at the end of the annual cycle.

Derived quantities are required by some processes, for example the Beverton-Holt recruitment process. The Beverton-Holt recruitment process requires an equilibrium biomass ( $B_0$ ) and annual

spawning stock biomass values ( $SSB_y$ ) to resolve the stock-recruit relationship. Here, these would be defined as the abundance or biomass of a part of the population at some point in the annual cycle for selected ages and categories, and would be calculated as a derived quantity.

As an example, to define a biomass derived quantity (say spawning stock biomass, SSB) for a model, evaluated at the end of the first time-step (labelled `step_one`) in the initialisation phases (and assuming two initialisation phases) and at the end of the first time-step otherwise, over areas defined by a layer as the spawning ground but counting all ‘mature’ individuals, we would use the syntax,

```
@derived_quantity SSB
type biomass
time_step step_one
initialisation_time_steps step_one step_one
categories mature
selectivity One
layer spawning_ground
```

#### 4.10. Derived layers

Some processes require, as arguments, a population value derived from the population state, but available for each cell of the population. These are termed *derived layers*. Derived layers are a layer of values, calculated by SPM as the end of a specified time-step in every year, and hence they have a single value for each cell in each year of the model. Derived layers can be calculated as either an abundance or as a biomass. Abundance derived layers are simply the count or sum within each cell for some categories (after applying a selectivity). Biomass derived layers are similar, except they are a measure of biomass. Derived layers are also calculated during the initialisation phases, and hence the time-step during each phase must also be specified. If the initialisation time-steps are not specified, SPM will calculate the derived layer during the initialisation phases in every year, at the end of the annual cycle.

Derived layers are required by some processes, for example the local Beverton-Holt recruitment process. The local Beverton-Holt recruitment process requires an equilibrium biomass ( $B_0$ ) and annual spawning stock biomass values ( $SSB_y$ ) in each cell to resolve the stock-recruit relationship for each cell. Here, these would be defined as the abundance or biomass of a part of the population at some point in the annual cycle for selected ages and categories, and would be calculated as a derived layer.

As an example, to define a biomass derived layer (say spawning stock biomass, SSB) for a model, evaluated at the end of the first time-step (labelled `step_one`) in the initialisation phases (and assuming two initialisation phases) and at the end of the first time-step otherwise, but counting all ‘mature’ individuals, we would use the syntax,

```
@derived_quantity SSB
type biomass
time_step step_one
initialisation_time_steps step_one step_one
categories mature
selectivity One
```

#### 4.11. Size-age relationship

The age-size relationship defines the size at age (and the weight at size, see Section 4.12) of individuals at age/category within the model. There are three size-age relationships available in

SPM. The first is the naive no relationship (where each individual has size 1 irrespective of age). The second and third are the von-Bertalanffy and Schnute relationships respectively. The size-at-age relationship is used to determine the size frequency, given age, and then with the size-weight relationship, a weight-at-age of individuals within an age/category.

The three age-size relationships are,

None: where the size of each individual is exactly 1 for all ages, in which case the none size-weight relationship must also be used.

von Bertalanffy: where size at age is defined as,

$$\bar{s}(age) = L_{\infty} (1 - \exp(-k(age - t_0))) \quad (4.51)$$

Schnute: where size at age is defined as,

$$\bar{s}(age) = \begin{cases} \left[ y_1^b + (y_2^b - y_1^b) \frac{1 - \exp(-a(age - \tau_1))}{1 - \exp(-a(\tau_2 - \tau_1))} \right]^{1/b}, & \text{if } a \neq 0 \text{ and } b \neq 0 \\ y_1 \exp \left[ \ln(y_2/y_1) \frac{1 - \exp(-a(age - \tau_1))}{1 - \exp(-a(\tau_2 - \tau_1))} \right], & \text{if } a \neq 0 \text{ and } b = 0 \\ \left[ y_1^b + (y_2^b - y_1^b) \frac{age - \tau_1}{\tau_2 - \tau_1} \right]^{1/b}, & \text{if } a = 0 \text{ and } b \neq 0 \\ y_1 \exp \left[ \ln(y_2/y_1) \frac{age - \tau_1}{\tau_2 - \tau_1} \right], & \text{if } a = 0 \text{ and } b = 0 \end{cases} \quad (4.52)$$

The von Bertalanffy curve is parameterised by  $L_{\infty}$ ,  $k$ , and  $t_0$ ; the Schnute curve (Schnute, 1981) by  $y_1$  and  $y_2$ , which are the mean sizes at reference ages  $\tau_1$  and  $\tau_2$ , and  $a$  and  $b$  (when  $b = 1$ , this reduces to the von Bertalanffy with  $k = a$ ).

When defining size-at-age in SPM, you must also define a size-weight relationship (see Section 4.12 below).

#### 4.12. Size-weight relationship

There are two size-weight relationships available in SPM. The first is the naive no relationship, where the weight of an individual, regardless of size is always 1. The second is the basic relationship.

The two size-weight relationships are,

- None: The size-weight relationship where

$$\text{mean weight} = 1 \quad (4.53)$$

- Basic: The size-weight relationship where

$$\text{mean weight} = a(\text{mean size-at-age})^b \quad (4.54)$$

Be careful about the scale of  $a$  — this can easily be specified incorrectly. If the catch is in tonnes and the growth curve in centimetres, then  $a$  should be on the right scale to convert a length in centimetres to a weight in tonnes. Note that there are reports available that can be used to help check that the units specified are plausible (see Section 7).

### 4.13. Selectivities

A selectivity is a function with a different value for each age class (i.e., for each column of the partition). Selectivities are used throughout SPM to interpret observations (Section 5) or to modify the effects of processes on each age class (Section 4). SPM implements a number of different parametric forms, including logistic, knife edge, and double normal selectivities.

A selectivity is always defined to apply just to one category of the population (i.e., row of the partition). To apply the same selectivity to more than one category, then just repeat the selectivity for each category that it is applied to.

Note that selectivities are indexed by age, with indices from `min_age` to `max_age`. For example, you might have an age-based selectivity that was logistic with 50% selected at age 5 and 95% selected at age 7. This would be defined by the `type=logistic` with parameters  $a_{50} = 5$  and  $a_{95} = (7 - 5) = 2$ . Then the value of the selectivity at age  $x = 7$  is 0.95 and the selectivity at  $x = 3$  is 0.05.

Note that the function values for some choices of parameters for some selectivities can result in a computer numeric overflow error (i.e., the number calculated from parameter values is either too large or too small to be represented in computer memory). SPM implements range checks on some parameters to test for a possible numeric overflow error before attempting to calculate function values. For example, the logistic selectivity is implemented such that if  $(a_{50} - x)/a_{95} > 5$  then the value of the selectivity at  $x = 0$ , i.e., for  $a_{50} = 5$ ,  $a_{95} = 0.1$ , then the value of the selectivity at  $x = 1$ , without range checking would be  $7.1 \times 10^{-52}$ . With range checking, that value is 0 (as  $(a_{50}x)/a_{95} = 40 > 5$ ).

The available selectivities are;

- Constant
- Knife-edge
- All values
- All values bounded
- Increasing
- Logistic
- Inverse logistic
- Logistic producing
- Double normal
- Double exponential

The available selectivities are described below.

#### 4.13.1. constant

$$f(x) = C \tag{4.55}$$

The constant selectivity has the estimable parameter  $C$ .

**4.13.2. knife\_edge**

$$f(x) = \begin{cases} 0, & \text{if } x < E \\ \alpha, & \text{if } x \geq E \end{cases} \quad (4.56)$$

The knife-edge ogive has the estimable parameter  $E$  and a scaling parameter  $\alpha$ , where the default value of  $\alpha = 1$

**4.13.3. all\_values**

$$f(x) = V_x \quad (4.57)$$

The all-values selectivity has estimable parameters  $V_{low}, V_{low+1} \dots V_{high}$ . Here, you need to provide the selectivity value for each age class.

**4.13.4. all\_values\_bounded**

$$f(x) = \begin{cases} 0, & \text{if } x < L \\ V_x, & \text{if } L \leq x \leq H \\ V_H, & \text{if } x > H \end{cases} \quad (4.58)$$

The all-values-bounded selectivity has non-estimable parameters  $L$  and  $H$ . The estimable parameters are  $V_L, V_{L+1} \dots V_H$ . Here, you need to provide an selectivity value for each age class from  $L \dots H$ .

**4.13.5. increasing**

$$f(x) = \begin{cases} 0, & \text{if } x < L \\ f(x-1) + \pi_x(\alpha - f(x-1)), & \text{if } L \leq x \leq H \\ f(\alpha), & \text{if } x \geq H \end{cases} \quad (4.59)$$

The increasing ogive has non-estimable parameters  $L$  and  $H$ . The estimable parameters are  $\pi_L, \pi_{L+1} \dots \pi_H$  (but if these are estimated, they should always be constrained to be between 0 and 1).  $\alpha$  is a scaling parameter, with default value of  $\alpha = 1$ . Note that the increasing ogive is similar to the all-values-bounded ogive, but is constrained to be non-decreasing.

**4.13.6. logistic**

$$f(x) = \alpha / [1 + 19^{(a_{50}-x)/a_{t095}}] \quad (4.60)$$

The logistic selectivity has estimable parameters  $a_{50}$  and  $a_{t095}$ .  $\alpha$  is a scaling parameter, with default value of  $\alpha = 1$ . The logistic selectivity takes values  $0.5\alpha$  at  $x = a_{50}$  and  $0.95\alpha$  at  $x = a_{50} + a_{t095}$ .

**4.13.7. inverse\_logistic**

$$f(x) = \alpha - \alpha / [1 + 19^{(a_{50}-x)/a_{t095}}] \quad (4.61)$$

The inverse logistic selectivity has estimable parameters  $a_{50}$  and  $a_{t095}$ .  $\alpha$  is a scaling parameter, with default value of  $\alpha = 1$ . The logistic selectivity takes values  $0.5\alpha$  at  $x = a_{50}$  and  $0.95\alpha$  at  $x = a_{50} - a_{t095}$ .

**4.13.8. logistic\_producing**

$$f(x) = \begin{cases} 0, & \text{if } x < L \\ \lambda(L), & \text{if } x = L \\ (\lambda(x) - \lambda(x-1)) / (1 - \lambda(x-1)), & \text{if } L < x < H \\ 1, & \text{if } x \geq H \end{cases} \quad (4.62)$$

The logistic-producing selectivity has the non-estimable parameters  $L$  and  $H$ , and has estimable parameters  $a_{50}$  and  $a_{to95}$ .  $\alpha$  is a scaling parameter, with default value of  $\alpha = 1$ . For category transitions,  $f(x)$  represents the proportion moving, not the proportion that have moved. This selectivity was designed for use in an age-based model to model maturity. In such a model, a logistic-producing maturation selectivity will (in the absence of other influences) make the proportions mature follow a logistic curve with parameters  $a_{50}$ ,  $a_{to95}$ .

**4.13.9. double\_normal**

$$f(x) = \begin{cases} \alpha 2^{-[(x-\mu)/\sigma_L]^2}, & \text{if } x \leq \mu \\ \alpha 2^{-[(x-\mu)/\sigma_R]^2}, & \text{if } x \geq \mu \end{cases} \quad (4.63)$$

The double-normal selectivity has estimable parameters  $a_1$ ,  $s_L$ , and  $s_R$ .  $\alpha$  is a scaling parameter, with default value of  $\alpha = 1$ . It has values  $\alpha$  at  $x = a_1$ , and  $0.5\alpha$  at  $x = a_1 - s_L$  and  $x = a_1 + s_R$ .

**4.13.10. double\_exponential**

$$f(x) = \begin{cases} \alpha y_0 (y_1/y_0)^{(x-x_0)/(x_1-x_0)}, & \text{if } x \leq x_0 \\ \alpha y_0 (y_2/y_0)^{(x-x_0)/(x_2-x_0)}, & \text{if } x > x_0 \end{cases} \quad (4.64)$$

The double-exponential selectivity has non-estimable parameters  $x_1$  and  $x_2$ , and estimable parameters  $x_0$ ,  $y_0$ ,  $y_1$ , and  $y_2$ .  $\alpha$  is a scaling parameter, with default value of  $\alpha = 1$ . It can be ‘U-shaped’. Bounds for  $x_0$  must be such that  $x_1 < x_0 < x_2$ . With  $\alpha = 1$ , the selectivity passes through the points  $(x_1, y_1)$ ,  $(x_0, y_0)$ , and  $(x_2, y_2)$ . If both  $y_1$  and  $y_2$  are greater than  $y_0$  the selectivity is ‘U-shaped’ with minimum at  $(x_0, y_0)$ .



---

## 5. The estimation section

### 5.1. Role of the estimation section

The role of the estimation section is to define the tasks carried out by SPM:

1. Define the objective function (see Section 5.2)
2. Define the parameters to be estimated (see Section 5.3)
3. Calculate a point estimate, i.e., the maximum posterior density estimate (MPD) (see Section 5.4).
4. Calculate a posterior profile selected parameters, i.e., find, for each of a series of values of a parameter, allowing the other estimated parameters to vary, the minimum value of the objective function (see Section 5.5).
5. Generate an MCMC sample from the posterior distribution (see Section 5.6).
6. Calculate the approximate covariance matrix of the parameters as the inverse of the minimizer's approximation to the Hessian, and the corresponding correlation matrix (see Section 5.4).

The estimation section defines The objective function is based on a goodness-of-fit measure of the model to observations, priors and penalties. The observation section describes the objective function, observations, priors and penalties.

### 5.2. The objective function

In Bayesian estimation, the objective function is a negative log-posterior,

$$Objective(p) = -\sum_i \log[L(\mathbf{p}|O_i)] - \log[\pi(\mathbf{p})] \quad (5.1)$$

where  $\pi$  is the joint prior density of the parameters  $p$ .

The contribution to the objective function from the likelihoods are defined in Section 6.1. In addition to likelihoods, priors (see Section 5.7) and penalties (see Section 5.8) are components of the objective function.

You will usually want to use penalties to ensure that the exploitation rate constraints on your fisheries are not breached (otherwise there is nothing to prevent the model from having abundances so low that the recorded catches could not have been taken), penalties on category transitions (to ensure there are enough individuals to move), and possibly penalties to encourage estimated values to be similar, smoothed, etc.

### 5.3. Specifying the parameters to be estimated

You need to tell SPM which of the estimable parameters are to be estimated by using `@estimate` commands (see Section 9). An `@estimate` command-block looks like,

```
@estimate process[MyRecruitment].r0
lower_bound 1000
```

```
upper_bound 100000  
prior uniform
```

See Section 3.5.5 for instructions on how to generate the parameter name. You have to specify at least one parameter to be estimated if doing an estimation, profile, or MCMC run. You still provide values for the parameters to be estimated, and these are used as the starting values for the minimiser. However, these may be overwritten if you provide a set of alternative starting values (i.e., using `spm -i`, see Section 3.4).

All parameters are estimated within bounds. For each parameter to be estimated, you need to specify the bounds and the prior (Section 5.7). Note that the bounds and prior for each parameter refer to the values of the parameters, not the actual values resulting from the application of the parameter to an equation. If you want to estimate only some elements of a vector, either define the elements of the vector to be estimated (see 3.5.5) or fix the others by setting the bounds equal.

The estimation of parameters can be phased. Here, some of the estimated parameters are initially held fixed, and a minimisation is carried out. Next, some or all of the remaining parameters that were initially held fixed are freed, and another minimisation is carried out. This process continues until all phases have been carried out.

#### 5.4. Point estimation

Point estimation is invoked with `spm -e`. Mathematically, it is an attempt to find a minimum of the objective function. SPM has two algorithms for solving (minimising) the optimisation problem. The first uses a quasi-Newton minimiser built which is a slightly modified implementation of the main algorithm of Dennis Jr. & Schnabel (Dennis Jr and Schnabel, 1996), while the second uses a genetic algorithm developed by Storn & Price (Storn and Price, 1995), the differential evolution minimiser.

##### 5.4.1. The numerical differences minimiser

The minimiser has three kinds of (non-error) exit status:

1. Successful convergence (suggests you have found a local minimum, at least).
2. Convergence failure (you have not reached a local minimum, though you may deem yourself to be ‘close enough’ at your own risk).
3. Convergence unclear (the minimiser halted but was unable to determine if convergence occurred. You may be at a local minimum, although you should check by restarting the minimiser at the final values of the estimated parameters).

You can choose the maximum number of quasi-Newton iterations and objective function evaluations allotted to the minimiser. If it exceeds either limit, it exits with a convergence failure. We recommend large numbers of evaluations and iterations (at least the defaults of 300 and 1000) unless you successfully reach convergence with less. You can also specify an alternative starting point of the minimiser using `spm -i`.

We want to stress that this is a local optimisation algorithm trying to solve a global optimisation problem. What this means is that, even if you get a ‘successful convergence’ message, your solution may be only a local minimum, not a global one. To diagnose this problem, try doing multiple runs from different starting points and comparing the results, or doing profiles of one or more key parameters and seeing if any of the profiled estimates finds a better optimum than the original point estimate.

The approximate covariance matrix of the estimated parameters can be calculated as the inverse of the minimiser's approximation to the Hessian, and the corresponding correlation matrix is also calculated. Be aware that

- the Hessian approximation develops over many minimiser steps, so if the minimiser has only run for a small number of iterations the covariance matrix can be a very poor approximation
- the inverse Hessian is not a good approximation to the covariance matrix of the estimated parameters, and may not be useful to construct, for example, confidence intervals.

Also note that if an estimated parameter has equal lower and upper bounds, it will have entries of '0' in the covariance matrix and NaN or -1.#IND (depending on the operating system) in the correlation matrix.

#### 5.4.2. The differential evolution minimiser

The differential evolution minimiser is a simple population based, stochastic function minimizer, but is claimed to be quite powerful in solving minimisation problems. It is a method of mathematical optimization of multidimensional functions and belongs to the class of evolution strategy optimizers. Initially, the procedure randomly generates and evaluates a number of solution vectors (the population size), each with  $p$  parameters. Then, for each generation (iteration), the algorithm creates a candidate solution for each existing solution by random mutation and uniform crossover. The random mutation generates a new solution by multiplying the difference between two randomly selected solution vectors by some scale factor, then adding the result to a third vector. Then an element-wise crossover takes place with probability  $P_{cr}$ , to generate a potential candidate solution. If this is better than the initial solution vector, it replaces it, otherwise the original solution is retained. The algorithm is terminated after either a predefined number of generations (`max_generations`) or when the maximum difference between the scaled individual parameters from the candidate solutions from all populations is less than some predefined amount `tolerance`.

The differential evolution minimiser can be good at finding global minimums in surfaces that may have local minima. However, the speed of the minimiser, and the ability to find a good minima depend on the number of initial 'populations'. Some authors recommend that the number of populations be set at about  $10 * p$ , where  $p$  is the number of free parameters. However, depending on your problem, you may find that you may need more, or that less will suffice.

We note that there is no proof of convergence for the differential evolution solver, but several papers have found it to be an efficient method of solving multidimensional problems. Our (limited) experience suggests that it can often find a better minima and may be faster or longer (depending on the actual model specification) at finding a solution when compared with the numerical differences minimiser. Comparisons with auto-differentiation minimisers or other more sophisticated algorithms have not been made.

### 5.5. Posterior profiles

If profiles are requested `spm -p`, SPM will first calculate a point estimate. For each scalar parameter or, in the case of vectors or selectivities, the element of the parameter to be profiled, SPM will fix its value at a sequence of  $n$  evenly spaced numbers (`step`) between a specified lower and upper bounds  $l$  and  $u$ , and calculate a point estimate at each value.

By default `step = 10`, and  $(l, u) = (\text{lower bound on parameter plus } (range/(2n)), \text{upper bound on parameter less } (range/(2n)))$ . Each minimisation starts at the final parameter values from the

previous resulting value of the parameter being profiled. SPM will report the objective function for each parameter value. Note that an initial point estimate should be compared with the profile, not least to check that none of the other points along the profile have a better objective function value than the initial ‘minimum’.

You specify which parameters are to be profiled, and optionally the number of steps, lower bound, and upper bound for each. In the case of vector parameters, you will also need to specify the element of the vector being profiled.

You can also supply the initial starting point for the estimation using `spm -i file` — this may improve the minimiser performance for the profiles.

If you get an implausible profile, it may be a result of not using enough iterations in the minimiser or a poor choice of minimiser control variables (e.g., the minimiser tolerance). It also may be useful to try both if the minimisers in SPM and compare the results.

## 5.6. Bayesian estimation

SPM can use a Monte Carlo Markov Chain to generate a sample from the posterior distribution of the estimated parameters `spm -m` and output the sampled values to a file (optionally keeping only every  $n$ th set of values).

As SPM has no post-processing capabilities. SPM cannot produce MCMC convergence diagnostics (use a package such as BOA) or plot/summarize the posterior distributions of the output quantities (for example, using a general-purpose statistical or spreadsheet package such as S-Plus, **R**, or Microsoft Excel).

Bayesian methodology and MCMC are both large and complex topics, and we do not describe either properly here. See Gelman et al. (1995) and Gilks et al. (1994) for details of both Bayesian analysis and MCMC methods. In addition, see Punt & Hilborn (2001) for an introduction to quantitative fish stock assessment using Bayesian methods.

This section only briefly describes the MCMC algorithms used in SPM. See Section 9.3 for a better description of the sequence of SPM commands used in a full Bayesian analysis.

SPM uses a straightforward implementation of the Metropolis-Hastings algorithm (Gelman et al., 1995, Gilks et al., 1994). The Metropolis-Hastings algorithm attempts to draw a sample from a Bayesian posterior distribution, and calculates the posterior density  $\pi$ , scaled by an unknown constant. The algorithm generates a ‘chain’ or sequence of values. Typically the beginning of the chain is discarded and every  $N$ th element of the remainder is taken as the posterior sample. The chain is produced by taking an initial point  $x_0$  and repeatedly applying the following rule, where  $x_i$  is the current point:

- Draw a candidate step  $s$  from a proposal distribution  $J$ , which should be symmetric i.e.,  $J(-s) = J(s)$ .
- Calculate  $r = \min(\pi(x_i + s)/\pi(x_i), 1)$ .
- Let  $x_{i+1} = x_i + s$  with probability  $r$ , or  $x_i$  with probability  $1 - r$ .

An initial point estimate is produced before the chain starts, which is done so as to calculate the approximate covariance matrix of the estimated parameters (as the inverse Hessian), and may also be used as the starting point of the chain.

The user can specify the starting point of the point estimate minimiser using `spm -i`. Don’t start it too close to the actual estimate (either by using `spm -i`, or by changing the initial parameter values

in input configuration file) as it takes a few iterations to form a reasonable approximation to the Hessian.

There are two options for the starting point of the Markov Chain:

- Start from the point estimate.
- Start from a random point near the point estimate (the point is generated from a multivariate normal distribution, centred on the point estimate, with covariance equal to the inverse Hessian times a user-specified constant). This may be useful if the chain gets ‘stuck’ at the point estimate, or if you wish to generate multiple chains from for later MCMC diagnostic tests.

The chain moves in natural space, i.e., no transformations are applied to the estimated parameters. The default proposal distribution is a multivariate t centred on the current point, with covariance matrix equal to a matrix based on the approximate covariance produced by the minimiser, times some step-size factor. The following steps define the initial covariance matrix of the proposal distribution:

- The covariance matrix is taken as the inverse of the approximate Hessian from the quasi-Newton minimiser.
- The covariance matrix is modified so as to decrease all correlations greater than `@mcmc.max_correlation` down to `@mcmc.max_correlation`, and similarly to increase all correlations less than `-@mcmc.max_correlation` up to `-@mcmc.max_correlation` (the `@mcmc.max_correlation` parameter defaults to 0.8). This should help to avoid getting ‘stuck’ in a lower-dimensional subspace.
- The covariance matrix is then modified either by,
  - if `@mcmc.adjustment_method=covariance`: that if the variance of the  $i$ th parameter is non-zero and less than `@mcmc.min_difference` times the difference between the parameters’ lower and upper bound, then the variance is changed, without changing the associated correlations, to  $k = \min\_diff(upper\_bound_i - lower\_bound_i)$ . This is done by setting

$$\text{Cov}(i, j)' = \text{sqrt}(k) \text{Cov}(i, j) / \text{sd}(i)$$

for  $i \neq j$ , and  $\text{var}(i)' = k$

- if `@mcmc.adjustment_method=correlation`: that if the variance of the  $i$ th parameter is non-zero and less than `@mcmc.min_difference` times the difference between the parameters’ lower and upper bound, then its variance is changed to  $k = \min\_diff(upper\_bound_i - lower\_bound_i)$ . This differs from (i) above in that the effect of this option is that it also modifies the resulting correlations between the  $i$ th parameter and all other parameters.

This allows each estimated parameter to move in the MCMC even if its variance is very small according to the inverse Hessian. In both cases, the `@mcmc.min_difference` parameter defaults to 0.0001.

- The `@mcmc.step_size` (a scalar factor applied to the covariance matrix to improve the acceptance probability) is chosen by the user. The default is  $2.4d^{-0.5}$  where  $d$  is the number of estimated parameters, as recommended by Gelman et al. (Gelman et al., 1995). However, you may find that a smaller value may often be better.

The proposal distribution can also change adaptively during the chain, using two different mechanisms. Both are offered as means of improving the convergence properties of the chain. It is

important to note that any adaptive behaviour must finish before the end of the burn-in period, i.e., the proposal distribution must be finalised before the kept portion of the chain starts. The adaptive mechanisms are as follows:

1. You can request that the step size change adaptively at one or more sample numbers. At each adaptation, the step size is doubled if the acceptance rate since the last adaptation is more than 0.5, or halved if the acceptance rate is less than 0.2. (See Gelman et al. (Gelman et al., 1995) for justification.)

The probability of acceptance for each jump is 0 if it would move out of the bounds, or 1 if it improves the posterior, or (new posterior/old posterior) otherwise. You can specify how often the position of the chain is recorded using the keep parameter. For example, with keep 10, only every 10th sample is recorded.

You have the option to specify that some of the estimated parameters are fixed during the MCMC. If the chain starts at the point estimate or at a random location, these fixed parameters are set to their values at the point estimate.

The posterior sample can also be used for simulations (Section sec:simulation-observations) with the values supplied using `spm -i file`.

## 5.7. Priors

In a Bayesian analysis, you need to give a prior for every parameter that is being estimated. There are no default priors.

Note that when some of these priors are parameterised in terms of mean, c.v., and standard deviation, these refer to the parameters of the distribution before bounds are applied. The moments of the prior after the bounds are applied may differ.

SPM has the following priors (expressed in terms of their contribution to the objective function):

1. Uniform

$$-\log(\pi(p)) = 0 \tag{5.2}$$

2. Uniform-log (i.e.,  $\log(p) \sim \text{uniform}$ )

$$-\log(\pi(p)) = \log(p) \tag{5.3}$$

3. Normal with mean  $\mu$  and c.v.  $c$

$$-\log(\pi(p)) = 0.5 \left( \frac{p - \mu}{c\mu} \right)^2 \tag{5.4}$$

4. Normal with mean  $\mu$  and standard deviation  $\sigma$

$$-\log(\pi(p)) = 0.5 \left( \frac{p - \mu}{\sigma} \right)^2 \tag{5.5}$$

5. Lognormal with mean  $\mu$  and c.v.  $c$ 

$$-\log(\pi(p)) = \log(p) + 0.5 \left( \frac{\log(p/\mu)}{s} + \frac{s}{2} \right)^2 \quad (5.6)$$

where  $s$  is the standard deviation of  $\log(p)$  and  $s = \sqrt{\log(1+c^2)}$ .

6. Beta with mean  $\mu$  and standard deviation  $\sigma$ , and range parameters  $A$  and  $B$ 

$$-\log(\pi(p)) = (1-m)\log(p-A) + (1-n)\log(B-p) \quad (5.7)$$

where  $v = \frac{\mu-A}{B-A}$ , and  $\tau = \frac{(\mu-A)(B-\mu)}{\sigma^2} - 1$  and then  $\mu = \tau v$  and  $n = \tau(1-v)$ . Note that the beta prior is undefined when  $\tau \leq 0$ .

## 5.8. Penalties

Penalties can be used to encourage or discourage parameter values or model outputs that are unlikely to be sensible, by adding a penalty to the objective function. For example, parameter estimates that do not allow a known mortality event to remove enough individuals from the population can be discouraged with an event mortality penalty. SPM requires penalty functions for processes that move or shift a *number* of individuals between categories or from the partition.

For most penalties, you need to specify a multiplier, and the objective function is increased by this multiplier times the penalty value as described below. In some cases you will need to make the multiplier quite large to prohibit some model behaviour.

Currently, the penalties for the processes `@process[label].type=event_mortality` and `@process[label].type=category_transition` are the only penalties implemented.

For both of these processes, two types of penalty can be defined, natural scale (the default) and log scale. Both of these types add a penalty value of the squared difference between the observed value (i.e., the actual number of individuals to be removed in an event mortality process or the actual number of individuals to shift in a category transition process), and the number that were moved (if less than or equal), times the penalty multiplier.

The natural scale penalty just uses at the squared difference on a natural scale, while the log scale penalty uses the squared difference of the logged values.





---

## 6. The observation section

### 6.1. Observations and likelihoods

Observations are typically supplied as observations at an instance in time, over some spatially aggregated area. Time series of observations can be supplied as separate observations for each year or point in time.

SPM allows the following types of observations;

Observations of proportions by age class within categories

Observations of proportions between categories within age classes

Relative and absolute abundance/biomass observations

The definitions for each type of observation are described below, including how the observed values should be supplied, how SPM calculates the expected values, and the likelihoods that are available for each type of observation.

SPM evaluates the observations at the end of a time-step (i.e., after all of the processes for that time-step have been applied). However, the observation can be applied to the abundance at the start of a time-step or part-way through a time-step by the use of the `proportion_time_step` subcommand.

By default (i.e., if `proportion_method = mean`), the partition at some point  $p$  during the time-step is then evaluated as the weighted sum between the start and end of the time-step, i.e, for any element  $i$  in the partition,  $n_i = (1 - p)n_i^{start} + pn_i^{end}$ . Note that it may not be sensible to use a value other than one, depending on the processes that happen during the time-step (for example, if the time-step contains an ageing process).

If the `proportion_method = difference`, then the observation is of the *difference* between the population state at the start of the time-step and the end. This can be used to generate expected values for observations of, for example removals due to a mortality event, by only having a single process in the time-step. In this case, the `proportion_time_step` is simply a multiplier of the population state.

### 6.2. Proportions-at-age observations

Proportions-at-age observations are observations of either the relative number of individuals at age or relative biomass at age.

The observation is supplied for a given year and time-step, for some selected age classes of the population (i.e., for a range of ages multiplied by a selectivity), for categories aggregated over a set of spatial cells. Note that the observations at age can include a plus group, which must be less than or equal to the maximum age defined for the partition.

The age range must be ages defined in the partition (i.e., between `@model.min_age` and `@model.max_age` inclusive), but the upper end of the age range can optionally be a plus group — which may or may not be the same as the plus group defined for the partition.

Proportions-at-age observations can be supplied for a single category, aggregated across categories, or be proportions of multiple categories. For example, for a model with the two categories *male* and *female*, we might supply either (i) observations of the proportions of males (or alternately female) within each age class; (ii) proportions of total individuals (males + females) at each age class, or (iii) the proportions of individuals for both male and female categories simultaneously. In addition, each category must have an associated selectivity, defined by `selectivities`.

The way the categories of the observation are defined specifies which of these alternatives to use. For example, to specify that the observations are of the proportions of male within each age class (example (i) above), then the subcommand `categories` for the `@observation[label].type=proportion.by_age` command is,

```
categories male
```

SPM then expects that there will be a vector of proportions supplied, with one proportion for each age class within the defined age range. For example, if the age range was 3 to 10, then 8 proportions should be supplied (one proportion for each of the ages 3, 4, 5, 6, 7, 8, 9, and 10). The expected values will be the expected proportions of males within each of these age classes, after applying a selectivity at the year and time-step specified. Note that the supplied vector of proportions (i.e., in this example, the 8 proportions) must sum to one (with a default tolerance of 0.001).

The observations must be supplied using all or some of the values of defined by a categorical layer. SPM calculates the expected values by summing over the defined ages (via the age range and selectivity) and categories for those spatial cells where the categorical layer has the same value as defined for each vector of observations.

For example, in a  $2 \times 2$  spatial model a categorical layer (e.g., with label *Area*) may define that cells (1,1) and (1,2) have value *A* and cells (2,1) and (2,2) have value *B*, i.e.,

```
@layer Area
type categorical
data A A
data B B
```

Here we supply observations for those spatial cells where the categorical layer has value *A* as,

```
@observation MyProportions
...
categories male female
min_age 1
max_age 5
obs A 0.01 0.05 0.10 0.20 0.20 0.01 0.05 0.15 0.20 0.03
...
```

Or, for both *A* and *B* as,

```
@observation MyProportions
...
categories male female
min_age 1
max_age 5
obs A 0.01 0.05 0.10 0.20 0.20 0.01 0.05 0.15 0.20 0.03
obs B 0.02 0.06 0.10 0.21 0.18 0.02 0.05 0.15 0.20 0.01
...
```

Or for example, 12 observations are required to describe immature males, mature males, and all females together, for ages 1–4,

```
@observation MyProportions
```

```

...
categories male_immature male_mature female_immature + female_mature
min_age 1
max_age 4
obs A 0.05 0.15 0.15 0.05 0.02 0.03 0.08 0.04 0.05 0.15 0.15 0.08
...

```

It may be useful at times to consider grouping categories together even though the data might have been collected separately, as the model cannot dissociate the uncertainty between age classes and that between the proportion of fish at age in each category. For example if observations have been collected for males and females separately, but very few females were caught, the uncertainty surrounding the ratio of males to females might be higher than the model applies, as it applies the same uncertainty to that surrounding the data. In this case an alternative is to provide the proportions at age for males and females together with appropriate uncertainty, and then the proportion-at-age (see Section 6.3) of males as a different observation with a different (and in this case higher) uncertainty.

To supply an observation for individual spatial cells, then define a categorical layer with a single, unique value for each spatial cell.

### 6.2.1. Likelihoods for proportions-at-age observations

SPM implements two likelihoods for proportions-at-age observations, the multinomial likelihood and the lognormal likelihood.

#### The multinomial likelihood

For the observed proportions at age  $O_i$  for age classes  $i$ , with sample size  $N$ , and the expected proportions at the same age classes  $E_i$ , the negative log-likelihood is defined as;

$$-\log(L) = -\log(N!) + \sum_i \log((NO_i)!) - NO_i \log(Z(E_i, \delta)) \quad (6.1)$$

where  $\sum_i O_i = 1$  and  $\sum_i E_i = 1$ .  $Z(\theta, \delta)$  is a robustifying function to prevent division by zero errors, with parameter  $\delta > 0$ .  $Z(\theta, \delta)$  is defined as,

$$Z(\theta, \delta) = \begin{cases} \theta, & \text{where } \theta \geq r \\ \delta / (2 - \theta / \delta), & \text{otherwise} \end{cases} \quad (6.2)$$

The default value of  $\delta$  is  $1 \times 10^{-11}$ .

#### The lognormal likelihood

For the observed proportions at age  $O_i$  for age classes  $i$ , with c.v.  $c_i$ , and the expected proportions at the same age classes  $E_i$ , the negative log-likelihood is defined as;

$$-\log(L) = \sum_i \left( \log(\sigma_i) + 0.5 \left( \frac{\log(O_i / Z(E_i, \delta))}{\sigma_i} + 0.5 \sigma_i \right)^2 \right) \quad (6.3)$$

where

$$\sigma_i = \sqrt{\log(1 + c_i^2)} \quad (6.4)$$

and the  $c_i$ 's are the c.v.s for each age class  $i$ , and  $Z(\theta, \delta)$  is a robustifying function to prevent division by zero errors, with parameter  $\delta > 0$ .  $Z(\theta, \delta)$  is defined as,

$$Z(\theta, \delta) = \begin{cases} \theta, & \text{where } \theta \geq r \\ \delta / (2 - \theta / \delta), & \text{otherwise} \end{cases} \quad (6.5)$$

The default value of  $\delta$  is  $1 \times 10^{-11}$ .

### 6.3. Proportions-by-category observations

Proportions-by-category observations are observations of either the relative number of individuals between categories within age classes, or relative biomass between categories within age classes.

The observation is supplied for a given year and time-step, for some selected age classes of the population (i.e., for a range of ages multiplied by a selectivity), for categories aggregated over a set of spatial cells.

The age range must be ages defined in the partition (i.e., between `@model.min_age` and `@model.max_age` inclusive), but the upper end of the age range can optionally be a plus group — which may or may not be the same as the plus group defined for the partition.

Proportions-by-category observations can be supplied for any set of categories as a proportion of themselves and any set of additional categories. For example, for a model with the two categories *male* and *female*, we might supply observations of the proportions of males in the population at each age class. The subcommand `categories` defines the categories for the numerator in the calculation of the proportion, and the subcommand `categories2` supplies the additional categories to be used in the denominator of the calculation. In addition, each category must have an associated selectivity, defined by `selectivities` for the numerator categories and `selectivities2` for the additional categories used in the denominator, e.g.,

```
categories male
categories2 female
selectivities male-selectivity
selectivities2 female-selectivity
```

defines that the proportion of males in each age class as a proportion of males + females. SPM then expects that there will be a vector of proportions supplied, with one proportion for each age class within the defined age range, i.e., if the age range was 3 to 10, then 8 proportions should be supplied (one proportion for each of the ages 3, 4, 5, 6, 7, 8, 9, and 10). The expected values will be the expected proportions of male to male + female within each of these age classes, after applying the selectivities at the year and time-step specified.

The observations must be supplied using all or some of the values defined by a categorical layer. SPM calculates the expected values by summing over the ages (via the age range and selectivity) and categories for those spatial cells where the categorical layer has the same value as defined for each vector of observations.

For example, in a  $2 \times 2$  spatial model a categorical layer (e.g., with label *Area*) may define that cells (1,1) and (1,2) have value *A* and cells (2,1) and (2,2) have value *B*, i.e.,

```
@layer Area
type categorical
data A A
data B B
```

Here we supply observations for those spatial cells where the categorical layer has value *A* as,

```
@observation MyProportions
...
```

```

categories male
categories2 female
min_age 1
max_age 5
obs A 0.01 0.05 0.10 0.20 0.20
...

```

Or, for both *A* and *B* as,

```

@observation MyProportions
...
categories male
categories2 female
min_age 1
max_age 5
obs A 0.01 0.05 0.10 0.20 0.20
obs B 0.02 0.06 0.10 0.21 0.18
...

```

To supply an observation for individual spatial cells, then you will need to define a categorical layer with a single, unique value for each spatial cell.

### 6.3.1. Likelihoods for proportions-by-category observations

SPM implements two likelihoods for proportions-by-category observations, the binomial likelihood, and the normal approximation to the binomial (binomial-approx).

#### The binomial likelihood

For observed proportions  $O_i$  for age class  $i$ , where  $E_i$  are the expected proportions for age class  $i$ , and  $N_i$  is the effective sample size for age class  $i$ , then the negative log-likelihood is defined as;

$$\begin{aligned}
 -\log(L) = & -\sum_i \log(N_i!) - \log((N_i(1 - O_i))!) - \log((N_i O_i)!) + N_i O_i \log(Z(E_i, \delta)) \\
 & + N_i(1 - O_i) \log(Z(1 - E_i, \delta))
 \end{aligned} \tag{6.6}$$

where  $Z(\theta, \delta)$  is a robustifying function to prevent division by zero errors, with parameter  $\delta > 0$ .  $Z(\theta, \delta)$  is defined as,

$$Z(\theta, \delta) = \begin{cases} \theta, & \text{where } \theta \geq r \\ \delta / (2 - \theta / \delta), & \text{otherwise} \end{cases} \tag{6.7}$$

The default value of  $\delta$  is  $1 \times 10^{-11}$ .

#### The normal approximation to the binomial likelihood

For observed proportions  $O_i$  for age class  $i$ , where  $E_i$  are the expected proportions for age class  $i$ , and  $N_i$  is the effective sample size for age class  $i$ , then the negative log-likelihood is defined as;

$$-\log(L) = \sum_i \log\left(\sqrt{Z(E_i, \delta)Z(1 - E_i, \delta)/N_i}\right) + \frac{1}{2} \left( \frac{O_i - E_i}{\sqrt{Z(E_i, \delta)Z(1 - E_i, \delta)/N_i}} \right)^2 \tag{6.8}$$

where  $Z(\theta, \delta)$  is a robustifying function to prevent division by zero errors, with parameter  $\delta > 0$ .  $Z(\theta, \delta)$  is defined as,

$$Z(\theta, \delta) = \begin{cases} \theta, & \text{where } \theta \geq r \\ \delta / (2 - \theta / \delta), & \text{otherwise} \end{cases} \quad (6.9)$$

The default value of  $\delta$  is  $1 \times 10^{-11}$ .

#### 6.4. Abundance or biomass observations

Abundance (or biomass) observations are observations of either a relative or absolute number (or biomass) of individuals from a set of categories after applying a selectivity. The observations classes are the same, except that a biomass observation will use the biomass as the observed (and expected) value (calculated from mean weight of individuals within each age and category) while an abundance observation is just the number of individuals.

Each observation is for a given year and time-step, for some selected age classes of the population (i.e., for a range of ages multiplied by a selectivity), for categories aggregated over a set of spatial cells. Further, you need to provide the label of the catchability coefficient  $q$ , which can either be estimated or fixed. For absolute abundance or absolute biomass observations, define a catchability where  $q = 1$ .

The observations can be supplied for any set of categories. For example, for a model with the two categories *male* and *female*, we might supply an observation of the total abundance/biomass (male + female) or just male abundance/biomass. The subcommand `categories` defines the categories used to aggregate the abundance/biomass. In addition, each category must have an associated selectivity, defined by `selectivities`, e.g.,

```
categories male
selectivities male-selectivity
```

defines an observation for males after applying the selectivity `male-selectivity`. SPM then expects that there will be a single observation supplied. The expected values for the observations will be the expected abundance (or biomass) of males, after applying the selectivities, at the year and time-step specified.

The observations must be supplied using all or some of the values of defined by a categorical layer. SPM calculates the expected values by summing over the defined ages (via the age range and selectivity) and categories for those spatial cells where the categorical layer has the same value as defined for each vector of observations.

For example, in a  $2 \times 2$  spatial model a categorical layer (e.g., with label `Area`) may define that cells (1,1) and (1,2) have value *A* and cells (2,1) and (2,2) have value *B*, i.e.,

```
@layer Area
type categorical
data A A
data B B
```

Here we supply observations for those spatial cells where the categorical layer has value *A* as,

```
@observation MyAbundance
...
categories male
obs A 1000
...
```

Or, for both  $A$  and  $B$  as,

```
@observation MyAbundance
...
categories male
obs A 1000
obs B 1200
...
```

To supply an observation for individual spatial cells, then you will need to define a categorical layer with a single, unique value for each spatial cell.

### 6.4.1. Likelihoods for abundance observations

#### The lognormal likelihood

For observations  $O_i$ , c.v.  $c_i$ , and expected values  $qE_i$ , the negative log-likelihood is defined as;

$$-\log(L) = \sum_i \left( \log(\sigma_i) + 0.5 \left( \frac{\log(O_i/qZ(E_i, \delta))}{\sigma_i} + 0.5\sigma_i \right)^2 \right) \quad (6.10)$$

where

$$\sigma_i = \sqrt{\log(1 + c_i^2)} \quad (6.11)$$

and  $Z(\theta, \delta)$  is a robustifying function to prevent division by zero errors, with parameter  $\delta > 0$ .  $Z(\theta, \delta)$  is defined as,

$$Z(\theta, \delta) = \begin{cases} \theta, & \text{where } \theta \geq r \\ \delta/(2 - \theta/\delta), & \text{otherwise} \end{cases} \quad (6.12)$$

The default value of  $\delta$  is  $1 \times 10^{-11}$ .

#### The normal likelihood

For observations  $O_i$ , c.v.  $c_i$ , and expected values  $qE_i$ , the negative log-likelihood is defined as;

$$-\log(L) = \sum_i \left( \log(c_i E_i) + 0.5 \left( \frac{O_i - E_i}{Z(c_i E_i, \delta)} \right)^2 \right) \quad (6.13)$$

and  $Z(\theta, \delta)$  is a robustifying function to prevent division by zero errors, with parameter  $\delta > 0$ .  $Z(\theta, \delta)$  is defined as,

$$Z(\theta, \delta) = \begin{cases} \theta, & \text{where } \theta \geq r \\ \delta/(2 - \theta/\delta), & \text{otherwise} \end{cases} \quad (6.14)$$

The default value of  $\delta$  is  $1 \times 10^{-11}$ .

### 6.5. Process error

Additional ‘process error’ can be defined for each set of observations. Additional process error has the effect of increasing the observation error in the data, and hence of decreasing the relative weight given to the data in the fitting process.

For observations where the likelihood is parameterised by the c.v., you can specify the process error for a given set of observations as a c.v., in which case all the c.v.s  $c_i$  are changed to

$$c'_i = \sqrt{c_i^2 + c_{process\_error}^2} \quad (6.15)$$

Note that  $c_{process\_error} \geq 0$ , and that  $c_{process\_error} = 0$  is equivalent to no process error.

Similarly, if the likelihood is parameterised by the effective sample size  $N$ ,

$$N'_i = \frac{1}{1/N_i + 1/N_{process\_error}} \quad (6.16)$$

Note that this requires that  $N_{process\_error} > 0$ , but we allow the special case of  $N_{process\_error} = 0$ , and define  $N_{process\_error} = 0$  as no process error (i.e., defined to be equivalent to  $N_{process\_error} = \infty$ ).

For both the c.v. and  $N$  process errors, the process error has more effect on small errors than on large ones. Be clear that a large value for the  $N$  process error means a small process error.

### 6.6. Ageing error

SPM can apply ageing error age frequency observations. Ageing error is applied to the expected values for proportions-at-age observations. The ageing error is applied as a misclassification matrix, which has the effect of ‘smearing’ the age frequencies. These are used in calculating the fits to the observed values, and hence the contribution to the total objective function.

Ageing error is optional, and if it is used, it may be omitted for any individual time series. Different ageing error models may be applied for different observation commands. See Section 7.15 for reporting the misclassification matrix.

The ageing error models implemented are,

1. None: The default model is to apply no ageing error.
2. Off by one: Proportion  $p_1$  of individuals of each age  $a$  are misclassified as age  $a - 1$  and proportion  $p_2$  are misclassified as age  $a + 1$ . Individuals of age  $a < k$  are not misclassified. If there is no plus group in the population model, then proportion  $p_2$  of the oldest age class will ‘fall off the edge’ and disappear.
3. Normal: Individuals of age  $a$  are classified as ages which are normally distributed with mean  $a$  and constant c.v.  $c$ . As above, if there is no plus group in the population model, some individuals of the older age classes may disappear. If  $c$  is high enough, some of the younger age classes may ‘fall off the other edge’. Individuals of age  $a < k$  are not misclassified.

Note that the expected values (fits) reported by SPM for observations with ageing error will have had the ageing error applied.

### 6.7. Simulating observations

SPM can generate simulated observations for a given model with given parameter values (using `spm -s`). Simulated observations are randomly distributed values, generated according to the error assumptions defined for each observation, around fits calculated from one or more sets of the ‘true’ parameter values. Simulating from a set of parameters can be used to generate observations from an operating model or as a form of parametric bootstrap.



The procedure SPM uses for simulating observations is to first run using the ‘true’ parameter values and generate the expected values. Then, if a set of observations uses ageing error, ageing error is applied. Finally a random value for each observed value is generated based on (i) the expected values, (ii) the type of likelihood specified, and (iii) the variability parameters (e.g., `error_value` and `process_error`).

Methods for generating the random error, and hence simulated values, depend on the specific likelihood type of each observation.

1. Normal likelihood parameterised by c.v.: Let  $E_i$  be the fitted value for observation  $i$ , and  $c_i$  be the corresponding c.v. (adjusted by the process error if applicable). Each simulated observation value  $S_i$  is generated as an independent normal deviate with mean  $E_i$  and standard deviation  $E_i c_i$ .
2. Log-normal likelihood: Let  $E_i$  be the fitted value for observation  $i$  and  $c_i$  be the corresponding c.v. (adjusted by the process error if applicable). Each simulated observation value  $S_i$  is generated as an independent lognormal deviate with mean and standard deviation (on the natural scale, not the log-scale) of  $E_i$  and  $E_i c_i$  respectively. The robustification parameter  $\delta$  is ignored.
3. Multinomial likelihood: Let  $E_i$  be the fitted value for observation  $i$ , for  $i$  between 1 and  $n$ , and let  $N$  be the sample size (adjusted by process error if applicable, and then rounded up to the next whole number). The robustification parameter  $\delta$  is ignored. Then,
  - (a) A sample of  $N$  values from 1 to  $n$  is generated using the multinomial distribution, using sample probabilities proportional to the values of  $E_i$ .
  - (b) Each simulated observation value  $S_i$  is calculated as the proportion of the  $N$  sampled values equalling  $i$
  - (c) The simulated observation values  $S_i$  are then rescaled so that their sum is equal to 1
4. Binomial and the normal approximation to the binomial likelihoods: Let  $E_i$  be the fitted value for observation  $i$ , for  $i$  between 1 and  $n$ , and  $N_i$  the corresponding equivalent sample size (adjusted by process error if applicable, and then rounded up to the next whole number). The robustification parameter  $\delta$  is ignored. Then,
  - (a) A sample of  $N_i$  independent binary variates is generated, equalling 1 with probability  $E_i$
  - (b) The simulated observation value  $S_i$  is calculated as the sum of these binary variates divided by  $N_i$

Note that SPM will report simulated observations using the usual observation report (`@report[label].type=observation`). The report `@report[label].type=simulated_observation` will generate simulated observations in a form suitable for use as input within a SPM input configuration file. See Section 7 for more detail.

## 6.8. Pseudo-observations

SPM can generate expected values for observations without them contributing to the total objective function. These are called pseudo-observations, and can be used to either generate the expected values from SPM for reporting or diagnostic purposes. To define an observation as a pseudo-observation, use the command `@observation[label].likelihood=none`. Any observation type can be used as a pseudo-observation. SPM can also generate simulated observations from pseudo-observations. Note that;

- Output will only be generated if a report command `@report[label].type=observation` is specified.
- The observed values should be supplied (even if they are ‘dummy’ observation). These will be processed by SPM as if they were actual observation values, and must conform to the validations carried out for the other types of likelihood.
- The subcommands `likelihood`, `obs`, `error_value` and `process_error` have no effect when generating the expected values for the pseudo-observation.
- When simulating observations, SPM needs the subcommand `simulation_likelihood` to tell it what sort of likelihood to use. In this case, the `obs`, `error_value` and `process_error` are used to determine the appropriate terms to use for the likelihood when simulating.



---

## 7. The report section

The report section specifies the printouts and other outputs from the model. SPM does not, in general, produce any output unless requested by a valid report.

Reports from SPM can be defined to print the spatial structure, partition and states objects at a particular point in time, as well as layers, observation summaries, estimated parameters and objective function values. See below for a more extensive list.

Reports from SPM all conform to a standard style (with one exception — the `estimate_values` report, see below). The standard style is that reports are prefixed with a user-defined label in square brackets (e.g., `[...]`), with the second line indicating the type of report, and the report ending with the line `*end`. For example,

```
[My-report]
report.type: ...
...
*end
```

This syntax should make it easier for external packages to be configured to read SPM output. The `extract` functions in the **R** `spm` package uses this information to identify and read SPM output.

Note that the `estimate_values` report does not print either a header (e.g., `[...]` or `*end` at the end of the report. This is as the `estimate_values` report is designed to provide a single line (or multi-line for more than one set) vector of the estimated parameter values, suitable for reading by SPM (with the command `spm -i`).

Reports, by default, are directed to standard out (see Section 3.3), but this default can be overwritten by specifying an output file (`@report[label].file_name`). Hence reports can be directed to separate files as required. Note that if an output file is defined, any data within it is deleted and replaced with the output from the report. To append data to an output file rather than replacing it, use the subcommand `@report[label].overwrite=false`.

However, some reports *require* that the results are directed to a file (for example, the `@report[label].MCMC_samples` and `@report[label].MCMC_objectives` reports). In these cases, a file name must be provided.

Note that reports can be defined that may not be generated. For example printing the partition for a year and/or time-step that does not exist or reporting the covariance matrix when not estimating. Such reports are ignored by SPM and the program will not generate any output for these reports — although they must still conform to SPMs syntax requirements.

Not all reports will be generated in all run modes. Some reports are only available in some run modes. For example, when simulating, only simulation reports will be output.

### 7.1. Print the model spatial map

Print the spatial co-ordinates of each spatial cell (i.e., row and column labels of each spatial cell) of the spatial structure.

### 7.2. Print the partition

Print the partition for a given year or given years and time-step. This prints out, for each row and column defined as a valid cell in the base layer (see Section 4.2), the numbers of individuals in each age class in the partition for each year. Note that this report is evaluated at the end of the time-step in the given year(s).

### 7.3. Print the partition biomass

Print the biomass in the partition for a given year or given years and time-step. This prints out, for each row and column defined as a valid cell in the base layer (see Section 4.2), the biomass of the individuals in each age class in the partition for each year. Note that this report is evaluated at the end of the time-step in the given year(s).

### 7.4. Print the partition at the end of an initialisation

Print the partition following an initialisation phase. This prints out, for each row and column defined as a valid cell in the base layer (see Section 4.2), the numbers of individuals in each age class in the partition at then end of that initialisation phase.

### 7.5. Print a process summary

Print a summary of a process. Depending on the process, different summaries are produced. These typically detail the type of process, its parameters and other options, and any associated details.

### 7.6. Print a preference function summary

Print a summary of a preference function. Depending on the preference function, different summaries are produced. These typically detail the type of preference function, its parameters and other options, and any associated details.

### 7.7. Print derived quantities

Print out the description of the derived parameter, and the values of the derived quantity as recorded in the model state, for each year of the model. and for all years in the initialisation phases.

### 7.8. Print derived layers

Print out the description of the derived layer, and the values of the derived layer as recorded in the model state, for each year of the model and optionally for all years in the initialisation phases.

### 7.9. Print the estimated parameters

Print a summary of the estimated parameters, including the parameter name, lower and upper bounds, the label of the prior, and its value.

### 7.10. Print the estimated parameters in a vector format

Print the estimated parameter values out as a vector, in a format suitable for use with `spm -i`. The `estimate_values` report prints two lines — a line for the labels of the estimated parameters, and then a line of the values of the estimated parameters. For run modes that produce multi-line output (for example, MCMCs or profiles), only the first line contains the labels of the estimated parameters. All subsequent lines are the values of the estimated parameters only (with each line representing a single set of parameter values).

Note that unlike other reports, the `estimate_values` report does not print either a header (e.g., `[...]` or `*end` at the end.

### 7.11. Print the objective function

Print the total objective function value, and the value of all observations, the values of all priors, and the value of any penalties that have been incurred in the model. Note that if an individual model run does not incur a penalty, then the penalty will not be reported.

### 7.12. Print the covariance matrix

Print the Hessian and covariance matrices if estimating and if the covariance has been requested by `@minimiser[label].covariance=true`.

### 7.13. Print observations, fits, and residuals

Prints out the area (from the observation categorical layer), observed values (as supplied in the input configuration file), expected values as calculated by the model, residuals (observed – expected), the error value (as modified by any additional process error), and the contribution to the total objective function of that individual point in the observation.

Note that constants in likelihoods are often ignored in the objective function score of individual points. Hence, the total score from an observation equals the contribution of the objective function scores from each individual point plus a constant term (if applicable). In likelihoods without a constant term, then the total score from an observation will equal the contribution of the objective function scores from each individual point.

If simulating, then the contribution to the objective function of each observation is reported as zero.

### 7.14. Print simulated observations

Prints out a complete observation definition (i.e., in the form defined by `@report[label].type=observation`), but with observed values replaced by randomly generated simulated values. The output is in a form suitable for use within a SPM input configuration file, reproducing the command and subcommands from the input configuration file.

### 7.15. Print the ageing error misclassification matrix

Prints out the ageing error misclassification matrix.

### 7.16. Print layers and meta-layers

Prints the values in the layer (including user supplied layers, abundance and biomass layers, derived layers, meta-layers and derived meta-layers) for given year and at the end of a given time-step.

### 7.17. Print a derived view via a categorical layer

Prints a summary of the partition, as seen via a categorical layer. Here, values within the spatial cells of a partition are aggregated within the regions defined by the categorical layer for a given age range and given model categories.

### 7.18. Print selectivities

Prints the values of a selectivity for each age in the partition, for a given year and at then end of a given time-step.

### 7.19. Print the random number seed

Prints the random number seed used by *SPM* to generate the random number sequence. Future runs made with the same random number seed and the same model will produce identical outputs.

### 7.20. Print the size-weight relationship

Prints a summary of the size-weight relationship used by *SPM* for each category by printing the mean weight for a list of sizes. Useful for verifying that the choice of parameters (and their magnitude) are sensible choices.

### 7.21. Print the size-at-age relationship

Prints a summary of the size-at-age relationship used by *SPM* for each category. For each age between `min_age` and `max_age`, prints the mean size. Useful for verifying that the choice of parameters (and their magnitude) are sensible choices.

### 7.22. Print the weight-at-age relationship

Prints a summary of the mean weight-at-age relationship used by *SPM* for each category. For each age between `min_age` and `max_age`, prints the mean weight. Useful for verifying that the choice of parameters (and their magnitude) are sensible choices.

### 7.23. Print the results of an MCMC

Print the MCMC samples, objective function values, and proposal covariance matrix following an MCMC.

### 7.24. Print the MCMC samples as they are calculated

Print the MCMC samples for each new *i*th sample as they are calculated while doing an MCMC. The output file will be updated with each new sample as it is calculated by *SPM*.

### 7.25. Print the MCMC objective function values as they are calculated

Print the MCMC objective function values (along with the proposal covariance matrix) for each new *i*th sample as they are calculated while doing an MCMC. The output file will be updated with each new set of objective function values as it is calculated by *SPM*.

---

## 8. Population command and subcommand syntax

### 8.1. Model structure

**@model1** Define the spatial structure, population structure, annual cycle, and model years

**nrows** The number of rows  $n_{rows}$  in the spatial structure

Type: Integer

Default: No default

Value: A positive integer,  $n_{rows} > 0$

**ncols** The number of columns  $n_{cols}$  in the spatial structure

Type: Integer

Default: No default

Value: A positive integer,  $n_{cols} > 0$

**layer** The label for the base layer

Type: String

Default: No default

Value: Must be a label of a `numeric` layer defined by `@layer`

**cell\_length** The length (distance) of one side of a cell

Type: Constant

Default: 1

Value: A positive real number

**categories** Labels of the categories (rows) of the population component of the partition

Type: Vector of strings, of length  $1 \dots n_{categories}$

Default: No default

Value: Names of categories must be unique

**min\_age** Minimum age of the population

Type: Integer

Default: No default

Value: A non-negative integer,  $age_{min} \geq 0$  and  $age_{min} \leq age_{max}$

**max\_age** Maximum age of the population

Type: Integer

Default: No default

Value: A non-negative integer,  $age_{max} \geq 0$  and  $age_{min} \leq age_{max}$

**age\_plus\_group** Define the largest age as a plus group

Type: Switch

Default: True

Value: Defines the largest age as a plus group

**age\_size** Define the label of the associated age-size relationship for each category

Type: Vector of strings, of length  $n_{categories}$   
 Default: No default  
 Value: Must be labels of command @age\_size

`initialisation_phases`      Define the labels of the phases of the initialisation

Type: Vector of strings, of length of the number of initialisation phases  
 Default: No default  
 Value: A valid label defined by @initialisation\_phase

`initial_year`      Define the first year of the model, immediately following initialisation

Type: Integer  
 Default: No default  
 Value: Defines the first year of the model,  $\geq 1$ , e.g. 1990

`current_year`      Define the current year of the model

Type: Integer  
 Default: No default  
 Value: Defines the current year of the model, i.e., the model is run from @model.first\_year to @model.current\_year

`time_steps`      Define the @time\_step labels (in order that they are applied) to form the annual cycle

Type: String vector  
 Default: No default  
 Value: Defines the labels of the time-steps that are run in each year

## 8.2. Initialisation

**@initialisation\_phase** *label*      Define the processes and years of the initialisation phase with label

`years`      Define the number of years to run

Type: Integer  
 Default: No default  
 Value: A non-negative integer

`processes`      Define the processes (in order of occurrence) to run in each year of the initialisation

Type: String vector  
 Default: No default  
 Value: A valid process label, from one of @process

## 8.3. Time-steps

**@time\_step** *label*      Define a time-step with label

`processes`      Define the process labels, in the order that they are applied, for the time-step



Type: String vector

Default: No default

Value: Defines the labels of the processes for that time-step

## 8.4. Processes

The population processes available are,

- Constant recruitment process
- Beverton-Holt stock-recruit relationship recruitment process
- Local Beverton-Holt stock-recruit relationship recruitment process
- Ageing process
- Constant relationship mortality rate process
- Annually varying relationship mortality rate process
- Mortality event (as a number) process
- Mortality event (as a biomass) process
- Holling mortality rate
- Prey-switch predation process
- Category transition process
- Category shift process

The movement processes available are,

- Migration movement
- Adjacent cell movement
- Preference movement

Each type of process requires a set of subcommands and arguments specific to that process.

**@process** *label*     Define a process with label

**type**     Define the type of process

Type: String

Default: No default

Value: A valid type of process

### 8.4.1. @process[label].type=constant\_recruitment

**r0**     Define the total amount of recruitment at equilibrium abundance levels

Type: Estimable

Default: No default

Value: Total amount (in numbers) of recruitment applied across all categories at equilibrium abundances

**categories**      Define the categories into which recruitment occurs

Type: String vector

Default: No default

Value: Valid categories from `@model.categories`

**proportions**      Define the proportion of recruitment that occurs into each category

Type: Estimable vector, of length `categories`

Default: No default

Value: Proportion of the annual recruitment that is applied to each category

**age**      Define the age that receives recruitment

Type: Integer

Default: The minimum age of the population

Value: The age class that receives recruitment

**layer**      Name of the layer used to determine where recruitment occurs

Type: String

Default: No default

Value: A valid layer as defined by `@layer`. If a numeric layer, then recruitment is in proportion to the layer values. Note that the layer values must be non-negative

### 8.4.2. `@process[label].type=bh_recruitment`

**r0**      Define the total amount of recruitment at equilibrium abundance levels

Type: Estimable

Default: No default

Value: Total amount (in numbers) of recruitment applied across all categories at equilibrium abundances

**categories**      Define the categories into which recruitment occurs

Type: String vector

Default: No default

Value: Valid categories from `@model.categories`

**proportions**      Define the proportion of recruitment that occurs into each category

Type: Estimable vector, of length `@process[label].categories`

Default: No default

Value: Proportion of the annual recruitment that is applied to each category

**age**      Define the age that receives recruitment

Type: Integer

Default: The minimum age of the population

Value: The age class that receives recruitment

**steepness**      Define the Beverton-Holt stock recruitment relationship steepness ( $h$ ) parameter

- Type: Estimable  
 Default: 1.0  
 Value: Steepness value between 0.2 and 1.0
- b0** Define the `@initialisation_phase` label for the value of the derived quantity to use as the value of the spawning stock biomass ( $B_0$ )  
 Type: String  
 Default: No default  
 Value: Must be a valid `@initialisation_phase` label
- ssb** Define the label of the `@derived_quantity` that defines the spawning stock biomass (SSB)  
 Type: String  
 Default: No default  
 Value: Must be a valid `@derived_quantity` label
- ssb\_offset** Define the offset (in years) for the year of the derived quantity that is to be applied as the SSB in the stock-recruit relationship  
 Type: Integer  
 Default: No default  
 Value: Must be a value  $\geq 0$
- ycs\_values** YCS values  
 Type: Estimable vector  
 Default: No default  
 Value: Must be vector of length `@model.initial` to `@model.current`
- standardise\_ycs\_years** Years for which the year class strength values are defined to have mean 1.0  
 Type: Integer vector or integer range  
 Default: No default  
 Value: The expanded vector must have values of years between `@model.initial` and `@model.current`
- layer** Name of the layer used to determine where recruitment occurs  
 Type: String  
 Default: No layer  
 Value: A valid layer as defined by `@layer`. If a numeric layer, then recruitment is in proportion to the layer values.

### 8.4.3. `@process[label].type=local_bh_recruitment`

- r0** Define a multiplier of `r0_layer` for calculating the amount of recruitment in each cell at equilibrium abundance levels  
 Type: Estimable  
 Default: No default  
 Value: Multiplier of `r0_layer` to calculate the amount in each cell (in numbers) of recruitment applied across all categories at equilibrium abundances

`categories`      Define the categories into which recruitment occurs

Type: String vector

Default: No default

Value: Valid categories from `@model.categories`

`proportions`      Define the proportion of recruitment that occurs into each category

Type: Estimable vector, of length `categories`

Default: No default

Value: Proportion of the annual recruitment that is applied to each category

`age`      Define the age that receives recruitment

Type: Integer

Default: No default

Value: The age class that receives recruitment

`steepness`      Define the Beverton-Holt stock recruitment relationship steepness ( $h$ ) parameter

Type: Estimable

Default: 1.0

Value: Steepness value between 0.2 and 1.0

`b0`      Define the `@initialisation_phase` label for the value of the derived quantity to use as the value of the spawning stock biomass ( $B_0$ ) in each cell

Type: String

Default: No default

Value: Must be a valid `@initialisation_phase` label

`ssb`      Define the label of the `@derived_layer` that defines the spawning stock biomass (SSB) in each cell

Type: String

Default: No default

Value: Must be a valid `@derived_layer` label

`ssb_offset`      Define the offset (in years) for the year of the derived layer that is to be applied as the SSB in the stock-recruit relationship

Type: Integer

Default: No default

Value: Must be a value  $\geq 0$

`ycs_years`      Years for year class strength values

Type: Integer vector or integer range

Default: No default

Value: The expanded vector must be valid model years

`ycs_values`      YCS values

Type: Estimable vector

Default: No default

Value: Must be vector of length @model.initial to @model.current

`standardise_ycs_years`      Years for which the year class strength values are defined to have mean 1.0

Type: Integer vector or integer range

Default: No default

Value: The expanded vector must have values of years between @model.initial and @model.current

`layer`      Define the label of the layer that defines the distribution of recruitment (as a multiplier of  $R_0$  at equilibrium abundances in each cell)

Type: String

Default: No layer

Value: A valid numeric layer as defined by @layer. The amount of recruitment in each cell is the product of  $r_0$  and the layer value in each cell.

#### 8.4.4. @process[label].type=ageing

`categories`      Define the categories that ageing is applied to

Type: String vector

Default: No default

Value: Valid categories from @model.categories

#### 8.4.5. @process[label].type=constant\_mortality\_rate

`m`      Define the constant mortality rate to be applied

Type: Estimable

Default: No default

Value: A positive real number

`categories`      Define the categories that mortality is applied to

Type: String vector

Default: No default

Value: Valid categories from @model.categories

`selectivities`      Define the selectivities applied to each category

Type: String vector, of length categories

Default: No default

Value: Valid selectivity labels defined by @selectivity

`layer`      Name of the layer

Type: String

Default: No layer

Value: A valid layer as defined by @layer. If a numeric layer, then mortality applied is the mortality rate

times the value of the layer. Note that the layer values must be non-negative

#### 8.4.6. `@process[label].type=annual_mortality_rate`

`years` Define the years when the mortality rates are applied

Type: Integer vector or integer range

Default: No default

Value: Valid model years

`m` Define the mortality rate to be applied for each year

Type: Estimable vector, of length `years` once expanded

Default: No default

Value: A vector of positive real numbers

`categories` Define the categories that mortality is applied to

Type: String vector

Default: No default

Value: A vector of valid categories from `@model.categories`

`selectivities` Define the selectivities applied to each category

Type: String vector of length `categories`

Default: No default

Value: A vector of valid selectivity labels defined by `@selectivity`

`layer` Name of the multiplicative layer to be applied to  $M$

Type: String

Default: No layer

Value: A valid numeric layer as defined by `@layer`. Note that the layer values must be non-negative

#### 8.4.7. `@process[label].type=event_mortality`

`categories` Define the categories that the event mortality is applied to

Type: String vector

Default: No default

Value: Valid categories from `@model.categories`

`years` Define the years where the mortality even is applied

Type: Integer vector or integer range

Default: No default

Value: Valid model years

`layers` Define the layers that specify the event mortality (as the abundance) in each year

Type: String vector, of length `years` once expanded

Default: No default

Value: Valid layers as defined by `@layer`. Note that the layer values must be non-negative

`u_max` Define the maximum exploitation rate

Type: Estimable

Default: 0.99

Value: Must be  $> 0$  and  $< 1$

`selectivities` Define the selectivities applied to each category

Type: String vector, of length `categories`

Default: No default

Value: Valid selectivity labels defined by `@selectivity`

`penalty` Define the event mortality penalty label

Type: String

Default: No default

Value: Valid penalty label defined by `@penalty`

#### **8.4.8. `@process[label].type=biomass_event_mortality`**

`categories` Define the categories that the event mortality is applied to

Type: String vector

Default: No default

Value: Valid categories from `@model.categories`

`years` Define the years where the mortality event is applied

Type: Integer vector or integer range

Default: No default

Value: Valid years for the model

`layers` Define the layers that specify the event mortality (as a biomass) in each year

Type: String vector, of length `years` once expanded

Default: No default

Value: Valid layers defined by `@layer`. Note that the layer values must be non-negative

`u_max` Define the maximum exploitation rate

Type: Constant

Default: 0.99

Value: Must be  $> 0$  and  $< 1$

`selectivities` Define the selectivities applied to each category

Type: String vector, of length `categories`

Default: No default

Value: Valid selectivity labels defined by `@selectivity`

`penalty` Define the event mortality penalty label

Type: String  
 Default: No default  
 Value: Valid penalty label defined by @penalty

#### 8.4.9. @process[label].type=Holling\_mortality\_rate

is\_abundance      Is the mortality applied as a biomass or as abundance  
 Type: Switch  
 Default: False  
 Value: Either True or False

a      Define the  $a$  parameter of the Holling function  
 Type: Constant  
 Default: No default  
 Value: A positive real number

b      Define the  $b$  parameter of the Holling function  
 Type: Constant  
 Default: No default  
 Value: A positive real number

x      Define the type of Holling function or Michaelis-Menton function  
 Type: Constant  
 Default: default 2  
 Value: A positive real number, use 2 for Holling type II or 3 for Holling Type III, or other positive real value for the generalised Michaelis-Menton function

categories      Define the categories that the Holling mortality rate is applied to  
 Type: String vector  
 Default: No default  
 Value: Valid categories from @model.categories

selectivities      Define the selectivities applied to each category  
 Type: String vector, of length categories  
 Default: No default  
 Value: Valid selectivity labels defined by @selectivity

predator\_categories      Define the categories of the predator  
 Type: String vector  
 Default: No default  
 Value: Valid categories from @model.categories

predator\_selectivities      Define the selectivities applied to each predator category  
 Type: String vector, of length predator\_categories  
 Default: No default  
 Value: Valid selectivity labels defined by @selectivity



`u_max`      Define the maximum exploitation rate  
Type: Constant  
Default: 0.99  
Value: Must be  $> 0$  and  $< 1$

`penalty`      Define the event mortality penalty label  
Type: String  
Default: No default  
Value: Valid penalty label defined by `@penalty`

#### **8.4.10. `@process[label].type=Prey-switch-predation`**

`is_abundance`      Is the mortality applied as a biomass or as abundance  
Type: Switch  
Default: False  
Value: Either True or False

`consumption_rate`      Define the total predator consumption rate  
Type: Numeric  
Default: No default  
Value: A positive real number

`prey`      Define the vector of labels for all the prey groups used  
Type: String vector  
Default: No default  
Value: Names must be unique  
Note: These are the labels which links to the relative electivities for groups of categories

`electivities`      Define the electivities applied to prey groups  $1 \dots n$   
Type: Constant vector, of length `prey`  
Default: No default  
Value: A vector of positive real numbers, must have values that sum to 1

`categories`      Define the categories that the predation mortality is applied to, for all prey groups  
Type: String vector  
Default: No default  
Value: Valid categories from `@model.categories`

`selectivities`      Define the selectivities applied to each prey category  
Type: String vector, of length `categories`  
Default: No default  
Value: Valid selectivity labels defined by `@selectivity`

`prey_groups`      Assign each prey category to a specific prey group

Type: String vector, of length `categories`

Default: No default

Value: Valid labels defined by `prey`

`predator_categories`      Define the categories of the predator

Type: String vector

Default: No default

Value: Valid categories from `@model.categories`

`predator_selectivities`      Define the selectivities applied to each predator category

Type: String vector, of length `predator_categories`

Default: No default

Value: Valid selectivity labels defined by `@selectivity`

`u_max`      Define the maximum exploitation rate

Type: Constant

Default: 0.99

Value: Must be  $> 0$  and  $< 1$

`penalty`      Define the process penalty label

Type: String

Default: No default

Value: Valid penalty label defined by `@penalty`

### 8.4.11. `@process[label].type=category_transition`

`from`      Define the categories that are the source of the transition process

Type: String vector

Default: No default

Value: A valid list of categories from `@model.categories`

`selectivities`      Define the selectivities applied to the source categories

Type: String vector, of length `from`

Default: No default

Value: A valid list of selectivity labels defined by `@selectivity`

`to`      Define the categories that are the sink of the transition process

Type: String vector

Default: No default

Value: A valid list of categories from `@model.categories`

`years`      Define the years where the category transition is applied

Type: Integer vector or integer range

Default: No default

Value: Valid model years

`layers` Define the layers that specify the event mortality (as N for each cell) in each year

Type: String vector, of length `years` once expanded

Default: No default

Value: Valid layers defined by `@layer`. Note that the layer values must be non-negative

`penalty` Define the penalty to encourage models parameter values away from those which result in not enough individuals to move

Type: String

Default: No default

Value: Valid penalty label defined by `@penalty`

#### 8.4.12. `@process[label].type=category_transition_rate`

`from` Define the category that is the source of the transition process

Type: String

Default: No default

Value: A valid category from `@model.categories`

`selectivities` Define the selectivities applied to the source categories

Type: String vector, of length `from`

Default: No default

Value: A valid list of selectivity labels defined by `@selectivity`

`to` Define the category that is the sink of the transition process

Type: String

Default: No default

Value: A valid category from `@model.categories`

`proportions` Define the proportion of individuals to move

Type: Estimable

Default: No default

Value: A value  $\geq 0$  and  $\leq 1$

`layer` Name of the layer

Type: String

Default: No default

Value: A valid layer as defined by `@layer`. If a numeric layer, then rate applied to each cell is multiplied by the value of the layer. Note that the layer values must be non-negative

#### 8.4.13. `@process[label].type=migration`

`categories` Define the categories that the migration movement event is applied to

Type: String vector

Default: No default

Value: Valid categories from `@model.categories`

`selectivities`      Define the selectivities applied to each category

Type: String vector, of length `categories`

Default: No default

Value: Valid selectivity labels defined by `@selectivity`

`proportion`      Define the constant multiplier for the proportion of individuals that migrate

Type: Estimable

Default: 1.0

Value: A real number between 0 and 1, inclusive

`source_layer`      Define the label of a layer that defines the source cells of the migration movement event

Type: String

Default: No default

Value: A valid layer defined by `@layer`

`sink_layer`      Define the label of a layer that defines the sink cells of the migration movement event

Type: String

Default: No default

Value: A valid layer defined by `@layer`

#### **8.4.14. `@process[label].type=adjacent_cell`**

`categories`      Define the categories that the adjacent cell movement event is applied to

Type: String vector

Default: No default

Value: Valid categories from `@model.categories`

`selectivities`      Define the selectivities applied to each category

Type: String vector, of length `categories`

Default: No default

Value: Valid selectivity labels defined by `@selectivity`

`layer`      Define the label of a gradient layer that defines the the relative strength of movement to adjacent cells

Type: String

Default: Default 1 in every cell, equivalent to uniform diffusion

Value: A valid layer defined by `@layer`

`proportion`      Define the constant multiplier for the proportion that moves from each cell to the neighbouring cell

Type: Estimable

Default: 1.0

Value: A real number between 0 and 1, inclusive

**8.4.15. @process[label].type=preference**

`categories` Define the categories that the preference function movement is applied to

Type: String vector

Default: No default

Value: Valid categories from `@model.categories`

`proportion` Define the constant multiplier for the proportion that the preference function movement is applied to

Type: Estimable

Default: 1.0

Value: A real number between 0 and 1, inclusive

`preference_functions` Define the labels of the individual preference functions that make up the total preference function

Type: String vector

Default: No default

Value: Valid preference function labels defined by `@preference_function`

**8.5. Preference functions**

The individual preference functions available are,

- Constant
- Normal
- Double normal
- Logistic
- Inverse logistic
- Exponential
- Threshold
- Categorical
- Monotonic categorical

Each type of preference function requires a set of subcommands and arguments specific to that function.

**@preference\_function label** Define a preference function with label

`type` Define the type of preference function

Type: String

Default: No default

Value: A valid type of preference function

### 8.5.1. `@preference_function[label].type=constant`

`layer` Defines the layer which supplies the preference function independent variable  
Type: String  
Default: No default  
Value: A valid layer defined by `@layer`

`alpha` Defines the multiplicative constant  $\alpha$   
Type: Estimable  
Default: No default

### 8.5.2. `@preference_function[label].type=normal`

`layer` Defines the layer which supplies the preference function independent variable  
Type: String  
Default: No default  
Value: A valid layer defined by `@layer`

`alpha` Defines the multiplicative constant  $\alpha$   
Type: Estimable  
Default: No default

`mu` Defines the  $\mu$  parameter of the normal preference function  
Type: Estimable  
Default: No default

`sigma` Defines the  $\sigma$  parameter of the normal preference function  
Type: Estimable  
Default: No default

### 8.5.3. `@preference_function[label].type=double_normal`

`layer` Defines the layer which supplies the preference function independent variable  
Type: String  
Default: No default  
Value: A valid layer defined by `@layer`

`alpha` Defines the multiplicative constant  $\alpha$   
Type: Estimable  
Default: No default

`mu` Defines the  $\mu$  parameter of the double-normal preference function  
Type: Estimable  
Default: No default

`sigma_l` Defines the  $\sigma_L$  parameter of the double-normal preference function  
Type: Estimable  
Default: No default

`sigma_r` Defines the  $\sigma_R$  parameter of the double-normal preference function  
Type: Estimable  
Default: No default

#### 8.5.4. `@preference_function[label].type=logistic`

`layer` Defines the layer which supplies the preference function independent variable  
Type: String  
Default: No default  
Value: A valid layer defined by `@layer`, with strictly positive values only

`alpha` Defines the multiplicative constant  $\alpha$   
Type: Estimable  
Default: No default

`a50` Defines the  $a_{50}$  parameter of the logistic preference function  
Type: Estimable  
Default: No default

`ato95` Defines the  $a_{to95}$  parameter of the logistic preference function  
Type: Estimable  
Default: No default

#### 8.5.5. `@preference_function[label].type=inverse_logistic`

`layer` Defines the layer which supplies the preference function independent variable  
Type: String  
Default: No default  
Value: A valid layer defined by `@layer`, with strictly positive values only

`alpha` Defines the multiplicative constant  $\alpha$   
Type: Estimable  
Default: No default

`a50` Defines the  $a_{50}$  parameter of the inverse-logistic preference function  
Type: Estimable  
Default: No default

`ato95` Defines the  $a_{to95}$  parameter of the inverse-logistic preference function

Type: Estimable  
Default: No default

### 8.5.6. `@preference_function[label].type=exponential`

`layer` Defines the layer which supplies the preference function independent variable  
Type: String  
Default: No default  
Value: A valid layer defined by `@layer` of positive values only

`alpha` Defines the multiplicative constant  $\alpha$   
Type: Estimable  
Default: No default

`lambda` Defines the  $\lambda$  parameter of the exponential preference function  
Type: Estimable  
Default: No default

### 8.5.7. `@preference_function[label].type=threshold`

`layer` Defines the layer which supplies the preference function independent variable  
Type: String  
Default: No default  
Value: A valid layer defined by `@layer`

`alpha` Defines the multiplicative constant  $\alpha$   
Type: Estimable  
Default: No default

`n` Defines the  $N$  parameter of the threshold preference function  
Type: Estimable  
Default: No default

`lambda` Defines the  $\lambda$  parameter of the threshold preference function  
Type: Estimable  
Default: No default

### 8.5.8. `@preference_function[label].type=categorical`

`layer` Defines the layer which supplies the preference function independent variable  
Type: String  
Default: No default  
Value: A valid layer defined by `@layer`



`alpha` Defines the multiplicative constant  $\alpha$

Type: Estimable

Default: No default

`category_labels` Defines the unique labels of `layer` in order of their coefficients

Type: String vector

Default: No default

Value: A complete set of unique values of labels in `layer` in order of `category_values`

`category_values` Defines the coefficients for each unique label of `layer` in order of their labels

Type: String vector

Default: No default

Value: A complete set of positive values of labels in `layer` in order of `category_labels`

### 8.5.9. `@preference_function[label].type=monotonic_categorical`

`layer` Defines the layer which supplies the preference function independent variable

Type: String

Default: No default

Value: A valid layer defined by `@layer`

`alpha` Defines the multiplicative constant  $\alpha$

Type: Estimable

Default: No default

`category_labels` Defines the unique labels of `layer` in order of their coefficients

Type: String vector

Default: No default

Value: A complete set of unique values of labels in `layer` in order of `category_values`

`category_values` Defines the coefficients for each unique label of `layer` in order of their labels

Type: Numeric vector

Default: No default

Value: A complete set of positive values of labels in `layer` in order of `category_labels`

## 8.6. Layers

The available layer types are,

- Numeric
- Categorical

- Distance
- Abundance
- Biomass
- Abundance density
- Biomass density
- Numeric meta-layer
- Categorical meta-layer
- Derived layer

**@layer** *label*     Define a layer function with label

**type**     Define the type of layer

Type: String

Default: No default

Value: A valid type of layer

#### 8.6.1. **@layer[label].type=numeric**

**data**     Define the values of the layer

Type: Constant vector, with total length  $@model.ncols \times @model.nrows$

Default: No default

Value: A vector of values of length equal to the number of elements defined for the spatial structure

#### 8.6.2. **@layer[label].type=categorical**

**data**     Define the values of the layer

Type: Constant vector, with total length  $@model.ncols \times @model.nrows$

Default: No default

Value: A vector of values of length equal to the number of elements defined for the spatial structure

#### 8.6.3. **@layer[label].type=distance**

There are no other subcommands for `@layer[label].type=distance`.

#### 8.6.4. **@layer[label].type=abundance**

**categories**     Define the categories are used to calculate the abundance

Type: String vector

Default: No default

Value: Valid categories from `@model.categories`

`selectivities`     Define the selectivities applied to each category  
Type: String vector, of length `categories`  
Default: No default  
Value: Valid selectivity labels from `@selectivity`

#### **8.6.5. `@layer[label].type=biomass`**

`categories`     Define the categories are used to calculate the biomass  
Type: String vector  
Default: No default  
Value: Valid categories from `@model.categories`

`selectivities`     Define the selectivities applied to each category  
Type: String vector, of length `categories`  
Default: No default  
Value: Valid selectivity labels from `@selectivity`

#### **8.6.6. `@layer[label].type=abundance_density`**

`categories`     Define the categories are used to calculate the abundance  
Type: String vector  
Default: No default  
Value: Valid categories from `@model.categories`

`selectivities`     Define the selectivities applied to each category  
Type: String vector, of length `categories`  
Default: No default  
Value: Valid selectivity labels from `@selectivity`

#### **8.6.7. `@layer[label].type=biomass_density`**

`categories`     Define the categories are used to calculate the biomass  
Type: String vector  
Default: No default  
Value: Valid categories from `@model.categories`

`selectivities`     Define the selectivities applied to each category  
Type: String vector, of length `categories`  
Default: No default  
Value: Valid selectivity labels from `@selectivity`

### 8.6.8. `@layer[label].type=numeric meta`

`default_layer`      Define the default layer to use in years or initialisation phases where it is not otherwise defined

Type: String

Default: No default

Condition: The argument must be a numeric layer

`years`      Define the years that have a non-default layer

Type: Integer vector or integer range

Default: No default

Value: Must be valid model years

`layers`      Define the layers for each of the years

Type: String vector, of length `year` once expanded

Default: No default

Condition: The arguments must be numeric layers

`initialisation_phases`      Define the initialisation phases that have a non-default layer

Type: String vector

Default: No default

Condition: The arguments must be numeric layers

`initialisation_layers`      Define the layers for each of the initialisation phases

Type: String vector, of length the number of `initialisation_phases`

Default: No default

Condition: The arguments must be numeric layers

### 8.6.9. `@layer[label].type=categorical meta`

`default_layer`      Define the default layer to use in years or initialisation phases where it is not otherwise defined

Type: String

Default: No default

Condition: The argument must be a categorical layer

`years`      Define the years that have a non-default layer

Type: Integer vector or integer range

Default: No default

Value: Must be valid model years

`layers`      Define the layers for each of the years

Type: String vector, of length `year` once expanded

Default: No default

Condition: The arguments must be categorical layers

`initialisation_phases`      Define the initialisation phases that have a non-default layer

Type: String vector

Default: No default

Condition: The arguments must be categorical layers

`initialisation_layers`      Define the layers for each of the initialisation phases

Type: String vector, of length the number of `initialisation_phases`

Default: No default

Condition: The arguments must be categorical layers

#### 8.6.10. `@layer[label].type=derived`

`years`      Define the years when the calculation is performed

Type: Integer vector or integer range

Default: If not specified, calculation is carried out at every model year

Value: Must be valid model years once expanded, including initialisation steps

`time_step`      Define the time-step at which the calculation is performed

Type: String

Default: No default

Value: Valid label from `@time_step`

`layers`      Define the layers to be used in the calculations

Type: String vector

Default: No default

Value: Valid layers or meta-layers

### 8.7. Derived quantities

The individual types of derived quantities available are,

- Abundance
- Biomass

**`@derived_quantity`** *label*      Define a derived quantity with label

`type`      Define the type of derived quantity

Type: String

Default: No default

Value: A valid type of derived quantity, either `abundance` or `biomass`

### 8.7.1. @derived\_quantity[label].type=abundance

categories      Define the categories are used to calculate the derived quantity

Type: String vector

Default: No default

Value: Valid categories from @model.categories

selectivities      Define the selectivities

Type: String vector, of length categories

Default: No default

Value: Valid selectivity labels from @selectivity

initialisation\_time\_steps      Define the time-steps during the initialisation phases at the end of which the derived quantity is calculated

Type: String

Default: No default

Value: A valid time-step label from @time\_step

time\_step      Define the time-step at the end of which the derived quantity is calculated

Type: String

Default: No default

Value: A valid time-step label from @time\_step

layer      Name of the layer

Type: String

Default: No default

Value: A valid layer as defined by @layer. If a numeric layer, then value is the sum of the each cell is multiplied by the value of the layer.

### 8.7.2. @derived\_quantity[label].type=biomass

categories      Define the categories are used to calculate the derived quantity

Type: String vector

Default: No default

Value: Valid categories from @model.categories

selectivities      Define the selectivities

Type: String vector, of length categories

Default: No default

Value: Valid selectivity labels from @selectivity

initialisation\_time\_steps      Define the time-steps during the initialisation phases at the end of which the derived quantity is calculated

Type: String

Default: No default

Value: A valid time-step label from @time\_step

`time_step` Define the time-step at the end of which the derived quantity is calculated  
 Type: String  
 Default: No default  
 Value: A valid time-step label from `@time_step`

`layer` Name of the layer  
 Type: String  
 Default: No default  
 Value: A valid layer as defined by `@layer`. If a numeric layer, then value is the sum of the each cell biomass multiplied by the value of the layer.

## 8.8. Age-size relationship

The individual types of size-at-age relationships available are,

- none
- von Bertalanffy
- Schnute

**`@age_size label`** Define an age-size relationship with label

`type` Define the type of size-at-age relationship  
 Type: String  
 Default: No default  
 Value: A valid type of size-at-age relationship

### 8.8.1. `@age_size[label].type=von_bertalanffy`

`linf` Define the  $L_{\infty}$  parameter of the von Bertalanffy relationship  
 Type: Estimable  
 Default: No default  
 Value: A positive real number  
 Condition: Only define if using the von Bertalanffy relationship

`k` Define the  $k$  parameter of the von Bertalanffy relationship  
 Type: Estimable  
 Default: No default  
 Value: A positive real number  
 Condition: Only define if using the von Bertalanffy relationship

`t0` Define the  $t_0$  parameter of the von Bertalanffy relationship  
 Type: Estimable  
 Default: No default  
 Value: A real number  
 Condition: Only define if using the von Bertalanffy relationship

size\_weight     Define the label of the associated size-weight relationship  
Type: String  
Default: No default  
Value: A valid label from @size\_weight

### 8.8.2. @age\_size[label].type=schnute

y1     Define the  $y_1$  parameter of the Schnute relationship  
Type: Estimable  
Default: No default  
Value: A positive real number  
Condition: Only define if using the Schnute relationship

y2     Define the  $y_2$  parameter of the Schnute relationship  
Type: Estimable  
Default: No default  
Value: A positive real number  
Condition: Only define if using the Schnute relationship

tau1     Define the  $\tau_1$  parameter of the Schnute relationship  
Type: Estimable  
Default: No default  
Value: A real number  
Condition: Only define if using the Schnute relationship

tau2     Define the  $\tau_2$  parameter of the Schnute relationship  
Type: String  
Default: Normal  
Value: Either normal or lognormal  
Condition: Only define if using the Schnute relationship

a     Define the  $a$  parameter of the Schnute relationship  
Type: String  
Default: Normal  
Value: Either normal or lognormal  
Condition: Only define if using the Schnute relationship

b     Define the  $b$  parameter of the Schnute relationship  
Type: String  
Default: Normal  
Value: Either normal or lognormal  
Condition: Only define if using the Schnute relationship

size\_weight     Define the label of the associated size-weight relationship



Type: String

Default: No default

Value: A valid label from @size\_weight

## 8.9. Size-weight

The individual types of size-weight relationship available are,

- None
- Basic

**@size\_weight label** Define a size-weight relationship with label

type Define the type of relationship

Type: String

Default: No default

Value: A valid type of size-weight relationship

### 8.9.1. @size\_weight[label].type=none

There are no other subcommands for @size\_weight[label].type=none.

### 8.9.2. @size\_weight[label].type=basic

a Define the  $a$  parameter of the basic size-weight relationship

Type: Estimable

Default: No default

Value: A positive real number

b Define the  $b$  parameter of the basic size-weight relationship

Type: Estimable

Default: No default

Value: A positive real number

## 8.10. Selectivities

The individual selectivity functions available are,

- Constant
- Knife edge
- All values
- All values bounded
- Increasing
- Logistic

- Inverse Logistic
- Logistic producing
- Double normal
- Double exponential

Each type of selectivity function requires a set of subcommands and arguments specific to that function.

**@selectivity** *label*     Define a selectivity function with label

**type**     Define the type of selectivity function

Type: String

Default: No default

Value: A valid type of selectivity function

#### **8.10.1. @selectivity[label].type=constant**

**c**     Defines the  $C$  parameter of the selectivity function

Type: Estimable

Default: No default

Value: A positive real number

#### **8.10.2. @selectivity[label].type=knife\_edge**

**e**     Defines the  $E$  parameter of the selectivity function

Type: Estimable

Default: No default

Value: A positive real number

#### **8.10.3. @selectivity[label].type=all\_values**

**v**     Defines the  $V$  parameters (one for each age class) of the selectivity function

Type: Estimable vector

Default: No default

Value: A vector of positive real numbers, of length equal to the number of age classes

#### **8.10.4. @selectivity[label].type=all\_values\_bounded**

**l**     Defines the  $L$  parameter of the selectivity function

Type: Integer

Default: No default

Value: A positive real number

- h Defines the  $H$  parameter of the selectivity function  
Type: Integer  
Default: No default  
Value: A positive real number, must be greater than  $L$
- v Defines the  $V$  parameters (one for each age class from  $L$  to  $H$ ) of the selectivity function  
Type: Estimable vector  
Default: No default  
Value: A vector of positive real numbers, of length equal to the number of age classes from  $L$  to  $H$

#### 8.10.5. @selectivity[label].type=increasing

- alpha Defines the  $\alpha$  parameter of the selectivity function  
Type: Estimable  
Default: No default  
Value: A positive real number
- l Defines the  $L$  parameter of the selectivity function  
Type: Integer  
Default: No default  
Value: A positive real number
- h Defines the  $H$  parameter of the selectivity function  
Type: Integer  
Default: No default  
Value: A positive real number, must be greater than  $L$
- v Defines the  $V$  parameters (one for each age class from  $L$  to  $H$ ) of the selectivity function  
Type: Estimable vector  
Default: No default  
Value: A vector of positive real numbers, of length equal to the number of age classes from  $L$  to  $H$

#### 8.10.6. @selectivity[label].type=logistic

- alpha Defines the  $\alpha$  parameter of the selectivity function  
Type: Estimable  
Default: No default  
Value: A positive real number
- a50 Defines the  $a_{50}$  parameter of the selectivity function  
Type: Estimable  
Default: No default  
Value: A positive real number
- ato95 Defines the  $a_{to95}$  parameter of the selectivity function

Type: Estimable  
Default: No default  
Value: A positive real number

#### **8.10.7. @selectivity[label].type=inverse\_logistic**

alpha     Defines the  $\alpha$  parameter of the selectivity function  
Type: Estimable  
Default: No default  
Value: A positive real number

a50     Defines the  $a_{50}$  parameter of the selectivity function  
Type: Estimable  
Default: No default  
Value: A positive real number

ato95     Defines the  $a_{to95}$  parameter of the selectivity function  
Type: Estimable  
Default: No default  
Value: A positive real number

#### **8.10.8. @selectivity[label].type=logistic\_producing**

alpha     Defines the  $\alpha$  parameter of the selectivity function  
Type: Estimable  
Default: No default  
Value: A positive real number

L     Defines the  $L$  parameter of the selectivity function  
Type: Integer  
Default: No default  
Value: A positive real number

h     Defines the  $H$  parameter of the selectivity function  
Type: Integer  
Default: No default  
Value: A positive real number, must be greater than  $L$

a50     Defines the  $a_{50}$  parameter of the selectivity function  
Type: Estimable  
Default: No default  
Value: A positive real number

ato95     Defines the  $a_{to95}$  parameter of the selectivity function

Type: Estimable  
Default: No default  
Value: A positive real number

#### **8.10.9. @selectivity[label].type=double normal**

alpha     Defines the  $\alpha$  parameter of the selectivity function  
Type: Estimable  
Default: No default  
Value: A positive real number

mu        Defines the  $\mu$  parameter of the selectivity function  
Type: Estimable  
Default: No default

sigma\_l    Defines the  $\sigma_L$  parameter of the selectivity function  
Type: Estimable  
Default: No default

sigma\_r    Defines the  $\sigma_R$  parameter of the selectivity function  
Type: Estimable  
Default: No default

#### **8.10.10. @selectivity[label].type=double exponential**

alpha     Defines the  $\alpha$  parameter of the selectivity function  
Type: Estimable  
Default: No default  
Value: A positive real number

x1        Defines the  $x_1$  parameter of the selectivity function  
Type: Integer  
Default: No default

x2        Defines the  $x_2$  parameter of the selectivity function  
Type: Integer  
Default: No default

x0        Defines the  $x_0$  parameter of the selectivity function  
Type: Estimable  
Default: No default

y0        Defines the  $y_0$  parameter of the selectivity function

Type: Estimable  
Default: No default

y1      Defines the  $y_1$  parameter of the selectivity function  
Type: Estimable  
Default: No default

y2      Defines the  $y_2$  parameter of the selectivity function  
Type: Estimable  
Default: No default

---

## 9. Estimation command and subcommand syntax

### 9.1. Estimation methods

#### **@estimation**

**minimiser**     The label of the minimiser to use, if doing a point estimate

Type: String

Default: No default

Value: A valid label from @minimiser

**mcmc**     The label of the MCMC to use, if doing an MCMC

Type: String

Default: No default

Value: A valid label from @mcmc

**profile**     The labels of the profiles to use, if doing a profile

Type: String

Default: No default

Value: A valid label from @mpd

### 9.2. Point estimation

Two methods of minimising when doing a point estimate are,

- Numerical differences minimiser
- Differential evolution minimiser

Note that point estimates are required for

- MPDs
- To generate the starting values and covariance matrix for an MCMC
- To calculate the point estimates for profiles

Each type of minimiser requires a set of subcommands and arguments specific to that minimiser. Different minimisers can be called for different model runs or for different run modes (i.e., MCMC, MPDs, or profiles).

**@minimiser** *label*     Define the an minimiser estimator with label

**type**     Define the type of minimiser

Type: String

Default: numerical\_differences

Value: A valid type of minimiser, either numerical\_differences or de\_solver

### 9.2.1. @minimiser[label].type=numerical\_differences

iterations      Define the maximum number of iterations for the minimiser

Type: Integer

Default: 1000

Value: A positive integer

evaluations      Define the maximum number of evaluations for the minimiser

Type: Integer

Default: 4000

Value: A positive integer

step\_size      Define the step-size for the minimiser

Type: Constant

Default: 1e-6

Value: A positive real number

tolerance      Define the convergence criteria (tolerance) for the minimiser

Type: Constant

Default: 0.002

Value: A positive real number

covariance      Specify if SPM should attempt to calculate the covariance matrix, if estimating

Type: Logical

Default: True

Value: Either true or false

### 9.2.2. @minimiser[label].type=de\_solver

population\_size      Define the minimisers number of populations to generate

Type: Integer

Default: 25

Value: A positive integer

crossover\_probability      Define the minimisers crossover probability

Type: Integer

Default: 0.9

Value: A positive integer

difference\_scale      Define the scale of the difference of the parent candidates for the minimiser

Type: Constant

Default: 0.02

Value: A positive real number

max\_generations      Define the maximum generations for the minimiser convergence



Type: Constant

Default: 0.002

Value: A positive real number

`tolerance` Define the convergence criteria (tolerance) for the minimiser

Type: Constant

Default: 0.01

Value: A positive real number

`covariance` Specify if SPM should attempt to calculate the covariance matrix, if estimating

Type: Logical

Default: True

Value: Either true or false

### 9.3. Monte Carlo Markov Chain (MCMC)

Only one method of carrying out MCMCs is available, Monte Carlo Markov Chain using Metropolis-Hastings

**@mcmc** *label* Define the MCMC estimation arguments

`type` Define the method of MCMC

Type: String

Default: `metropolis_hastings`

Value: A valid type of MCMC. Currently only Metropolis-Hastings is available

#### 9.3.1. @mcmc.type=metropolis\_hastings

`start` Covariance multiplier for the starting point of the Markov chain

Type: Constant

Default: 0

Value: If 0, defines the starting point of the chain as the point estimate. If  $> 0$ , defines the starting point as randomly generated, with covariance matrix equal to the approximate covariance (inverse Hessian) times the value of this start parameter

`length` Length of the Markov chain

Type: Integer

Default: No default

Value: Defines the length of the Markov chain (as a number of iterations)

`keep` Spacing between recorded values in the chain

Type: Integer

Default: 1

Value: Defines the spacing between recorded values in the chain. Samples from the posterior are written to file only if their sample number is evenly divisible by `keep`

- max\_correlation**      Maximum absolute correlation in the covariance matrix of the proposal distribution  
Type: Constant  
Default: 0.8  
Value: Defines the maximum correlation in the covariance matrix of the proposal distribution. Correlations greater than `max_correlation` are decreased to `max_correlation`, and those less than `-max_correlation` are increased to `-max_correlation`
- covariance\_adjustment\_method**      Method for adjusting small variances in the covariance proposal matrix  
Type: String  
Default: covariance  
Value: Defines the method (either correlation or covariance) for the adjusting small variances in the covariance matrix of the proposal distribution
- correlation\_adjustment\_diff**      Minimum non-zero variance times the range of the bounds in the covariance matrix of the proposal distribution  
Type: Constant  
Default: 0.0001  
Value: Defines the minimum non-zero variance times the difference in the bounds of each parameter in the covariance matrix of the proposal distribution
- step\_size**      Initial step-size (as a multiplier of the approximate covariance matrix)  
Type: Constant  
Default:  $2.4d^{-0.5}$  where  $d$  is the number of estimated parameters  
Value: The covariance of the proposal distribution is the approximate covariance (inverse Hessian) times this step-size parameter
- proposal\_distribution**      The shape of the proposal distribution (either *t* or normal)  
Type: String  
Default: t  
Value: Either `t` or `normal`. Defines whether the proposal distribution should be multivariate *t* rather than multivariate normal
- df**      Degrees of freedom of the multivariate *t* proposal distribution  
Type: Integer  
Default: 4  
Value: Defines the degrees of freedom of the multivariate *t* proposal distribution
- adapt\_stepsize\_at**      Iterations in the chain to check and resize the MCMC step-size  
Type: Vector of integers  
Default: no default  
Value: Defines the points during the MCMC iterations to re-evaluate the MCMC step-size argument

## 9.4. Profiles

**@profile** *label*     Define the profile parameters and arguments

*parameter*     Name of the parameter to be profiled

Type: String

Default: No default

Value: Defines the name of the parameter to be profiled

*steps*     Number of steps (values) at which to profile the parameter

Type: Integer

Default: 10

Value: Defines the steps (number of values) at which to profile the parameter

*lower\_bound*     lower bound on parameter

Type: Integer

Default: No default

Value: Defines the lower bound on the range of the parameter to profile

*upper\_bound*     Upper bound on parameter

Type: Integer

Default: No default

Value: Defines the upper bound on the range of the parameter to profile

## 9.5. Defining the parameters to be estimated and their priors

**@estimate** *parameter\_name*     Estimate an estimable parameter *parameter\_name*

The SPM name of the parameter to estimate

Type: string

Default: No default

Value: A valid SPM parameter name

*same*     Names of the other parameters which are constrained to have the same value

Type: String Vector

Default: No default

Value: Defines the names of all the other parameters which are constrained to have the same value as this parameter

*estimation\_phase*     Phase at which this parameter should be estimated, in point estimation

Type: Integer

Default: 1

Value: Defines the phase at which this parameter should be freed

*lower\_bound*     Lower bounds on this parameter

Type: Constant vector, of length equal to the parameter length

Default: No default

Value: Defines the lower bound(s) on this parameter

`upper_bound`      Upper bound on this parameter

Type: Constant vector, of length equal to the parameter length

Default: No default

Value: Defines the upper bound(s) on this parameter

`mcmc_fixed`      Should this parameter be fixed during MCMC?

Type: Switch

Default: False

Value: Define this parameter as fixed during MCMC (i.e., considered a constant for the MCMC)

`prior`      Defines the label for the prior for this parameter

Type: String

Default: No default

Value: Defines the label of the prior on this parameter

## 9.6. Priors

The available priors are,

- uniform
- uniform log
- normal
- normal by standard deviation
- lognormal
- Beta

**@prior** *label*      Define the prior label

*type*      Define the type of prior

Type: String

Default: No default

Value: A valid type of prior

### 9.6.1. @prior[label].type=uniform

The command `@prior[label].type=uniform` has no other subcommands.

### 9.6.2. @prior[label].type=uniform\_log

The command `@prior[label].type=uniform_log` has no other subcommands.

**9.6.3. @prior[label].type=normal**

**mu** Defines the mean  $\mu$  of the normal prior

Type: Constant

Default: No default

Value: Defines the mean of the normal prior

**cv** Defines the c.v.  $c$  of the normal prior

Type: Constant

Default: No default

Value: Defines the c.v. of the normal prior

**9.6.4. @prior[label].type=normal\_by\_stdev**

**mu** Defines the mean  $\mu$  of the normal by standard deviation prior

Type: Constant

Default: No default

Value: Defines the mean of the normal by standard deviation prior

**sigma** Defines the standard deviation  $\sigma$  of the normal by standard deviation prior

Type: Constant

Default: No default

Value: Defines the standard deviation of the normal by standard deviation prior

**9.6.5. @prior[label].type=lognormal**

**mu** Defines the mean  $\mu$  of the lognormal prior

Type: Constant

Default: No default

Value: Defines the mean of the lognormal prior

**cv** Defines the c.v.  $c$  of the lognormal prior

Type: Constant

Default: No default

Value: Defines the c.v. of the lognormal prior

**9.6.6. @prior[label].type=beta**

**a** The lower value of the range parameter  $A$  of the Beta prior

Type: Constant

Default: No default

Value: Defines the lower value of the range parameter  $A$  of the Beta prior

**b** The upper value of the range parameter  $B$  of the Beta prior

Type: Constant

Default: No default

Value: Defines the upper value of the range parameter  $B$  of the Beta prior

`mu` Defines the mean  $\mu$  of the Beta prior

Type: Constant

Default: No default

Value: Defines the mean of the Beta prior

`sigma` Defines the standard deviation  $\sigma$  of the Beta prior

Type: Constant

Default: No default

Value: Defines the standard deviation of the Beta prior

## 9.7. Defining catchability constants

**@catchability** *label* Define a catchability constant with *label*

`q` Value of the  $q$  parameter

Type: Estimable

Default: No default

Value: Defines the value of the catchability  $q$  parameter, a real positive number

## 9.8. Defining penalties

**@penalty** *label* Define a penalty with *label*

`log_scale` Defines if the penalty is calculated in log space

Type: Switch

Default: False

Value: Defines if the value of the penalty is calculated as the squared difference or the squared difference in log space

`multiplier` Penalty multiplier

Type: Constant

Default: 1.0

Value: Defines the penalty multiplier

---

## 10. Observation command and subcommand syntax

### 10.1. Observation types

The observation types available are,

Observations of proportions of individuals by age class

Observations of proportions of individuals between categories within each age class

Relative and absolute abundance observations

Relative and absolute biomass observations

Each type of observation requires a set of subcommands and arguments specific to that process.

**@observation** *label*     Define an observation

**type**     Define the type of observation

Type: String

Default: No default

Value: A valid type of observation

#### 10.1.1. @observation[label].type=proportions\_at\_age

**year**     Define the year that the observation applies to

Type: Integer

Default: No default

Value: A positive integer between @model.initial\_year and @model.current\_year

**time\_step**     Define the time-step that the observation applies to

Type: Integer

Default: No default

Value: A valid time-step

**proportion\_method**     Define the method for interpolating the time-step for calculating the expected value of the observation

Type: String

Default: mean

Value: Either mean for the weighted mean, or difference for the difference between the start and end state

**proportion\_time\_step**     Define the interpolated proportion through the time-step for calculating the expected value of the observation

Type: Constant

Default: 1.0

Value: A real number between 0 and 1, inclusive

**categories**     Define the categories

Type: String vector  
Default: No default  
Value: Valid categories from @model.categories

**selectivities** Define the selectivities applied to each category

Type: String vector  
Default: No default  
Value: Valid selectivity labels defined by @selectivity

**min\_age** Define the minimum age for the observation

Type: Integer  
Default: No default  
Value: A valid age in the range @model.min\_age and @model.max\_age

**max\_age** Define the maximum age for the observation

Type: Integer  
Default: No default  
Value: A valid age in the range @model.min\_age and @model.max\_age

**age\_plus\_group** Define is the the maximum age for the observation is a plus group

Type: Switch  
Default: True  
Value: Either true or false

**ageing\_error** Define the label of the ageing-error matrix to be applied (if any)

Type: String  
Default: No default  
Value: A valid ageing error label

**layer** Name of the categorical layer used to group the spatial cells for the observation

Type: String  
Default: No default  
Value: A valid layer as defined by @layer. Must be a layer of type=categorical

**obs [label]** Define the following data as observations for the categorical layer with value

[label]  
Type: Constant vector  
Default: No default  
Value: The label is valid value from the associated observation layer. It is followed by a vector of values giving the proportions at age. This subcommand is repeated for each unique value of label

**tolerance** Define the tolerance on the sum-to-one error check in SPM

Type: Constant  
Default: 0.001  
Value: The tolerance on the sum to one error check. If  $abs(1 - \sum O_i) > tolerance$  then SPM will report an error



`error_value [label]` Define the following data as error values (e.g.,  $N$  for multinomial likelihoods, c.v. for lognormal likelihoods, etc.) for the categorical layer with value `[label]`  
Type: Constant  
Default: No default  
Value: A valid value from the associated observation layer. This subcommand is repeated for each unique value of `label`

`likelihood` Define the likelihood for the observation  
Type: String  
Default: No default  
Value: A valid likelihood

`delta` Define the delta robustifying constant for the likelihood  
Type: Constant  
Default:  $1e-11$   
Value: A non-negative real number

`process_error` Define the process error term  
Type: Constant  
Default: No process error  
Value: A non-negative real number

`simulation_likelihood` Define the likelihood when doing simulations, if the observations is a pseudo-observation  
Type: String  
Default: No default  
Value: A valid likelihood, except not `none`. Note that this command is ignored if the observation is not a pseudo-observation

### 10.1.2. `@observation[label].type=proportions by category`

`year` Define the year that the observation applies to  
Type: Integer  
Default: No default  
Value: A positive integer between `@model.initial_year` and `@model.current_year`

`time_step` Define the time-step that the observation applies to  
Type: Integer  
Default: No default  
Value: A valid time-step

`proportion_time_step` Define the interpolated proportion of the time-step passes that the observation applies to  
Type: Constant  
Default: 1.0  
Value: A real number between 0 and 1, inclusive

`categories`      Define the categories

Type: String vector

Default: No default

Value: Valid categories from `@model.categories`

`categories2`      Define the categories

Type: String vector

Default: No default

Value: Valid categories from `@model.categories`

`selectivities`      Define the selectivities applied to each category

Type: String vector

Default: No default

Value: Valid selectivity labels defined by `@selectivity`

`selectivities2`      Define the selectivities applied to each category

Type: String vector

Default: No default

Value: Valid selectivity labels defined by `@selectivity`

`min_age`      Define the minimum age for the observation

Type: Integer

Default: No default

Value: A valid age in the range `@model.min_age` and `@model.max_age`

`max_age`      Define the maximum age for the observation

Type: Integer

Default: No default

Value: A valid age in the range `@model.min_age` and `@model.max_age`

`age_plus_group`      Define is the the maximum age for the observation is a plus group

Type: Switch

Default: True

Value: Either true or false

`ageing_error`      Define the label of the ageing-error matrix to be applied

Type: String

Default: No default

Value: A valid ageing error label

`layer`      Name of the categorical layer used to group the spacial cells for the observation

Type: String

Default: No default

Value: A valid layer as defined by `@layer`. Must be a categorical layer

`obs [label]`      Define the following data as observations for the categorical layer with value `[label]`  
Type: Constant vector  
Default: No default  
Value: The label is valid value from the associated observation layer. It is followed by a vector of values giving the proportions at age. This subcommand is repeated for each unique value of label

`error_value [label]`      Define the following data as error values (e.g.,  $N$  for multinomial likelihoods, c.v. for lognormal likelihoods, etc.) for the categorical layer with value `[label]`  
Type: Constant  
Default: No default  
Value: A valid value from the associated observation layer. This subcommand is repeated for each unique value of label

`likelihood`      Define the likelihood for the observation  
Type: String  
Default: No default  
Value: A valid likelihood

`delta`      Define the delta robustifying constant for the likelihood  
Type: Constant  
Default:  $1e-11$   
Value: A non-negative real number

`process_error`      Define the process error term  
Type: Constant  
Default: No process error  
Value: A non-negative real number

`simulation_likelihood`      Define the likelihood when doing simulations, if the observations is a pseudo-observation  
Type: String  
Default: No default  
Value: A valid likelihood, except not `none`. Note that this command is ignored if the observation is not a pseudo-observation

### 10.1.3. `@observation[label].type=abundance`

`year`      Define the year that the observation applies to  
Type: Integer  
Default: No default  
Value: A positive integer between `@model.initial_year` and `@model.current_year`

`time_step`      Define the time-step that the observation applies to

Type: Integer  
Default: No default  
Value: A valid time-step

`proportion_time_step`      Define the interpolated proportion of the time-step passes that the observation applies to  
Type: Constant  
Default: 1.0  
Value: A real number between 0 and 1, inclusive

`catchability`      Define the catchability constant label for the observation  
Type: String  
Default: No default  
Value: A valid `@catchability` label

`categories`      Define the categories for which the observations occur  
Type: String vector  
Default: No default  
Value: Valid categories from `@model.categories`

`selectivities`      Define the selectivities applied to each category  
Type: String vector  
Default: No default  
Value: Valid selectivity labels defined by `@selectivity`

`layer`      Name of the categorical layer used to group the spacial cells for the observation  
Type: String  
Default: No default  
Value: A valid layer as defined by `@layer`. Must be a categorical layer

`obs [label]`      Define the following data as observations for the categorical layer with value `[label]`  
Type: Constant  
Default: No default  
Value: The label is valid value from the associated observation layer. It is followed by a value giving the abundance. This subcommand is repeated for each unique value of label

`error_value [label]`      Define the following data as error values (e.g.,  $N$  for multinomial likelihoods, c.v. for lognormal likelihoods, etc.) for the categorical layer with value `[label]`  
Type: Constant  
Default: No default  
Value: A valid value from the associated observation layer. This subcommand is repeated for each unique value of label

`likelihood`      Define the likelihood for the observation

Type: String  
Default: No default  
Value: A valid likelihood

`delta` Define the delta robustifying constant for the likelihood  
Type: Constant  
Default: 1e-11  
Value: A non-negative real number

`process_error` Define the process error term  
Type: Constant  
Default: No process error  
Value: A non-negative real number

`simulation_likelihoood` Define the likelihood when doing simulations, if the observations is a pseudo-observation  
Type: String  
Default: No default  
Value: A valid likelihood, except not `none`. Note that this command is ignored if the observation is not a pseudo-observation

#### 10.1.4. `@observation[label].type=biomass`

`year` Define the year that the observation applies to  
Type: Integer  
Default: No default  
Value: A positive integer between `@model.initial_year` and `@model.current_year`

`time_step` Define the time-step that the observation applies to  
Type: Integer  
Default: No default  
Value: A valid time-step

`proportion_time_step` Define the interpolated proportion of the time-step passes that the observation applies to  
Type: Constant  
Default: 1.0  
Value: A real number between 0 and 1, inclusive

`catchability` Define the catchability constant label for the observation  
Type: String  
Default: No default  
Value: A valid `@catchability` label

`categories` Define the categories into which recruitment occurs

Type: String vector  
Default: No default  
Value: Valid categories from @model.categories

**selectivities**      Define the selectivities applied to each category

Type: String vector  
Default: No default  
Value: Valid selectivity labels defined by @selectivity

**layer**      Name of the categorical layer used to group the spacial cells for the observation

Type: String  
Default: No default  
Value: A valid layer as defined by @layer. Must be a categorical layer

**obs [label]**      Define the following data as observations for the categorical layer with value [label]

Type: Constant vector  
Default: No default  
Value: The label is valid value from the associated observation layer. It is followed by a value giving the biomass. This subcommand is repeated for each unique value of label

**error.value [label]**      Define the following data as error values (e.g.,  $N$  for multinomial likelihoods, c.v. for lognormal likelihoods, etc.) for the categorical layer with value [label]

Type: Constant  
Default: No default  
Value: A valid value from the associated observation layer. This subcommand is repeated for each unique value of label

**likelihood**      Define the likelihood for the observation

Type: String  
Default: No default  
Value: A valid likelihood

**delta**      Define the delta robustifying constant for the likelihood

Type: Constant  
Default: 1e-11  
Value: A non-negative real number

**process.error**      Define the process error term

Type: Constant  
Default: 0  
Value: A non-negative real number

**simulation\_likelihood**      Define the likelihood when doing simulations, if the observations is

a pseudo-observation

Type: String

Default: No default

Value: A valid likelihood, except not `none`. Note that this command is ignored if the observation is not a pseudo-observation

## 10.2. Defining ageing error

Three methods for including ageing error into estimation with observations are,

- None
- Normal
- Off-by-one

Each type of ageing error requires a set of subcommands and arguments specific to its type.

**@ageing\_error label** Define ageing error with `label`

`type` The type of ageing error

Type: String

Default: No default

Value: Defines the type of ageing error to use

### 10.2.1. @ageing\_error[label].type=none

The `@ageing_error[label].type=none` has no other subcommands.

### 10.2.2. @ageing\_error[label].type=normal

`cv` Parameter of the normal ageing error model

Type: Constant

Default: No default

Value: Define the c.v. of misclassification

`k` The  $k$  parameter of the normal ageing error model

Type: Integer

Default: 0

Value: `cv` defines the proportions of misclassification down and up using the normal model.  $k$  defines the minimum age of individuals which can be misclassified, e.g., individuals under age  $k$  have no ageing error

### 10.2.3. @ageing\_error[label].type=off by one

`p1` The  $p_1$  parameter of the off-by-one ageing error model

Type: Constant

Default: No default

Value:  $p_1$  and  $p_2$  define the proportions of misclassification down and up by 1 year respectively.  $k$  defines

the minimum age of individuals which can be misclassified, e.g. individuals under age  $k$  have no ageing error

$p_2$  The  $p_2$  parameter of the off-by-one ageing error model

Type: Constant

Default: No default

Value:  $p_1$  and  $p_2$  define the proportions of misclassification down and up by 1 year respectively.  $k$  defines the minimum age of individuals which can be misclassified, e.g., individuals under age  $k$  have no ageing error

$k$  The  $k$  parameter of the off-by-one ageing error model

Type: Integer

Default: 0

Value:  $p_1$  and  $p_2$  define the proportions of misclassification down and up by 1 year respectively.  $k$  defines the minimum age of individuals which can be misclassified, e.g., individuals under age  $k$  have no ageing error



---

## 11. Report command and subcommand syntax

### 11.1. Available reports

The report types available are,

1. Print the map (i.e., row and column labels of each spatial cell) of the spatial structure
2. Print the partition at a specific time-step for any number of years
3. Print the biomass of the partition at a specific time-step for any number of years
4. Print the partition at the end of an initialisation
5. Print a summary of a process
6. Print a summary of a preference function
7. Print a derived quantity
8. Print a derived layer
9. Print a summary of the estimated parameters
10. Print the estimated parameters in a vector format (suitable for use with `spm -i`)
11. Print the objective function values
12. Print the covariance matrix
13. Print an observation values, fits, and residuals
14. Print a simulated observation suitable for use in a SPM input configuration file.
15. Print the ageing error misclassification matrix
16. Print a layer
17. Print a derived view via a categorical layer
18. Print a selectivity's values
19. Print the random number seed
20. Print the age-size relationship
21. Print the age-weight relationship
22. Print the size-weight relationship
23. Print the results of an MCMC
24. Print the MCMC samples as they are calculated
25. Print the MCMC objective function values as they are calculated

Each type of report requires a set of subcommands and arguments specific to that report.

### 11.2. Report commands and subcommands

**@report** *label*     Define an output report

*type*     Define the type of report

Type: String

Default: No default

Value: A valid type of report

**11.2.1. @report [label] .type=spatial\_map**

`file_name` Define the name of the output file where the report is written  
Type: String  
Default: No default  
Value: A valid file name. If not supplied, then output is directed to the standard out  
Note: Some reports *require* that a file name is provided.

**11.2.2. @report [label] .type=partition**

`years` Define the years that the partition report applies to  
Type: Integer vector or integer range  
Default: No default  
Value: Valid model years between `@model.initial_year` and `@model.current_year`

`time_step` Define the time-step that the partition report applies to  
Type: Integer  
Default: No default  
Value: A valid time-step

`file_name` Define the name of the output file where the report is written  
Type: String  
Default: No default  
Value: A valid file name. If not supplied, then output is directed to the standard out

`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to  
Type: Switch  
Default: True  
Value: Either True or False

**11.2.3. @report [label] .type=partition\_biomass**

`years` Define the years that the partition\_biomass report applies to  
Type: Integer vector or integer range  
Default: No default  
Value: Valid model years between `@model.initial_year` and `@model.current_year`

`time_step` Define the time-step that the partition\_biomass report applies to  
Type: Integer  
Default: No default  
Value: A valid time-step

`file_name` Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. If not supplied, then output is directed to the standard out

`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

#### 11.2.4. **@report [label] .type=initialisation**

`initialisation_phase` Define the phase of initialisation that the partition report applies to

Type: string

Default: No default

Value: A valid phase label, from @initialisation\_phase

`file_name` Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. If not supplied, then output is directed to the standard out

`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

#### 11.2.5. **@report [label] .type=process**

`process` Define the label of the process to summarise

Type: String

Default: No default

Value: A valid label from @process

`file_name` Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. If not supplied, then output is directed to the standard out

`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

### 11.2.6. @report [label] .type=preference\_function

preference\_function     Define the label of the preference function to summarise

Type: String

Default: No default

Value: A valid label from @preference\_function

file\_name     Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. If not supplied, then output is directed to the standard out

overwrite     Specify if any previous file with the same name as the output file should be overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

### 11.2.7. @report [label] .type=derived\_quantity

derived\_quantity     Define the label of the derived quantity to print

Type: String

Default: No default

Value: A valid label from @derived\_quantity

file\_name     Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. If not supplied, then output is directed to the standard out

overwrite     Specify if any previous file with the same name as the output file should be overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

### 11.2.8. @report [label] .type=derived\_layer

derived\_layer     Define the label of the derived layer to print

Type: String

Default: No default

Value: A valid label from @derived\_layer

`initialisation` Specify if the derived layer values for each year of the initialisation phases should be also be output

Type: Switch

Default: False

Value: Either True or False

`file_name` Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. If not supplied, then output is directed to the standard out

`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

### 11.2.9. `@report [label] .type=estimate_summary`

`file_name` Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. If not supplied, then output is directed to the standard out

`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

### 11.2.10. `@report [label] .type=estimate_value`

Prints the estimated parameters in a format suitable for use with `spm -i`.

`file_name` Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. If not supplied, then output is directed to the standard out

`header` Specify if the output contains the standard SPM style header at the start of the output

Type: Switch

Default: False

Value: Either True or False

`overwrite` Specify if any previous file with the same name as the output file should be

overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

#### **11.2.11. @report [label] .type=objective\_function**

file\_name Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. If not supplied, then output is directed to the standard out

overwrite Specify if any previous file with the same name as the output file should be overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

#### **11.2.12. @report [label] .type=covariance**

file\_name Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. If not supplied, then output is directed to the standard out

overwrite Specify if any previous file with the same name as the output file should be overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

#### **11.2.13. @report [label] .type=observation**

observation Define the label of the observation to print

Type: String

Default: No default

Value: A valid label from @Observation

file\_name Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. If not supplied, then output is directed to the standard out

overwrite Specify if any previous file with the same name as the output file should be

overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

#### **11.2.14. @report [label] .type=simulated\_observation**

`observation` Define the label of the observation from which to simulate values

Type: String

Default: No default

Value: A valid label from @observation

`file_name` Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. If not supplied, then output is directed to the standard out

`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

#### **11.2.15. @report [label] .type=ageing\_error**

`ageing_error` Define the label of the ageing\_error misclassification matrix

Type: String

Default: No default

Value: A valid label from @ageing\_error

`file_name` Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. If not supplied, then output is directed to the standard out

`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

**11.2.16. @report [label] .type=layer**

layer Define the label of the layer to print

Type: String

Default: No default

Value: A valid label from @layer

years Define the years for the printing of the layer

Type: Integer vector or integer range

Default: The first year of the model, @model.initial\_year

Value: Valid model years between @model.initial\_year and @model.current\_year

time\_step Define the time-step for the printing of the layer

Type: Integer

Default: The first time-step of the model

Value: A valid time-step

file\_name Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. If not supplied, then output is directed to the standard out

overwrite Specify if any previous file with the same name as the output file should be overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

**11.2.17. @report [label] .type=layer\_derived\_view**

layer Define the label of the layer to print

Type: String

Default: No default

Value: A valid label from @layer of type categorical

years Define the years for the printing of the layer

Type: Integer vector or integer range

Default: No default

Value: Valid model years between @model.initial\_year and @model.current\_year

time\_step Define the time-step for the printing of the layer

Type: Integer

Default: The first time-step of the model

Value: A valid time-step

file\_name Define the name of the output file where the report is written



Type: String

Default: No default

Value: A valid file name. If not supplied, then output is directed to the standard out

`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

### 11.2.18. `@report[label].type=selectivity`

`selectivity` Define the label of the selectivity to print

Type: String

Default: No default

Value: A valid label from `@selectivity`

`year` Define the year for the printing of the selectivity

Type: Integer

Default: No default

Value: A positive integer between `@model.initial_year` and `@model.current_year`

`time_step` Define the time-step for the printing of the selectivity

Type: Integer

Default: No default

Value: A valid time-step

`file_name` Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. If not supplied, then output is directed to the standard out

`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

### 11.2.19. `@report[label].type=random_number_seed`

`file_name` Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. If not supplied, then output is directed to the standard out

`overwrite`      Specify if any previous file with the same name as the output file should be overwritten or appended to  
Type: Switch  
Default: True  
Value: Either True or False

#### **11.2.20. @report [label] .type=age\_size**

`age_size`      Define the label of the age-size relationship  
Type: String  
Default: No default  
Value: A valid label from @age\_age

`file_name`      Define the name of the output file where the report is written  
Type: String  
Default: No default  
Value: A valid file name. If not supplied, then output is directed to the standard out

`overwrite`      Specify if any previous file with the same name as the output file should be overwritten or appended to  
Type: Switch  
Default: True  
Value: Either True or False

#### **11.2.21. @report [label] .type=size\_weight**

`size_weight`      Define the label of the size-weight relationship  
Type: String  
Default: No default  
Value: A valid label from @size\_weight

`sizes`      Define the sizes for which to report the mean weights  
Type: Constant vector  
Default: No default  
Value: Values of sizes to report the mean weight

`file_name`      Define the name of the output file where the report is written  
Type: String  
Default: No default  
Value: A valid file name. If not supplied, then output is directed to the standard out

`overwrite`      Specify if any previous file with the same name as the output file should be

overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

### 11.2.22. **@report [label] .type=age\_weight**

age\_size      Define the label of the age-size relationship

Type: String

Default: No default

Value: A valid label from @age\_size

file\_name      Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. If not supplied, then output is directed to the standard out

overwrite      Specify if any previous file with the same name as the output file should be overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

### 11.2.23. **@report [label] .type=MCMC**

file\_name      Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. If not supplied, then output is directed to the standard out

overwrite      Specify if any previous file with the same name as the output file should be overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

### 11.2.24. **@report [label] .type=MCMC\_samples**

file\_name      Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. Must be supplied.

overwrite      Specify if any previous file with the same name as the output file should be

overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

#### 11.2.25. @report [label] .type=MCMC\_objectives

file\_name Define the name of the output file where the report is written

Type: String

Default: No default

Value: A valid file name. Must be supplied.

overwrite Specify if any previous file with the same name as the output file should be overwritten or appended to

Type: Switch

Default: True

Value: Either True or False

---

## 12. Other commands and subcommands

**@include** *file*    Include an external file

*file*    The name of the external file to include

Type: string

Default: No default

Value: A valid external file

Condition: The file name must be enclosed in double quotes

Example: @include "my\_file.txt"

Note: @include does not denote the end of the previous command block as is the case for all other commands



---

## 13. Examples

We provide some simple examples to illustrate the syntax of the input configuration file, provide an introduction to the command calls to *SPM*, and show respective outputs. Note, we reproduce only a subset of the input configuration files — for more detail, see the example files.

Two examples are provided. The first implements a simple population that resides in a single cell, without movement. The second example has a similar population structure inside a  $10 \times 6$  spatial matrix, and moves immature and mature fish according to preference function movement process.

### 13.1. An example of a simple $1 \times 1$ non-spatial model

This example implements a very simple single spatial cell model (i.e., a model with no movement, and the entire population enclosed within a  $1 \times 1$  spatial structure) with recruitment, maturation, natural and exploitation mortality, and an annual age increment. The population structure has ages  $1 - 50^+$  with categories labelled immature and mature.

The model was initialised over a 200 year period, and applies the following processes,

1. A Beverton-Holt recruitment process, recruiting a constant number of individuals to the first age class (i.e.,  $age = 1$ ) in the category labelled immature.
2. A maturation process, where individuals are moved from the immature to the mature categories with a logistic-producing selectivity labelled ‘maturation’.
3. A constant mortality process representing natural mortality, applied as two repeats of the ‘halfM’ process. (Half  $M$  used so-as to be able to mimic a  $\frac{1}{2}M + F + \frac{1}{2}M$  natural and fishing exploitation set of processes after initialisation.)
4. An ageing process, where all individuals are aged by one year, and with a plus group accumulator age class at  $age = 50$ .

A second phase of initialisation, of period one year, is applied to allow external validation that the initialisation process has stabilised the population to equilibrium (i.e., by confirming that there is no or at least only a small difference in the partition at the end of first and second phases).

Following initialisation, the model runs from the years 1994 to 2007 iterating through two time-steps. The first time-step applies processes of recruitment, maturation, and  $\frac{1}{2}M + F + \frac{1}{2}M$  processes. The exploitation process (fishing) is applied in the years 1998–2007, with catches defined by the layers Fishing\_1998 to Fishing\_2007.

The second time-step applies an age increment.

The first 50 lines of the main section of the input configuration file are,

```
#####  
# Example 1: Simple 1x1 spatial model without movement  
#####  
  
# Model structure  
@model  
nrows 1  
ncols 1  
layer Base  
categories immature mature  
min_age 1  
max_age 35  
age_plus_group True
```

```
initial_year 1994
current_year 2007
cell_length 1
initialisation_phases Phase1 Phase2
time_steps step_one step_two
age_size VB VB

@age_size VB
type von_bertalanffy
size_weight basic
k 0.093
t0 -0.256
linf 169.07

@size_weight basic
type basic
a 1.387e-008
b 2.965

# Initialisation
@initialisation_phase Phase1
years 200
time_steps Phase1a Phase1b

@initialisation_phase Phase2
years 1
time_steps Phase1a Phase1c

@time_step Phase1a
processes BHrecruitment Maturation halfM

@time_step Phase1b
processes halfM Ageing

@time_step Phase1c
processes halfM Ageing
```

The input configuration file includes definitions of required layers and the estimation, observation, and report parameters as external files.

To carry out a run of the model (to verify that the model runs without any syntax errors), use the command `spm -r -c config.spm`. Note that as SPM looks for a file named `config.spm` by default, we can simplify the command to `spm -r`.

To run an estimation, and hence estimate the parameters defined in the file `estimation.spm` (the catchability constant  $q$ , recruitment  $R_0$ , and the selectivity parameters  $a_{50}$  and  $a_{t095}$ ), use `spm -e`. Here, we have piped the output to `estimate.log` using the command `spm -e > estimate.log`. SPM reports a the results of each iteration of the estimation, and ends with successful convergence,

```
Convergence was successful
Total elapsed time: 1 second
```

The main part of the output from the estimation run is summarised in the file `estimate.log`, and the final objective function is,

```
[Objective_Score]
report.type: objective_function
obs->CAA-year-1998: 26.9694
obs->CAA-year-1999: 33.0978
obs->CAA-year-2000: 27.9806
obs->CAA-year-2001: 27.2654
```



```

obs->CAA-year-2002: 26.1027
obs->CAA-year-2003: 32.2526
obs->CAA-year-2004: 31.8428
obs->CAA-year-2005: 28.0623
obs->CAA-year-2006: 26.7903
obs->CAA-year-2007: 28.9865
obs->CPUE-1998: -1.19468
obs->CPUE-1999: -1.26929
obs->CPUE-2000: -0.799571
obs->CPUE-2001: 1.7364
obs->CPUE-2002: -1.24109
obs->CPUE-2003: -1.61201
obs->CPUE-2004: -1.42141
obs->CPUE-2005: -1.48186
obs->CPUE-2006: -1.61493
obs->CPUE-2007: -1.19333
prior->catchability[CPUEq].q: 0
prior->process[BHrecruitment].r0: 0
prior->selectivity[FishingSel].a50: 0
prior->selectivity[FishingSel].ato95: 0
total_score: 279.259
*end

```

with parameter estimates,

```

catchability[CPUEq].q,process[BHrecruitment].r0,selectivity[FishingSel].a50,selectivity[
  FishingSel].ato95
0.000132342,344357,8.61959,3.28979

```

A profile on the  $R_0$  parameter can also be run, using `spm -p > profile.log`. See the examples folder for an example of the output.

Simulations were run using command `spm -s 10 > simulations.log`. The first 20 lines of the first simulation are,

```

#[CAA-1998]
#report.type: simulated_observation
#observation.label: CAA-year-1998
@observation CAA-year-1998
age_plus_group True
ageing_error normal
categories immature mature
delta 1e-11
layer SSRU
likelihood multinomial
max_age 35
min_age 1
process_error 25
selectivities FishingSel FishingSel
time_step step_one
type proportions_at_age
year 1998
obs All 0 0 0 0 0 0 0.04166666666666664 0 0 0.083333333333333329 0.083333333333333329
      0.083333333333333329 0.083333333333333329 0.125 0.125 0.04166666666666664
      0.04166666666666664 0 0 0.04166666666666664 0.04166666666666664 0.083333333333333329
      0.04166666666666664 0 0.04166666666666664 0 0 0 0 0 0.04166666666666664 0 0
error_value All 343
#end

```

An estimate of the posterior distribution can be found using the command `spm -m -g 0 > MCMC.log`. The first set of output describes the covariance matrix and the MCMC proposal matrix.

```
SPM (Spatial Population Model)
Call: spm -m -q -g 0
Date: Sat Mar 02 22:17:06 2013
v1.1-2013-03-02 (rev. 4884). Copyright (c) 2008-2013, NIWA
User name: dunn
Machine name: NIWA-34253 (Windows_NT, PID=5392)
```

```
[MCMC]
report.type: MCMC
Original covariance matrix:
1.5176e-009,-2.81463,6.63317e-006,4.30669e-006
-2.81463,5.67601e+009,-6629.78,-4345.92
6.63317e-006,-6629.78,0.205587,0.171766
4.30669e-006,-4345.92,0.171766,0.257573
Proposal distribution covariance matrix:
1e-006,-60.2715,0.000170272,0.000110552
-72.2509,5.67601e+009,-6629.78,-4345.92
0.000170272,-6629.78,0.205587,0.171766
0.000110552,-4345.92,0.171766,0.257573
```

Following this, the log file contains the iterations, objective functions values, MCMC acceptance rate, and the step size.

```
MCMC objective function values:
iteration, score, penalty, prior, likelihood, acceptance_rate, acceptance_rate_since_adapt,
step_size
0,279.259,0,0,279.259,0,0,1.2
500,280.713,0,0,280.713,0.00795317,0.00795317,1.2
1000,281.809,0,0,281.809,0.0070204,0.0070204,1.2
1500,281.604,0,0,281.604,0.0103525,0.203998,0.035102
2000,280.292,0,0,280.292,0.0135521,0.194666,0.035102
2500,282.216,0,0,282.216,0.0166476,0.194049,0.035102
3000,281.876,0,0,281.876,0.0196159,0.190567,0.035102
3500,281.379,0,0,281.379,0.0224512,0.185846,0.035102
4000,281.815,0,0,281.815,0.0252081,0.184763,0.035102
4500,280.398,0,0,280.398,0.0279097,0.186249,0.035102
5000,282.257,0,0,282.257,0.0306292,0.192298,0.035102
5500,281.882,0,0,281.882,0.0332813,0.19723,0.035102
6000,281.168,0,0,281.168,0.0358663,0.20124,0.035102
6500,283.89,0,0,283.89,0.0383748,0.204157,0.035102
7000,279.873,0,0,279.873,0.040736,0.204109,0.035102
7500,280.709,0,0,280.709,0.0431292,0.206651,0.035102
8000,284.112,0,0,284.112,0.0454669,0.208893,0.035102
8500,280.29,0,0,280.29,0.0477308,0.210438,0.035102
9000,280.415,0,0,280.415,0.0499456,0.211898,0.035102
9500,280.332,0,0,280.332,0.052087,0.212793,0.035102
10000,280.651,0,0,280.651,0.0542393,0.214664,0.035102
10500,283.776,0,0,283.776,0.0565194,0.354862,0.0313964
11000,280.612,0,0,280.612,0.0587218,0.338295,0.0313964
11500,281.027,0,0,281.027,0.0608549,0.325662,0.0313964
```

The actual MCMC samples are listed at the end of the file.

```
MCMC samples:
catchability[CPUEq].q,process[BHrecruitment].r0,selectivity[FishingSel].a50,selectivity[
FishingSel].ato95
0.000132342,344357,8.61959,3.28979
0.000102228,397790,7.8984,2.71669
9.4818e-005,484658,8.73298,2.89724
8.8761e-005,475851,7.95917,2.51774
8.31511e-005,492521,8.17484,2.94261
7.79492e-005,581250,9.07356,3.41974
```

```

7.8913e-005,540903,8.1619,2.55435
7.37041e-005,598350,8.76242,3.24838
8.53819e-005,551454,8.81046,3.35038
0.000103378,450492,8.88806,3.38724
0.000135259,367253,8.45822,2.63464
9.69254e-005,392904,7.6978,2.74668
9.87004e-005,395569,7.80506,2.63369
0.000110845,478319,9.50454,3.84909
0.000108822,412442,8.4096,3.17506
9.98064e-005,411174,8.78281,3.70964
0.000114158,425020,8.74743,2.59945
0.000110415,427687,8.91301,3.68328
9.49127e-005,432607,8.73753,3.44166
0.000117585,350399,8.27968,3.37995
0.000123312,334557,8.54507,3.10544
0.000172495,251405,7.73917,2.7972
0.000163009,322406,8.99344,3.28607
0.000127201,331985,7.90627,2.94224

```

### 13.2. An example of a simple $10 \times 6$ spatial model with movement

This example implements a  $10 \times 6$  spatial cell model, with preference function movement processes. The population has recruitment, maturation, natural and exploitation mortality, and annual age increment processes, with ages  $1 - 50^+$  and categories labelled immature and mature.

The model was initialised over a 100 year period, and applies the following population processes;

1. A Beverton-Holt recruitment process, recruiting a constant number of individuals to the first age class (i.e.,  $age = 1$ ) in the category labelled immature.
2. A maturation process, where individuals are moved from the immature to the mature categories with a logistic-producing selectivity labelled ‘maturation’.
3. A constant mortality process representing natural mortality.
4. An ageing process, where all individuals are aged by one year, and with a plus group accumulator age class at  $age = 50$ .

The second phase of initialisation also covers 100 years, but includes movement processes in addition to the population processes above;

1. For immature fish, a preference function process that applies movement according to distance, depth, and latitude.
2. For mature fish, a preference function process that applies movement also according to distance, depth, and latitude, but with different functional forms and parameters to the immature movement.

A third phase of initialisation, of period one year, is applied to allow external validation that the initialisation process has stabilised the population to equilibrium (i.e., by confirming that there is no or at least only a small difference in the partition at the end of second and third phases).

Following initialisation, the model runs from the years 1994 to 2007 iterating through two time-steps. The first time-step applies processes of recruitment, maturation, and  $M + F$  processes. The exploitation process (fishing) is applied in the years 1998–2007, with catches defined by the layers Fishing.1998 to Fishing.2007. Movement is applied along with ageing in the second time-step.

The first 60 lines of the main section of the input configuration file are,

```
#####
# Example 2: 10x6 spatial model with preference movement processes
#####

# Model Structure
@model
nrows 6
ncols 10
layer Base
categories immature mature
min_age 1
max_age 30
age_plus_group True
initialisation_phases Phase1 Phase2 Phase3
initial_year 1995
current_year 2007
cell_length 100
time_steps one two
age_size none none

@age_size none
type none
size_weight none

@size_weight none
type none

# Initialisation
@initialisation_phase Phase1
years 100
time_steps initial_step_one

@initialisation_phase Phase2
years 100
time_steps initial_step_two

@initialisation_phase Phase3
years 1
time_steps initial_step_two

@time_step initial_step_one
processes BHrecruitment Maturation M Ageing

@time_step initial_step_two
processes BHrecruitment Maturation M MoveImmature MoveMature Ageing

# Annual Cycle
@time_step one # Summer
processes BHrecruitment Maturation M Fishing

@time_step two # Winter
processes MoveImmature MoveMature Ageing

# Derived quantities
@derived_quantity SSB
type abundance
time_step one
initialisation_time_steps initial_step_one initial_step_two initial_step_two
categories mature
selectivities One
```

The input configuration file includes definitions of required layers and the estimation, observation, and report parameters as external files.

To carry out a run of the model (to verify that the model runs without any syntax errors), use the command `spm -r -c config.spm`. Note that as SPM looks for a file named `config.spm` by default, we can simplify the command to `spm -r`.

To run an estimation, and hence estimate the parameters defined in the file `estimation.spm` (the catchability constant  $q$ , recruitment  $R_0$ , and the selectivity parameters  $a_{50}$  and  $a_{t095}$ ), use `spm -e`. Here, we have piped the output to `estimate.log` using the command `spm -e > estimate.log`. SPM reports a the results of each iteration of the estimation, and ends with successful convergence,

```
Convergence was successful
Total elapsed time: 30 minutes
```

The main part of the output from the estimation run is summarised in the file `estimate.log`, and the final objective function is,

```
[Objective_Score]
report.type: objective_function
obs->mature-2002: 103.484
obs->mature-2003: 93.3921
obs->mature-2004: 121.795
obs->mature-2005: 295.131
obs->mature-2006: 130.959
obs->mature-2007: 190.749
obs->CAA-1998: 258.11
obs->CAA-1999: 197.655
obs->CAA-2000: 115.617
obs->CAA-2001: 356.268
obs->CAA-2002: 350.86
obs->CAA-2003: 305.307
obs->CAA-2004: 475.316
obs->CAA-2005: 488.706
obs->CAA-2006: 315.752
obs->CAA-2007: 421.203
obs->cpue-1998: 29.5441
obs->cpue-1999: 14.1781
obs->cpue-2000: 0.928955
obs->cpue-2001: 31.5182
obs->cpue-2002: 64.906
obs->cpue-2003: 31.3321
obs->cpue-2004: 29.9035
obs->cpue-2005: 19.2172
obs->cpue-2006: 76.8854
obs->cpue-2007: 100.059
obs->CAA-1998-pseudo: 0
obs->cpue-1998-pseudo: 0
prior->catchability[CPUEq].q: 0
prior->preference_function[ImmatureDistance].lambda: 0
prior->preference_function[ImmatureDepth].a50: 0
prior->preference_function[ImmatureDepth].ato95: 0
prior->preference_function[ImmatureLatitude].a50: 0
prior->preference_function[ImmatureLatitude].ato95: 0
prior->preference_function[MatureDistance].lambda: 0
prior->preference_function[MatureDepth].mu: 0
prior->preference_function[MatureDepth].sigma_l: 0
prior->preference_function[MatureDepth].sigma_r: 0
prior->preference_function[MatureLatitude].a50: 0
prior->preference_function[MatureLatitude].ato95: 0
prior->selectivity[FishingSel].a50: 0
```

```
prior->selectivity[FishingSel].ato95: 0
prior->selectivity[Maturation].a50: 0
prior->selectivity[Maturation].ato95: 0
prior->process[BHrecruitment].r0: 0
total_score: 4618.78
*end
```

with parameter estimates,

```
catchability[CPUEq].q, preference_function[ImmatureDistance].lambda, preference_function[
  ImmatureDepth].a50, preference_function[ImmatureDepth].ato95, preference_function[
  ImmatureLatitude].a50, preference_function[ImmatureLatitude].ato95, preference_function[
  MatureDistance].lambda, preference_function[MatureDepth].mu, preference_function[
  MatureDepth].sigma_l, preference_function[MatureDepth].sigma_r, preference_function[
  MatureLatitude].a50, preference_function[MatureLatitude].ato95, selectivity[FishingSel].
  a50, selectivity[FishingSel].ato95, selectivity[Maturation].a50, selectivity[Maturation].
  ato95, process[BHrecruitment].r0
0.000108444, 0.000105271, 3967.75, 1327.03, 71.391, 5.1804, 0.00659763, 4982.86, 2477.32,
  7450.35, 60.7963, 27.2408, 12.3835, 6.22481, 15.1975, 10.8642, 1e+007
```

A profile on the  $R_0$  parameter can also be run, using `spm -p > profile.log`. See the examples folder for an example of the output.

Simulations were run using command `spm -s 10 > simulations.log`. The first 20 lines of the first simulation are,

```
#[CAA-1998-pseudo-simulated]
#report.type: simulated_observation
#observation.label: CAA-1998-pseudo
@observation CAA-1998-pseudo
age_plus_group True
categories immature mature
delta 1e-11
layer cell
likelihood multinomial
#simulation_likelihood multinomial
max_age 30
min_age 1
process_error 50
selectivities FishingSel FishingSel
time_step one
tolerance 0.01
type proportions_at_age
year 1998
obs r2-c5 0 0 0 0 0.10526315789473684 0.052631578947368418 0.026315789473684209
  0.052631578947368418 0.15789473684210525 0.15789473684210525 0.15789473684210525
  0.13157894736842105 0.052631578947368418 0.026315789473684209 0.026315789473684209
  0.026315789473684209 0 0 0 0.026315789473684209 0 0 0 0 0 0 0 0 0
obs r3-c5 0 0 0 0 0 0 0 0 0 0 0.16216216216216217 0.27027027027027029 0.081081081081081086
  0.081081081081081086 0.054054054054054057 0.054054054054054057 0.027027027027027029
  0.027027027027027029 0.027027027027027029 0 0 0.10810810810810811 0 0 0 0
  0.10810810810810811
```

An estimate of the posterior distribution can be found using the command `spm -m -g 0 > MCMC.log`. The first set of output describes the covariance matrix and the MCMC proposal matrix. Following this, the log file contains the iterations, objective functions values, MCMC acceptance rate, and the step size.

The actual MCMC samples are listed at the end of the file.

---

## 14. Post processing output using R

The **R** package `spm` contains a set of **R** functions for reading SPM output, and is available as a precompiled binary for Microsoft Windows (.zip file) or as a source package (.gz file) for Linux. To check the version number and date of the `spm` **R** package (useful for checking that you have the most recent version), use the function `spm.version()`.

The `spm` **R** package includes a range of extract and write functions to aid post-processing of SPM input configuration files and output. The main extract functions are briefly described below. In addition, the package also some undocumented helper functions, that could be useful for writing you own analysis functions. See the the **R** help for more detail e.g., `help(spm)`

### 14.1. Read and extract reports from a SPM output file.

Command: `extract()`

Usage: `extract(file, path = "", ignore.unknown=FALSE)`

Arguments:

**file** the name of the SPM output file to read

**path** Optionally, the operating system path to the directory of the output file.

**ignore.unknown** Ignore unknown reports when reading. (This can be useful to read files that contain undocumented reports or other output)

Output: A list object with elements for each report type.





---

## 15. Troubleshooting

### 15.1. Introduction

SPM is a complex system, providing many opportunities for error — either because the parameter files do not correctly specify the model, or because the model specified does not work as expected. When in doubt, ask an experienced user. Debugging versions of SPM can also be compiled that help to track down cryptic errors.

When SPM generates an error and the error message makes no sense, please let the SPM authors know. Even if you manage to fix the problem yourself, we may be able to implement a more helpful error message and make life easier for the next person to encounter the problem. Guidelines for reporting an error are given in Section 15.3.

Some parameter values of functions or selectivities can result in either very large or very small numbers. These can, on occasion, generate internal numeric overflow errors within SPM. This is the most common cause of an overflow error, and can result in parameter estimates of NaN. The work-around to this type of error is to impose bounds on parameters that exclude the possibility of an overflow error.

### 15.2. Reporting errors

When reporting a bug or problem with SPM, please send a bug report to the authors. Use the text SPM: as the start of the subject line in the email. Note that following these guidelines will assist the SPM authors identify, reproduce, and hopefully solve any reported bugs.

Note that SPM is distributed as unsupported software. We are unable to provide much assistance to users — although we will usually endeavour to try. While we would appreciate being notified of any problems or errors in SPM, please note that we may not be able to provide timely solutions.

### 15.3. Guidelines for reporting a bug in SPM

1. Detail the version of SPM are you using? e.g., “SPM v1.1-2013-03-02 (rev. 4887) Microsoft Windows executable”
2. What operating system or environment are you using? e.g., “IBM-PC Intel CPU running Microsoft Windows 7 Enterprise, Service Pack 1”.
3. Give a brief one-line description of the problem, e.g., “a segmentation fault was reported”.
4. If the problem is reproducible, please list the exact steps required to cause it, remembering to include the relevant SPM configuration file, other input files, and any out generated. Specify the *exact* command line arguments that were used, e.g., “Using the command `spm -e config.spm -q > logfile.out` reports a segmentation fault. The input configuration files are attached.”
5. If the problem is not reproducible (only happened once, or occasionally for no apparent reason), please describe the circumstances in which it occurred and the symptoms observed (but note it is much harder to reproduce and hence fix non-reproducible bugs, but if several reports are made over time that relate to the same thing, then this may help to track down the problem), e.g., “SPM crashed, but I cannot reproduce how I did it. It seemed to be related to a local network crash but I cannot be sure.”

6. If the problem causes any error messages to appear, please give the *exact* text displayed, e.g.,  
segmentation fault (core dumped).
7. Remember to attach all relevant input and output files so that the problem can be reproduced (it can be helpful to compress these into a single file). Without these, it may not be possible to determine the cause of the problem. Note that it is helpful to be as specific as possible when describing the problem.

---

## 16. Acknowledgements

We thank Nokome Bentley (TROPHIA) and Ian Ball (Australian Antarctic Division) for their ideas that led to the development of the movement paradigm employed in this program. Thanks also to Andy McKenzie, Dave Gilbert, and Murray Smith (NIWA) for helpful discussions with the authors. The SPM logo was designed by Erika Mackay (NIWA).

Much of the structure of SPM, equations, and documentation in this manual draw heavily on similar components of the fisheries population model CASAL (Bull et al., 2012). We thank the authors of CASAL for their permission to use their work as the basis for parts of SPM and allow the use of some of the definitions, concepts, and documentation from CASAL in SPM.

The development of SPM was funded by the New Zealand Ministry for Primary Industries, the Ministry of Business, Innovation & Employment (Project C01X1001, Protecting Ross Sea Ecosystems), and the National Institute of Water & Atmospheric Research Ltd. (NIWA) under NIWAs Fisheries Centre Research Programmes 1 and 3.



---

## 17. Quick reference

### 17.1. Population command and subcommand syntax

**@model**      Define the spatial structure, population structure, annual cycle, and model years

nrows      The number of rows  $n_{rows}$  in the spatial structure

ncols      The number of columns  $n_{cols}$  in the spatial structure

layer      The label for the base layer

cell\_length      The length (distance) of one side of a cell

categories      Labels of the categories (rows) of the population component of the partition

min\_age      Minimum age of the population

max\_age      Maximum age of the population

age\_plus\_group      Define the largest age as a plus group

age\_size      Define the label of the associated age-size relationship for each category

initialisation\_phases      Define the labels of the phases of the initialisation

initial\_year      Define the first year of the model, immediately following initialisation

current\_year      Define the current year of the model

time\_steps      Define the @time\_step labels (in order that they are applied) to form the annual cycle

**@initialisation\_phase label**      Define the processes and years of the initialisation phase with label

years      Define the number of years to run

processes      Define the processes (in order of occurrence) to run in each year of the initialisation

**@time\_step label**      Define a time-step with label

processes      Define the process labels, in the order that they are applied, for the time-step

**@process label**      Define a process with label

type      Define the type of process

#### **@process[label].type=constant\_recruitment**

r0      Define the total amount of recruitment at equilibrium abundance levels

categories      Define the categories into which recruitment occurs

proportions      Define the proportion of recruitment that occurs into each category

age      Define the age that receives recruitment

layer      Name of the layer used to determine where recruitment occurs

#### **@process[label].type=bh\_recruitment**

r0      Define the total amount of recruitment at equilibrium abundance levels

categories      Define the categories into which recruitment occurs

proportions      Define the proportion of recruitment that occurs into each category

age      Define the age that receives recruitment

steepness      Define the Beverton-Holt stock recruitment relationship steepness ( $h$ ) parameter

b0      Define the @initialisation\_phase label for the value of the derived quantity to use as the

value of the spawning stock biomass ( $B_0$ )

`ssb` Define the label of the `@derived_quantity` that defines the spawning stock biomass (SSB)

`ssb_offset` Define the offset (in years) for the year of the derived quantity that is to be applied as the SSB in the stock-recruit relationship

`ycs_values` YCS values

`standardise_ycs_years` Years for which the year class strength values are defined to have mean 1.0

`layer` Name of the layer used to determine where recruitment occurs

#### **`@process[label].type=local_bh_recruitment`**

`r0` Define a multiplier of `r0_layer` for calculating the amount of recruitment in each cell at equilibrium abundance levels

`categories` Define the categories into which recruitment occurs

`proportions` Define the proportion of recruitment that occurs into each category

`age` Define the age that receives recruitment

`steepness` Define the Beverton-Holt stock recruitment relationship steepness ( $h$ ) parameter

`b0` Define the `@initialisation_phase` label for the value of the derived quantity to use as the value of the spawning stock biomass ( $B_0$ ) in each cell

`ssb` Define the label of the `@derived_layer` that defines the spawning stock biomass (SSB) in each cell

`ssb_offset` Define the offset (in years) for the year of the derived layer that is to be applied as the SSB in the stock-recruit relationship

`ycs_years` Years for year class strength values

`ycs_values` YCS values

`standardise_ycs_years` Years for which the year class strength values are defined to have mean 1.0

`layer` Define the label of the layer that defines the distribution of recruitment (as a multiplier of  $R_0$  at equilibrium abundances in each cell)

#### **`@process[label].type=ageing`**

`categories` Define the categories that ageing is applied to

#### **`@process[label].type=constant_mortality_rate`**

`m` Define the constant mortality rate to be applied

`categories` Define the categories that mortality is applied to

`selectivities` Define the selectivities applied to each category

`layer` Name of the layer

#### **`@process[label].type=annual_mortality_rate`**

`years` Define the years when the mortality rates are applied

`m` Define the mortality rate to be applied for each year

`categories` Define the categories that mortality is applied to

`selectivities` Define the selectivities applied to each category

`layer` Name of the multiplicative layer to be applied to  $M$

#### **`@process[label].type=event_mortality`**

`categories`     Define the categories that the event mortality is applied to  
`years`        Define the years where the mortality even is applied  
`layers`        Define the layers that specify the event mortality (as the abundance) in each year  
`u_max`        Define the maximum exploitation rate  
`selectivities`     Define the selectivities applied to each category  
`penalty`        Define the event mortality penalty label

**@process[label].type=biomass\_event\_mortality**

`categories`     Define the categories that the event mortality is applied to  
`years`        Define the years where the mortality event is applied  
`layers`        Define the layers that specify the event mortality (as a biomass) in each year  
`u_max`        Define the maximum exploitation rate  
`selectivities`     Define the selectivities applied to each category  
`penalty`        Define the event mortality penalty label

**@process[label].type=Holling\_mortality\_rate**

`is_abundance`     Is the mortality applied as a biomass or as abundance  
`a`        Define the  $a$  parameter of the Holling function  
`b`        Define the  $b$  parameter of the Holling function  
`x`        Define the type of Holling function or Michaelis-Menton function  
`categories`     Define the categories that the Holling mortality rate is applied to  
`selectivities`     Define the selectivities applied to each category  
`predator_categories`     Define the categories of the predator  
`predator_selectivities`     Define the selectivities applied to each predator category  
`u_max`        Define the maximum exploitation rate  
`penalty`        Define the event mortality penalty label

**@process[label].type=Prey-switch\_predation**

`is_abundance`     Is the mortality applied as a biomass or as abundance  
`consumption_rate`     Define the total predator consumption rate  
`prey`        Define the vector of labels for all the prey groups used  
`electivities`     Define the electivities applied to prey groups  $1 \dots n$   
`categories`     Define the categories that the predation mortality is applied to, for all prey groups  
`selectivities`     Define the selectivities applied to each prey category  
`prey_groups`     Assign each prey category to a specific prey group  
`predator_categories`     Define the categories of the predator  
`predator_selectivities`     Define the selectivities applied to each predator category  
`u_max`        Define the maximum exploitation rate  
`penalty`        Define the process penalty label

**@process[label].type=category\_transition**

`from`        Define the categories that are the source of the transition process  
`selectivities`     Define the selectivities applied to the source categories  
`to`        Define the categories that are the sink of the transition process  
`years`        Define the years where the category transition is applied  
`layers`        Define the layers that specify the event mortality (as N for each cell) in each year  
`penalty`        Define the penalty to encourage models parameter values away from those which

result in not enough individuals to move

**@process[label].type=category\_transition\_rate**

from     Define the category that is the source of the transition process  
selectivities     Define the selectivities applied to the source categories  
to     Define the category that is the sink of the transition process  
proportions     Define the proportion of individuals to move  
layer     Name of the layer

**@process[label].type=migration**

categories     Define the categories that the migration movement event is applied to  
selectivities     Define the selectivities applied to each category  
proportion     Define the constant multiplier for the proportion of individuals that migrate  
source\_layer     Define the label of a layer that defines the source cells of the migration movement event  
sink\_layer     Define the label of a layer that defines the sink cells of the migration movement event

**@process[label].type=adjacent\_cell**

categories     Define the categories that the adjacent cell movement event is applied to  
selectivities     Define the selectivities applied to each category  
layer     Define the label of a gradient layer that defines the the relative strength of movement to adjacent cells  
proportion     Define the constant multiplier for the proportion that moves from each cell to the neighbouring cell

**@process[label].type=preference**

categories     Define the categories that the preference function movement is applied to  
proportion     Define the constant multiplier for the proportion that the preference function movement is applied to  
preference\_functions     Define the labels of the individual preference functions that make up the total preference function

**@preference\_function label**     Define a preference function with label

type     Define the type of preference function

**@preference\_function[label].type=constant**

layer     Defines the layer which supplies the preference function independent variable  
alpha     Defines the multiplicative constant  $\alpha$

**@preference\_function[label].type=normal**

layer     Defines the layer which supplies the preference function independent variable



alpha     Defines the multiplicative constant  $\alpha$   
mu        Defines the  $\mu$  parameter of the normal preference function  
sigma     Defines the  $\sigma$  parameter of the normal preference function

**@preference\_function[label].type=double\_normal**

layer     Defines the layer which supplies the preference function independent variable  
alpha     Defines the multiplicative constant  $\alpha$   
mu        Defines the  $\mu$  parameter of the double-normal preference function  
sigma\_l    Defines the  $\sigma_L$  parameter of the double-normal preference function  
sigma\_r    Defines the  $\sigma_R$  parameter of the double-normal preference function

**@preference\_function[label].type=logistic**

layer     Defines the layer which supplies the preference function independent variable  
alpha     Defines the multiplicative constant  $\alpha$   
a50       Defines the  $a_{50}$  parameter of the logistic preference function  
ato95     Defines the  $a_{to95}$  parameter of the logistic preference function

**@preference\_function[label].type=inverse\_logistic**

layer     Defines the layer which supplies the preference function independent variable  
alpha     Defines the multiplicative constant  $\alpha$   
a50       Defines the  $a_{50}$  parameter of the inverse-logistic preference function  
ato95     Defines the  $a_{to95}$  parameter of the inverse-logistic preference function

**@preference\_function[label].type=exponential**

layer     Defines the layer which supplies the preference function independent variable  
alpha     Defines the multiplicative constant  $\alpha$   
lambda    Defines the  $\lambda$  parameter of the exponential preference function

**@preference\_function[label].type=threshold**

layer     Defines the layer which supplies the preference function independent variable  
alpha     Defines the multiplicative constant  $\alpha$   
n         Defines the  $N$  parameter of the threshold preference function  
lambda    Defines the  $\lambda$  parameter of the threshold preference function

**@preference\_function[label].type=categorical**

layer     Defines the layer which supplies the preference function independent variable  
alpha     Defines the multiplicative constant  $\alpha$   
category\_labels    Defines the unique labels of layer in order of their coefficients  
category\_values    Defines the coefficients for each unique label of layer in order of their labels

**@preference\_function[label].type=monotonic\_categorical**

layer     Defines the layer which supplies the preference function independent variable

`alpha`      Defines the multiplicative constant  $\alpha$   
`category_labels`      Defines the unique labels of `layer` in order of their coefficients  
`category_values`      Defines the coefficients for each unique label of `layer` in order of their labels

**@layer *label***      Define a layer function with label

`type`      Define the type of layer

**@layer[*label*].type=numeric**

`data`      Define the values of the layer

**@layer[*label*].type=categorical**

`data`      Define the values of the layer

**@layer[*label*].type=distance**

**@layer[*label*].type=abundance**

`categories`      Define the categories are used to calculate the abundance

`selectivities`      Define the selectivities applied to each category

**@layer[*label*].type=biomass**

`categories`      Define the categories are used to calculate the biomass

`selectivities`      Define the selectivities applied to each category

**@layer[*label*].type=abundance\_density**

`categories`      Define the categories are used to calculate the abundance

`selectivities`      Define the selectivities applied to each category

**@layer[*label*].type=biomass\_density**

`categories`      Define the categories are used to calculate the biomass

`selectivities`      Define the selectivities applied to each category

**@layer[*label*].type=numeric\_meta**

`default_layer`      Define the default layer to use in years or initialisation phases where it is not otherwise defined

`years`      Define the years that have a non-default layer

`layers`      Define the layers for each of the years

`initialisation_phases`      Define the initialisation phases that have a non-default layer

`initialisation_layers`      Define the layers for each of the initialisation phases

**@layer[*label*].type=categorical\_meta**

`default_layer`      Define the default layer to use in years or initialisation phases where it is not

otherwise defined

years      Define the years that have a non-default layer  
layers      Define the layers for each of the years  
initialisation\_phases      Define the initialisation phases that have a non-default layer  
initialisation\_layers      Define the layers for each of the initialisation phases

**@layer[label].type=derived**

years      Define the years when the calculation is performed  
time\_step      Define the time-step at which the calculation is performed  
layers      Define the layers to be used in the calculations

**@derived\_quantity label**      Define a derived quantity with label

type      Define the type of derived quantity

**@derived\_quantity[label].type=abundance**

categories      Define the categories are used to calculate the derived quantity  
selectivities      Define the selectivities  
initialisation\_time\_steps      Define the time-steps during the initialisation phases at the end of which the derived quantity is calculated  
time\_step      Define the time-step at the end of which the derived quantity is calculated  
layer      Name of the layer

**@derived\_quantity[label].type=biomass**

categories      Define the categories are used to calculate the derived quantity  
selectivities      Define the selectivities  
initialisation\_time\_steps      Define the time-steps during the initialisation phases at the end of which the derived quantity is calculated  
time\_step      Define the time-step at the end of which the derived quantity is calculated  
layer      Name of the layer

**@age\_size label**      Define an age-size relationship with label

type      Define the type of size-at-age relationship

**@age\_size[label].type=von\_bertalanffy**

linf      Define the  $L_{\infty}$  parameter of the von Bertalanffy relationship  
k      Define the  $k$  parameter of the von Bertalanffy relationship  
t0      Define the  $t_0$  parameter of the von Bertalanffy relationship  
size\_weight      Define the label of the associated size-weight relationship

**@age\_size[label].type=schnute**

y1      Define the  $y_1$  parameter of the Schnute relationship

`y2` Define the  $y_2$  parameter of the Schnute relationship  
`tau1` Define the  $\tau_1$  parameter of the Schnute relationship  
`tau2` Define the  $\tau_2$  parameter of the Schnute relationship  
`a` Define the  $a$  parameter of the Schnute relationship  
`b` Define the  $b$  parameter of the Schnute relationship  
`size_weight` Define the label of the associated size-weight relationship

**@size\_weight *label*** Define a size-weight relationship with label  
`type` Define the type of relationship

**@size\_weight [*label*].type=none**

**@size\_weight [*label*].type=basic**

`a` Define the  $a$  parameter of the basic size-weight relationship  
`b` Define the  $b$  parameter of the basic size-weight relationship

**@selectivity *label*** Define a selectivity function with label  
`type` Define the type of selectivity function

**@selectivity [*label*].type=constant**

`c` Defines the  $C$  parameter of the selectivity function

**@selectivity [*label*].type=knife\_edge**

`e` Defines the  $E$  parameter of the selectivity function

**@selectivity [*label*].type=all\_values**

`v` Defines the  $V$  parameters (one for each age class) of the selectivity function

**@selectivity [*label*].type=all\_values\_bounded**

`l` Defines the  $L$  parameter of the selectivity function  
`h` Defines the  $H$  parameter of the selectivity function  
`v` Defines the  $V$  parameters (one for each age class from  $L$  to  $H$ ) of the selectivity function

**@selectivity [*label*].type=increasing**

`alpha` Defines the  $\alpha$  parameter of the selectivity function  
`l` Defines the  $L$  parameter of the selectivity function  
`h` Defines the  $H$  parameter of the selectivity function  
`v` Defines the  $V$  parameters (one for each age class from  $L$  to  $H$ ) of the selectivity function

**@selectivity [*label*].type=logistic**

`alpha` Defines the  $\alpha$  parameter of the selectivity function  
`a50` Defines the  $a_{50}$  parameter of the selectivity function  
`ato95` Defines the  $a_{to95}$  parameter of the selectivity function

**@selectivity[label].type=inverse\_logistic**

alpha     Defines the  $\alpha$  parameter of the selectivity function  
a50       Defines the  $a_{50}$  parameter of the selectivity function  
ato95     Defines the  $a_{to95}$  parameter of the selectivity function

**@selectivity[label].type=logistic\_producing**

alpha     Defines the  $\alpha$  parameter of the selectivity function  
l          Defines the  $L$  parameter of the selectivity function  
h          Defines the  $H$  parameter of the selectivity function  
a50       Defines the  $a_{50}$  parameter of the selectivity function  
ato95     Defines the  $a_{to95}$  parameter of the selectivity function

**@selectivity[label].type=double\_normal**

alpha     Defines the  $\alpha$  parameter of the selectivity function  
mu        Defines the  $\mu$  parameter of the selectivity function  
sigma\_l    Defines the  $\sigma_L$  parameter of the selectivity function  
sigma\_r    Defines the  $\sigma_R$  parameter of the selectivity function

**@selectivity[label].type=double\_exponential**

alpha     Defines the  $\alpha$  parameter of the selectivity function  
x1        Defines the  $x_1$  parameter of the selectivity function  
x2        Defines the  $x_2$  parameter of the selectivity function  
x0        Defines the  $x_0$  parameter of the selectivity function  
y0        Defines the  $y_0$  parameter of the selectivity function  
y1        Defines the  $y_1$  parameter of the selectivity function  
y2        Defines the  $y_2$  parameter of the selectivity function

**17.2. Estimation command and subcommand syntax****@estimation**

minimiser   The label of the minimiser to use, if doing a point estimate  
mcmc        The label of the MCMC to use, if doing an MCMC  
profile      The labels of the profiles to use, if doing a profile

**@minimiser label**     Define the an minimiser estimator with label

type        Define the type of minimiser

**@minimiser[label].type=numerical\_differences**

iterations   Define the maximum number of iterations for the minimiser

`evaluations`     Define the maximum number of evaluations for the minimiser  
`step_size`     Define the step-size for the minimiser  
`tolerance`     Define the convergence criteria (tolerance) for the minimiser  
`covariance`     Specify if SPM should attempt to calculate the covariance matrix, if estimating

**@minimiser[label].type=de\_solver**

`population_size`     Define the minimisers number of populations to generate  
`crossover_probability`     Define the minimisers crossover probability  
`difference_scale`     Define the scale of the difference of the parent candidates for the minimiser  
`max_generations`     Define the maximum generations for the minimiser convergence  
`tolerance`     Define the convergence criteria (tolerance) for the minimiser  
`covariance`     Specify if SPM should attempt to calculate the covariance matrix, if estimating

**@mcmc label**     Define the MCMC estimation arguments

`type`     Define the method of MCMC

**@mcmc.type=metropolis\_hastings**

`start`     Covariance multiplier for the starting point of the Markov chain  
`length`     Length of the Markov chain  
`keep`     Spacing between recorded values in the chain  
`max_correlation`     Maximum absolute correlation in the covariance matrix of the proposal distribution  
`covariance_adjustment_method`     Method for adjusting small variances in the covariance proposal matrix  
`correlation_adjustment_diff`     Minimum non-zero variance times the range of the bounds in the covariance matrix of the proposal distribution  
`step_size`     Initial step-size (as a multiplier of the approximate covariance matrix)  
`proposal_distribution`     The shape of the proposal distribution (either *t* or normal)  
`df`     Degrees of freedom of the multivariate t proposal distribution  
`adapt_stepsize_at`     Iterations in the chain to check and resize the MCMC step-size

**@profile label**     Define the profile parameters and arguments

`parameter`     Name of the parameter to be profiled  
`steps`     Number of steps (values) at which to profile the parameter  
`lower_bound`     lower bound on parameter  
`upper_bound`     Upper bound on parameter

**@estimate parameter\_name**     Estimate an estimable parameter

`same`     Names of the other parameters which are constrained to have the same value  
`estimation_phase`     Phase at which this parameter should be estimated, in point estimation  
`lower_bound`     Lower bounds on this parameter  
`upper_bound`     Upper bound on this parameter  
`mcmc_fixed`     Should this parameter be fixed during MCMC?  
`prior`     Defines the label for the prior for this parameter

**@prior** *label*     Define the prior label

*type*     Define the type of prior

**@prior[label].type=uniform**

**@prior[label].type=uniform.log**

**@prior[label].type=normal**

*mu*     Defines the mean  $\mu$  of the normal prior

*cv*     Defines the c.v.  $c$  of the normal prior

**@prior[label].type=normal.by.stdev**

*mu*     Defines the mean  $\mu$  of the normal by standard deviation prior

*sigma*     Defines the standard deviation  $\sigma$  of the normal by standard deviation prior

**@prior[label].type=lognormal**

*mu*     Defines the mean  $\mu$  of the lognormal prior

*cv*     Defines the c.v.  $c$  of the lognormal prior

**@prior[label].type=beta**

*a*     The lower value of the range parameter  $A$  of the Beta prior

*b*     The upper value of the range parameter  $B$  of the Beta prior

*mu*     Defines the mean  $\mu$  of the Beta prior

*sigma*     Defines the standard deviation  $\sigma$  of the Beta prior

**@catchability** *label*     Define a catchability constant with *label*

*q*     Value of the  $q$  parameter

**@penalty** *label*     Define a penalty with *label*

*log\_scale*     Defines if the penalty is calculated in log space

*multiplier*     Penalty multiplier

### 17.3. Observation command and subcommand syntax

**@observation** *label*     Define an observation

*type*     Define the type of observation

**@observation[label].type=proportions.at.age**

*year*     Define the year that the observation applies to

*time\_step*     Define the time-step that the observation applies to

*proportion\_method*     Define the method for interpolating the time-step for calculating the expected value of the observation

*proportion\_time\_step*     Define the interpolated proportion through the time-step for calculating

the expected value of the observation

categories     Define the categories

selectivities     Define the selectivities applied to each category

min\_age     Define the minimum age for the observation

max\_age     Define the maximum age for the observation

age\_plus\_group     Define is the the maximum age for the observation is a plus group

ageing\_error     Define the label of the ageing-error matrix to be applied (if any)

layer     Name of the categorical layer used to group the spatial cells for the observation

obs [label]     Define the following data as observations for the categorical layer with value [label]

tolerance     Define the tolerance on the sum-to-one error check in SPM

error\_value [label]     Define the following data as error values (e.g.,  $N$  for multinomial likelihoods, c.v. for lognormal likelihoods, etc.) for the categorical layer with value [label]

likelihood     Define the likelihood for the observation

delta     Define the delta robustifying constant for the likelihood

process\_error     Define the process error term

simulation\_likelihood     Define the likelihood when doing simulations, if the observations is a pseudo-observation

#### **@observation[label].type=proportions\_by\_category**

year     Define the year that the observation applies to

time\_step     Define the time-step that the observation applies to

proportion\_time\_step     Define the interpolated proportion of the time-step passes that the observation applies to

categories     Define the categories

categories2     Define the categories

selectivities     Define the selectivities applied to each category

selectivities2     Define the selectivities applied to each category

min\_age     Define the minimum age for the observation

max\_age     Define the maximum age for the observation

age\_plus\_group     Define is the the maximum age for the observation is a plus group

ageing\_error     Define the label of the ageing-error matrix to be applied

layer     Name of the categorical layer used to group the spacial cells for the observation

obs [label]     Define the following data as observations for the categorical layer with value [label]

error\_value [label]     Define the following data as error values (e.g.,  $N$  for multinomial likelihoods, c.v. for lognormal likelihoods, etc.) for the categorical layer with value [label]

likelihood     Define the likelihood for the observation

delta     Define the delta robustifying constant for the likelihood

process\_error     Define the process error term

simulation\_likelihood     Define the likelihood when doing simulations, if the observations is a pseudo-observation

#### **@observation[label].type=abundance**

year     Define the year that the observation applies to

time\_step     Define the time-step that the observation applies to

proportion\_time\_step     Define the interpolated proportion of the time-step passes that the



observation applies to

catchability Define the catchability constant label for the observation  
categories Define the categories for which the observations occur  
selectivities Define the selectivities applied to each category  
layer Name of the categorical layer used to group the spacial cells for the observation  
obs [label] Define the following data as observations for the categorical layer with value [label]  
error\_value [label] Define the following data as error values (e.g.,  $N$  for multinomial likelihoods, c.v. for lognormal likelihoods, etc.) for the categorical layer with value [label]  
likelihood Define the likelihood for the observation  
delta Define the delta robustifying constant for the likelihood  
process\_error Define the process error term  
simulation\_likelihood Define the likelihood when doing simulations, if the observations is a pseudo-observation

#### **@observation[label].type=biomass**

year Define the year that the observation applies to  
time\_step Define the time-step that the observation applies to  
proportion\_time\_step Define the interpolated proportion of the time-step passes that the observation applies to  
catchability Define the catchability constant label for the observation  
categories Define the categories into which recruitment occurs  
selectivities Define the selectivities applied to each category  
layer Name of the categorical layer used to group the spacial cells for the observation  
obs [label] Define the following data as observations for the categorical layer with value [label]  
error\_value [label] Define the following data as error values (e.g.,  $N$  for multinomial likelihoods, c.v. for lognormal likelihoods, etc.) for the categorical layer with value [label]  
likelihood Define the likelihood for the observation  
delta Define the delta robustifying constant for the likelihood  
process\_error Define the process error term  
simulation\_likelihood Define the likelihood when doing simulations, if the observations is a pseudo-observation

**@ageing\_error label** Define ageing error with label

type The type of ageing error

#### **@ageing\_error[label].type=none**

#### **@ageing\_error[label].type=normal**

cv Parameter of the normal ageing error model  
k The  $k$  parameter of the normal ageing error model

#### **@ageing\_error[label].type=off\_by\_one**

p1 The  $p_1$  parameter of the off-by-one ageing error model  
p2 The  $p_2$  parameter of the off-by-one ageing error model  
k The  $k$  parameter of the off-by-one ageing error model

#### 17.4. Report command and subcommand syntax

**@report** *label*     Define an output report

*type*     Define the type of report

**@report [label] .type=spatial\_map**

*file\_name*     Define the name of the output file where the report is written

**@report [label] .type=partition**

*years*     Define the years that the partition report applies to

*time\_step*     Define the time-step that the partition report applies to

*file\_name*     Define the name of the output file where the report is written

*overwrite*     Specify if any previous file with the same name as the output file should be overwritten or appended to

**@report [label] .type=partition\_biomass**

*years*     Define the years that the partition\_biomass report applies to

*time\_step*     Define the time-step that the partition\_biomass report applies to

*file\_name*     Define the name of the output file where the report is written

*overwrite*     Specify if any previous file with the same name as the output file should be overwritten or appended to

**@report [label] .type=initialisation**

*initialisation\_phase*     Define the phase of initialisation that the partition report applies to

*file\_name*     Define the name of the output file where the report is written

*overwrite*     Specify if any previous file with the same name as the output file should be overwritten or appended to

**@report [label] .type=process**

*process*     Define the label of the process to summarise

*file\_name*     Define the name of the output file where the report is written

*overwrite*     Specify if any previous file with the same name as the output file should be overwritten or appended to

**@report [label] .type=preference\_function**

*preference\_function*     Define the label of the preference function to summarise

*file\_name*     Define the name of the output file where the report is written

*overwrite*     Specify if any previous file with the same name as the output file should be overwritten or appended to

**@report [label] .type=derived\_quantity**

`derived_quantity` Define the label of the derived quantity to print  
`file_name` Define the name of the output file where the report is written  
`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

**@report [label] .type=derived\_layer**

`derived_layer` Define the label of the derived layer to print  
`initialisation` Specify if the derived layer values for each year of the initialisation phases should be also be output  
`file_name` Define the name of the output file where the report is written  
`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

**@report [label] .type=estimate\_summary**

`file_name` Define the name of the output file where the report is written  
`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

**@report [label] .type=estimate\_value**

`file_name` Define the name of the output file where the report is written  
`header` Specify if the output contains the standard SPM style header at the start of the output  
`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

**@report [label] .type=objective\_function**

`file_name` Define the name of the output file where the report is written  
`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

**@report [label] .type=covariance**

`file_name` Define the name of the output file where the report is written  
`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

**@report [label] .type=observation**

`observation` Define the label of the observation to print  
`file_name` Define the name of the output file where the report is written  
`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

**@report [label] .type=simulated\_observation**

`observation` Define the label of the observation from which to simulate values  
`file_name` Define the name of the output file where the report is written  
`overwrite` Specify if any previous file with the same name as the output file should be

overwritten or appended to

**@report[label].type=ageing\_error**

ageing\_error    Define the label of the ageing\_error misclassification matrix  
file\_name      Define the name of the output file where the report is written  
overwrite      Specify if any previous file with the same name as the output file should be  
overwritten or appended to

**@report[label].type=layer**

layer          Define the label of the layer to print  
years          Define the years for the printing of the layer  
time\_step      Define the time-step for the printing of the layer  
file\_name      Define the name of the output file where the report is written  
overwrite      Specify if any previous file with the same name as the output file should be  
overwritten or appended to

**@report[label].type=layer\_derived\_view**

layer          Define the label of the layer to print  
years          Define the years for the printing of the layer  
time\_step      Define the time-step for the printing of the layer  
file\_name      Define the name of the output file where the report is written  
overwrite      Specify if any previous file with the same name as the output file should be  
overwritten or appended to

**@report[label].type=selectivity**

selectivity    Define the label of the selectivity to print  
year          Define the year for the printing of the selectivity  
time\_step      Define the time-step for the printing of the selectivity  
file\_name      Define the name of the output file where the report is written  
overwrite      Specify if any previous file with the same name as the output file should be  
overwritten or appended to

**@report[label].type=random\_number\_seed**

file\_name      Define the name of the output file where the report is written  
overwrite      Specify if any previous file with the same name as the output file should be  
overwritten or appended to

**@report[label].type=age\_size**

age\_size      Define the label of the age-size relationship  
file\_name      Define the name of the output file where the report is written  
overwrite      Specify if any previous file with the same name as the output file should be  
overwritten or appended to

**@report[label].type=size\_weight**

`size_weight` Define the label of the size-weight relationship  
`sizes` Define the sizes for which to report the mean weights  
`file_name` Define the name of the output file where the report is written  
`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

**@report [label] .type=age\_weight**

`age_size` Define the label of the age-size relationship  
`file_name` Define the name of the output file where the report is written  
`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

**@report [label] .type=MCMC**

`file_name` Define the name of the output file where the report is written  
`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

**@report [label] .type=MCMC\_samples**

`file_name` Define the name of the output file where the report is written  
`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

**@report [label] .type=MCMC\_objectives**

`file_name` Define the name of the output file where the report is written  
`overwrite` Specify if any previous file with the same name as the output file should be overwritten or appended to

## 17.5. Other commands and subcommands

**@include** *file* Include an external file



---

## 18. References

- I. Ball and A Constable. Fish heaven: A Monte Carlo, spatially explicit single species fishery model for the testing of parameter estimation methods. Technical Report WG-FSA-00/36, Australian Antarctic Division, October 2000.
- I. Ball and A.T. Williamson. Fish heaven user's manual. Technical report, Australian Antarctic Division, August 2003.
- N. Bentley, C.R. Davies, S.E. McNeill, and N.M. Davies. A framework for evaluating spatial closures as a fisheries management tool. New Zealand Fisheries Assessment Report, Ministry of Fisheries, 2004a.
- N. Bentley, N.M. Davies, and S.E. McNeill. A spatially explicit model of the snapper (*Pagrus auratus*) fishery in SNA1. New Zealand Fisheries Assessment Report, Ministry of Fisheries, 2004b.
- R.J.H. Beverton and S.J. Holt. *On the dynamics of exploited fish populations*. Fishery investigations. HMSO, London, 1957.
- B. Bull, R.I.C.C. Francis, A. Dunn, A. McKenzie, D.J. Gilbert, M.H. Smith, R. Bian, and D. Fu. CASAL C++ Algorithmic Stock Assessment Laboratory): CASAL user manual v2.30-2012/03/21. Technical Report 135, NIWA, 2012.
- J. E. Dennis Jr and R.B. Schnabel. *Numerical methods for unconstrained optimisation and nonlinear equations*. Classics in Applied Mathematics. Prentice Hall, 1996.
- A B Gelman, J S Carlin, H S Stern, and D B Rubin. *Bayesian data analysis*. Chapman and Hall, London, 1995.
- W R Gilks, A Thomas, and D J Spiegelhalter. A language and program for complex Bayesian modelling. *The Statistician*, 43(1):169–177, 1994.
- C. S. Holling. The components of predation as revealed by a study of small-mammal predation of the european pine sawfly. *The Canadian Entomologist*, 91:293–320, 1959.
- Makoto Matsumoto and Takuji Nishimura. Mersenne twister: a 623-dimensionally equidistributed uniform pseudo-random number generator. *ACM Transactions on Modeling and Computer Simulation: Special Issue on Uniform Random Number Generation*, 8(1):3–30, January 1998.
- M.I. Michaelis and L. Menten. Die kinetik der invertinwirkung. *Biochemische Zeitschrift*, 49: 333369, 1913.
- Andre E. Punt and Ray Hilborn. *BAYES-SA. Bayesian stock assessment methods in fisheries. User's manual. FAO Computerized information series (fisheries) 12*. Food and Agriculture Organisation of the United Nations, Rome (Italy)., 2001.
- J Schnute. A versatile growth model with statistically stable parameters. *Canadian Journal of Fisheries and Aquatic Sciences*, 38(9):1128–1140, 1981.
- Rainer Storn and Kenneth Price. Differential evolution - a simple and efficient adaptive scheme for global optimization over continuous spaces. Technical Report TR-95-012, International Computer Science Institute, Berkeley, CA, 1995. URL <http://citeseer.ist.psu.edu/182432.html>.





---

## 19. Spatial Population Model software license

THE ACCOMPANYING PROGRAM IS PROVIDED UNDER THE TERMS OF THIS COMMON PUBLIC LICENSE ("AGREEMENT"). ANY USE, REPRODUCTION OR DISTRIBUTION OF THE PROGRAM CONSTITUTES RECIPIENT'S ACCEPTANCE OF THIS AGREEMENT.

### 1. DEFINITIONS

"Contribution" means:

- a) in the case of the initial Contributor, the initial code and documentation distributed under this Agreement, and
- b) in the case of each subsequent Contributor:
  - i) changes to the Program, and
  - ii) additions to the Program;

where such changes and/or additions to the Program originate from and are distributed by that particular Contributor. A Contribution 'originates' from a Contributor if it was added to the Program by such Contributor itself or anyone acting on such Contributor's behalf. Contributions do not include additions to the Program which: (i) are separate modules of software distributed in conjunction with the Program under their own license agreement, and (ii) are not derivative works of the Program.

"Contributor" means any person or entity that distributes the Program.

"Licensed Patents " mean patent claims licensable by a Contributor which are necessarily infringed by the use or sale of its Contribution alone or when combined with the Program.

"Program" means the Contributions distributed in accordance with this Agreement.

"Recipient" means anyone who receives the Program under this Agreement, including all Contributors.

### 2. GRANT OF RIGHTS

a) Subject to the terms of this Agreement, each Contributor hereby grants Recipient a non-exclusive, worldwide, royalty-free copyright license to reproduce, prepare derivative works of, publicly display, publicly perform, distribute and sublicense the Contribution of such Contributor, if any, and such derivative works, in source code and object code form.

b) Subject to the terms of this Agreement, each Contributor hereby grants Recipient a non-exclusive, worldwide, royalty-free patent license under Licensed Patents to make, use, sell, offer to sell, import and otherwise transfer the Contribution of such Contributor, if any, in source code and object code form. This patent license shall apply to the combination of the Contribution and the Program if, at the time the Contribution is added by the Contributor, such addition of the Contribution causes such combination to be covered by the Licensed Patents. The patent license shall not apply to any other combinations which include the Contribution. No hardware per se is licensed hereunder.

c) Recipient understands that although each Contributor grants the licenses to its Contributions set forth herein, no assurances are provided by any Contributor that the Program does not infringe the patent or other intellectual property rights of any other entity. Each Contributor disclaims any liability to Recipient for claims brought by any other entity based on infringement of intellectual property rights or otherwise. As a condition to exercising the rights and licenses granted hereunder, each Recipient hereby assumes sole responsibility to secure any other intellectual property rights needed, if any. For example, if a third party patent license is required to allow Recipient to distribute the Program, it is Recipient's responsibility to acquire that license before distributing the Program.

d) Each Contributor represents that to its knowledge it has sufficient copyright rights in its Contribution, if any, to grant the copyright license set forth in this Agreement.

### 3. REQUIREMENTS

A Contributor may choose to distribute the Program in object code form under its own license agreement, provided that:

- a) it complies with the terms and conditions of this Agreement; and
- b) its license agreement:
  - i) effectively disclaims on behalf of all Contributors all warranties and conditions, express and implied, including warranties or conditions of title and non-infringement, and implied warranties or conditions of merchantability and fitness for a particular purpose;
  - ii) effectively excludes on behalf of all Contributors all liability for damages, including direct, indirect, special, incidental and consequential damages, such as lost profits;
  - iii) states that any provisions which differ from this Agreement are offered by that Contributor alone and not by any other party; and
  - iv) states that source code for the Program is available from such Contributor, and informs licensees how to obtain it in a reasonable manner on or through a medium customarily used for software exchange.

When the Program is made available in source code form:

- a) it must be made available under this Agreement; and
- b) a copy of this Agreement must be included with each copy of the Program.

Contributors may not remove or alter any copyright notices contained within the Program.

Each Contributor must identify itself as the originator of its Contribution, if any, in a manner that reasonably allows subsequent Recipients

to identify the originator of the Contribution.

#### 4. COMMERCIAL DISTRIBUTION

Commercial distributors of software may accept certain responsibilities with respect to end users, business partners and the like. While this license is intended to facilitate the commercial use of the Program, the Contributor who includes the Program in a commercial product offering should do so in a manner which does not create potential liability for other Contributors. Therefore, if a Contributor includes the Program in a commercial product offering, such Contributor ("Commercial Contributor") hereby agrees to defend and indemnify every other Contributor ("Indemnified Contributor") against any losses, damages and costs (collectively "Losses") arising from claims, lawsuits and other legal actions brought by a third party against the Indemnified Contributor to the extent caused by the acts or omissions of such Commercial Contributor in connection with its distribution of the Program in a commercial product offering. The obligations in this section do not apply to any claims or Losses relating to any actual or alleged intellectual property infringement. In order to qualify, an Indemnified Contributor must: a) promptly notify the Commercial Contributor in writing of such claim, and b) allow the Commercial Contributor to control, and cooperate with the Commercial Contributor in, the defense and any related settlement negotiations. The Indemnified Contributor may participate in any such claim at its own expense.

For example, a Contributor might include the Program in a commercial product offering, Product X. That Contributor is then a Commercial Contributor. If that Commercial Contributor then makes performance claims, or offers warranties related to Product X, those performance claims and warranties are such Commercial Contributor's responsibility alone. Under this section, the Commercial Contributor would have to defend claims against the other Contributors related to those performance claims and warranties, and if a court requires any other Contributor to pay any damages as a result, the Commercial Contributor must pay those damages.

#### 5. NO WARRANTY

EXCEPT AS EXPRESSLY SET FORTH IN THIS AGREEMENT, THE PROGRAM IS PROVIDED ON AN "AS IS" BASIS, WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, EITHER EXPRESS OR IMPLIED INCLUDING, WITHOUT LIMITATION, ANY WARRANTIES OR CONDITIONS OF TITLE, NON-INFRINGEMENT, MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. Each Recipient is solely responsible for determining the appropriateness of using and distributing the Program and assumes all risks associated with its exercise of rights under this Agreement, including but not limited to the risks and costs of program errors, compliance with applicable laws, damage to or loss of data, programs or equipment, and unavailability or interruption of operations.

#### 6. DISCLAIMER OF LIABILITY

EXCEPT AS EXPRESSLY SET FORTH IN THIS AGREEMENT, NEITHER RECIPIENT NOR ANY CONTRIBUTORS SHALL HAVE ANY LIABILITY FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING WITHOUT LIMITATION LOST PROFITS), HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE OR DISTRIBUTION OF THE PROGRAM OR THE EXERCISE OF ANY RIGHTS GRANTED HEREUNDER, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

#### 7. GENERAL

If any provision of this Agreement is invalid or unenforceable under applicable law, it shall not affect the validity or enforceability of the remainder of the terms of this Agreement, and without further action by the parties hereto, such provision shall be reformed to the minimum extent necessary to make such provision valid and enforceable.

If Recipient institutes patent litigation against a Contributor with respect to a patent applicable to software (including a cross-claim or counterclaim in a lawsuit), then any patent licenses granted by that Contributor to such Recipient under this Agreement shall terminate as of the date such litigation is filed. In addition, if Recipient institutes patent litigation against any entity (including a cross-claim or counterclaim in a lawsuit) alleging that the Program itself (excluding combinations of the Program with other software or hardware) infringes such Recipient's patent(s), then such Recipient's rights granted under Section 2(b) shall terminate as of the date such litigation is filed.

All Recipient's rights under this Agreement shall terminate if it fails to comply with any of the material terms or conditions of this Agreement and does not cure such failure in a reasonable period of time after becoming aware of such noncompliance. If all Recipient's rights under this Agreement terminate, Recipient agrees to cease use and distribution of the Program as soon as reasonably practicable. However, Recipient's obligations under this Agreement and any licenses granted by Recipient relating to the Program shall continue and survive.

Everyone is permitted to copy and distribute copies of this Agreement, but in order to avoid inconsistency the Agreement is copyrighted and may only be modified in the following manner. The Agreement Steward reserves the right to publish new versions (including revisions) of this Agreement from time to time. No one other than the Agreement Steward has the right to modify this Agreement. IBM is the initial Agreement Steward. IBM may assign the responsibility to serve as the Agreement Steward to a suitable separate entity. Each new version of the Agreement will be given a distinguishing version number. The Program (including Contributions) may always be distributed subject to the version of the Agreement under which it was received. In addition, after a new version of the Agreement is published, Contributor may elect to distribute the Program (including its Contributions) under the new version. Except as expressly stated in Sections 2(a) and 2(b) above, Recipient receives no rights or licenses to the intellectual property of any Contributor under this Agreement, whether expressly, by implication, estoppel or otherwise. All rights in the Program not expressly granted under this Agreement are reserved.

This Agreement is governed by the laws of the State of New York and the intellectual property laws of the United States of America. No party to this Agreement will bring a legal action under this Agreement more than one year after the cause of action arose. Each party waives its rights to a jury trial in any resulting litigation.

## 20. Index

- SPM source code, 2
- About SPM, 3
- Abundance layers, 16
- Abundance or biomass observations, 50
- Abundance-density layers, 16
- Adjacent cell movement, 19, 29
- Age-size relationship, 83
- Ageing, 18, 22
- Ageing error, 52
- Annual cycle, 3, 13, 17, 18
- Annual mortality, 23
- Available reports, 109
- Base layer, 13, 15
- Basic size-weight relationship, 33
- Bayesian estimation, 40
- Beta prior, 43
- Beverton-Holt recruitment, 19
- Biomass layers, 16
- Biomass-density layers, 16
- BOOST C++ library, 2
- Bounds, 38
- CASAL, 4
- Categorical layers, 15
- Categorical meta-layers, 17
- Categorical preference function, 31
- Category transition, 18, 27
- Cell area, 13
- Citation, 1
- Citing SPM, 1
- Classification layers, 15
- Command
  - age\_size, 83, 143
  - ageing\_error, 107, 149
  - catchability, 98, 147
  - derived\_quantity, 81, 143
  - estimate, 95, 146
  - estimation, 91, 145
  - include, 121, 153
  - Include files, 11
  - initialisation\_phase, 60, 137
  - layer, 78, 142
  - mcmc, 93, 146
  - minimiser, 91, 145
  - model, 59, 137
  - observation, 99, 147
  - penalty, 98, 147
  - preference\_function, 73, 140
  - prior, 96, 147
  - process, 61, 137
  - profile, 95, 146
  - report, 109, 150
  - selectivity, 86, 144
  - size\_weight, 85, 144
  - time\_step, 60, 137
- Command block format, 10
- Command line arguments, 7, 8
- Commands, 9
- Commands
  - Subcommands, 9
- Commenting input configuration file, 11
- Comments, 11
- Common Public License, 1
- Constant mortality, 23
- Constant preference function, 30
- Convergence failure, 38
- Correlation matrix, 39
- Covariance matrix, 37, 39
- Covariate layers, 15
- Defining ageing error, 107
- Defining catchability constants, 98
- Defining penalties, 98
- Density-dependent prey-switching, 26
- Derived layers, 16, 32
- Derived meta-layers, 3
- Derived quantities, 3, 31, 81
- Determining parameter names, 11
- Differential evolution minimiser, 2, 38
- Distance layers, 15
- Double-normal preference function, 30
- Estimable parameters, 7
- Estimated parameters, 4, 7
- Estimating parameters, 37
- Estimation methods, 91
- Estimation section, 4
- Event mortality, 24
- Examples, 123
- Examples
  - Example 1, 123
  - Example 2, 127
- Exit status value, 11
- Exponential preference function, 31

- Finite differences minimiser, 2, 38
- Getting help, 2
- Hessian, 39
- Holling mortality, 25
- Include an external file, 121, 153
- Including external files, 7
- Initialisation, 13, 17, 60
  - phases, 17
- Input configuration file, 4, 7
- Input configuration file syntax, 9
- Inter-cell distance, 14
- Inverse-Logistic preference function, 31
- Layers, 15, 77
- Layers
  - the base layer, 15
- Likelihoods, 45
- Linux, 1, 2, 4, 7
- local Beverton-Holt recruitment, 19
- Local minimums, 38
- Logistic preference function, 31
- Lognormal prior, 43
- Maximum exploitation rate, 24–26
- Maximum size of the spatial grid, 13
- MCMC, 37, 40
- Meta-layers, 16
- Microsoft Windows, 1, 2, 4, 7
- Migration, 18
- Migration movement, 28
- Mingw, 2
- Model
  - annual cycle, 3
  - derived meta-layers, 3
  - derived quantities, 3
  - initialisation, 13
  - partition, 3
  - processes, 3
  - state, 3
  - structure, 3
  - time-steps, 3
- Model overview, 3
- Model structure, 59
- Model years, 18
- Monotonic categorical preference function, 31
- Monte Carlo Markov Chain, 40
- Monte Carlo Markov Chain (MCMC), 93
- Mortality, 18, 23
- Movement, 18, 28
- Movement processes, 18, 28
- MPD, 37
- Necessary files, 2
- Normal preference function, 30
- Normal prior, 42
- Notifying errors, 2
- Numeric layers, 15
- Numeric meta-layers, 17
- Objective function, 38
- Objective function evaluations, 38
- Observation section, 4, 5
- Observation types, 99
- Observations, 45
- Optional command line arguments, 9
- Output header information, 8
- Parameter names, 11
- Partition, 3
- Point estimation, 38, 91
- Population processes, 18, 19
- Population section, 4, 13
- Population structure, 14
- Posterior profiles, 39
- Preference function, 29, 30
- Preference function
  - Categorical, 31
  - Constant, 30
  - Double-Normal, 30
  - Exponential, 31
  - Inverse-Logistic, 31
  - Logistic, 31
  - Monotonic categorical, 31
  - Normal, 30
  - Threshold, 31
- Preference functions, 73
- Preference movement, 19, 29
- Print a derived view via a categorical layer, 57
- Print a preference function summary, 56
- Print a process summary, 56
- Print derived layers, 56
- Print derived quantities, 56
- Print layers and meta-layers, 57
- Print observations, fits, and residuals, 57
- Print selectivities, 57
- Print simulated observations, 57
- Print the ageing error misclassification matrix, 57
- Print the covariance matrix, 57

- 
- Print the estimated parameters, 56
  - Print the estimated parameters in a vector format, 56
  - Print the MCMC objective function values as they are calculated, 58
  - Print the MCMC samples as they are calculated, 58
  - Print the model spatial map, 55
  - Print the objective function, 57
  - Print the partition, 55
  - Print the partition at the end of an initialisation, 56
  - Print the partition biomass, 56
  - Print the random number seed, 58
  - Print the results of an MCMC, 58
  - Print the size-at-age relationship, 58
  - Print the size-weight relationship, 58
  - Print the weight-at-age relationship, 58
  - Priors, 38, 96
    - Beta, 43
    - Lognormal, 43
    - Normal, 42
    - Uniform, 42
    - Uniform-log, 42
  - Process error, 52
  - Processes, 3, 4, 18, 61
  - Profiles, 37, 95
  - Proportions-at-age observations, 45
  - Proportions-by-category observations, 48
  - Pseudo-observations, 53
  - Quasi-Newton iterations, 38
  - Random number generator, 2
  - Recruitment, 18, 19
  - Recruitment
    - Beverton-Holt, 19
    - Constant, 19
    - Local Beverton-Holt, 19
  - Redirecting standard error, 8
  - Redirecting standard out, 8
  - Redirecting standard output, 8
  - Report commands and subcommands, 109
  - Report section, 4, 5
  - Reports, 55
  - Reports
    - Ageing error misclassification matrix, 57
    - Covariance Matrix, 57
    - Derived layers, 56
    - Derived quantities, 56
    - Derived view, 57
    - Estimated parameters, 56
    - Hessian, 57
    - Initialisation, 56
    - Layers and meta-layers, 57
    - MCMC, 58
    - MCMC objective functions, 58
    - MCMC samples, 58
    - Objective function, 57
    - Observations, 57
    - Partition, 55
    - Partition biomass, 56
    - Preference Functions, 56
    - Processes, 56
    - Random number seed, 58
    - Selectivities, 57
    - Simulated observations, 57
    - Size-at-age, 58
    - Size-weight, 58
    - Spatial map, 55
    - standard style, 55
    - Weight-at-age, 58
  - Reports section, 55
  - Run years, 17
  - Running SPM, 7
  - Schnute growth curve, 33
  - Selectivities, 34, 85
  - Simulating observations, 52
  - Size-age relationship, 32
  - Size-weight, 85
  - Size-weight relationship, 33
  - Software license, 1
  - Spatial structure, 13
  - Specifying the parameters to be estimated, 37
  - standard error, 8
  - standard output, 8
  - State, 3
  - Subcommand argument type, 10
  - Successful convergence, 38
  - System requirements, 1
  - Tasks, 7
  - Technical specifications, 2
  - The differential evolution minimiser, 39
  - The estimation section, 4, 37
  - The numerical differences minimiser, 38
  - The objective function, 37
  - The observation section, 5
  - The population section, 4, 13
  - The report section, 5, 55

Threshold preference function, 31  
Time sequences, 17  
Time-steps, 60  
time-steps, 3  
Total preference function, 30  
  
Uniform prior, 42  
Uniform-log prior, 42  
User assistance, 2  
Using SPM, 7  
  
Version number, 1  
von Bertalanffy growth curve, 33